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DESIGNING OF CONTINUOUS DAM MONITORING USING GLOBAL NAVIGATION SATELLITE SYSTEMS

Abstract

The paper presents the procedure for designing a geodetic system for continuous dam monitoring and equipment necessary for the application of the *Global Navigation Satellite System (GNSS)*. It also points out the conditions that must be respected when choosing the position of the network points and indicates the advantages and disadvantages of this system in relation to systems based on terrestrial methods. Basically, both systems provide the data necessary to monitor dam stability. Theoretical considerations have been applied to monitoring system of *Soubella* earth-filled dam, in Algeria. The dam created an artificial lake with a capacity of 160,000,000 m^3, providing water for irrigation in the settlement below the dam. Due to the settlement vicinity, it is planned to carry out continuous dam monitoring.

Keywords: continuous monitoring, global navigation satellite system, dam

ПРОЈЕКТОВАЊЕ КОНТИНУИРАНОГ МОНИТОРИНГА БРАНА ПОМОЋУ ГЛОБАЛНИХ НАВИГАЦИОНИХ САТЕЛИТСКИХ СИСТЕМА

Сажетак

У раду је приказан поступак пројектовања геодетског система за континуирани мониторинг брана и опрема неопходна за примјену Глобалног Навигационог Сателитског Система (ГНСС). Наглашени су услови који се морају поштовати при избору положаја тачака мреже. Наведене су предности и недостаци овог система у односу на системе засноване на терестричким методама. У суштини, оба система дају податке неопходне за осматрање стабилности бране. Теоријска разматрања су примјењена на систему за осматрање земљане бране *Soubella*, у Алжиру. Изградњом бране формирано је вјештачко језеро капацитета 16000000 m^3 из којег се обезбјеђује вода за заливање у насељу непосредно испод бране. Због близине насеља предвиђено је континуирано праћење бране.

Кључне ријечи: континуирани мониторинг, глобални навигациони сателитски систем, брана

1. INTRODUCTION

Structural deformations occur under the influence of the following causes: general (physical and mechanical properties of the soil, tendency of soil to plastic or elastic deformations, heterogeneous composition of the soil, hydro technical conditions) and special (deficiencies and inaccuracies in geological and hydrological soil examination, poor water drainage, washing soil particles, scouring from surface waters, wetting of loess soil, dissolution of frozen soil, artificial lowering of groundwater, omissions during construction, upgrades, etc.) [1].

Construction monitoring is carried out: to prevent human and material disasters, improve the quality of future construction, as well as for scientific purposes. Monitoring could be defined as research that includes several professions: civil engineering, geodesy and mining. The geodetic profession discretizes the object in visible points of the structure and determines the displacements in the absolute (system of the object) and relative system. Geodetic monitoring may be carried out in epochs or continuously. Other professions determine the displacements in relative terms using sensors (inclinometers, extensometers, inverted pendulum, etc.) that are built into the structure during construction [2]. Modern devices from other professions intended for continuous monitoring have the ability to collect data with high frequency (up to 300 Hz), as opposed to the geodetic devices in which the frequencies are significantly lower (5 Hz do 50 Hz) [3].

Development of robotic total stations and introduction of GNSS technology initiated the era of continuous geodetic monitoring. Ever since the introduction of GNSS technology, researchers showed interest in the possibility of its use for the purpose of monitoring facilities. Researchers at the University of Nottingham tested measuring of high-frequency deformations (short-period deformations) using GPS (*Global Positioning System*) technology, and the measurements were compared with accelerometer measurements [4], [5]. It is known that GPS is used to measure movements of maximum frequency up to 10 Hz, that is long-period changes. The development of a new GPS receiver, manufactured by the *Javad Navigation System*, and the application of program developed at the University of Nottingham enabled measuring movement frequencies of 50 Hz, with centimeter accuracy. In one study, the authors [6] compared the estimates of the displacement vector obtained using GNSS technology and an inclinometer. They pointed out that the geodetic measurement technology obtained a spatiotemporal series of displacements in the absolute system, and geotechnical in the relative 2D coordinate system. Considering the fact that the research provided almost identical estimates, they concluded that GNSS technology can be used successfully. Researchers [7] concluded that GNSS technology and longer measurement sessions can achieve a 1 mm precision in the 2D coordinate system and 2 mm precision in the 1D coordinate system.

Apart from the development of measurement sensors and measuring technology in general, great progress in the field of monitoring infrastructure facilities has occurred after the development of the Internet, mobile technology, wireless and time series data processing software [8]. These technical improvements enabled the possibility of networking of measurement sensors and the development of real-time permanent monitoring systems. Modern research is focused on the integration of geodetic and sensors of other professions (primarily geotechnical) and the establishment of active systems for Structural Health Monitoring (SHM). Many research papers have presented the possibilities of GNSS technology in specific experimental settings [9]. However, the systematization of these findings and defining procedures for permanent monitoring designing require particular attention.

This paper presents the process of designing a geodetic system for continuous dam monitoring, with particular reference to the equipment necessary for the application of GNSS technology and its networking into a single system and the specifics that must be observed in selecting the position of control geodetic network points. In order to review all system elements, we carried out research on the existing solutions for continuous monitoring and presented their development. The results of practical research are presented through the project solution of permanent monitoring of the earth-filled *Soubella* dam, particularly emphasizing the following: influence of satellite geometry quality on positioning accuracy, defining the coordinate system of the basic network obtained by GNSS measurements and system components with the most important characteristics. Additionally, it presents the criteria for the geodetic network quality and the displacement measures (movement) that can be detected, obtained by calculating the accuracy for the defined geometry, the observation plan and the adopted measurement precision.

2. DEVELOPMENT OF SYSTEMS FOR PERMANENT GEODETIC MONITORING USING GNSS TECHNOLOGY

The geodetic network for continuous monitoring consists of, as all geodetic networks in engineering, basic network points, which are placed outside the deformation zone, and points on the facility. On the basic network points are installed stationary GNSS receivers or total stations, whereas stationary GNSS receivers, rover stations or prisms may be installed at the points on the facility.

Considering the fact that the permanent monitoring systems are intended for monitoring deformation processes at critical locations, the system management and data processing are carried out in special centers. There are local and management centers. The local center is connected to computers and measurement sensors are attached to it. The connection between local centers and computers is made using cables or wireless (usually radio modems). Vectors are processed in local centers, and they are further forwarded to the control center and corrections are sent to sensors. The number of local centers depends on the size of the monitored location and the configuration of the terrain, that is on the possibility of establishing a direct connection with the sensors. The control center processes measurements from all local centers. Data processing is automatic, and it is conducted using a specially developed program. The system in the control center is often supported by light signals. Usually, if the displacement is within the allowable range, the green lamp is on, in case of alarm (displacement is close to the allowed range), the orange lamp is on, and in case the displacement is outside the allowed range, red lamp goes on, followed by an alert message. However, the final decision on the alert is made by the responsible person due to possible errors in the system. Later in this chapter are presented some of the most frequently used systems for permanent geodetic monitoring.

The best-known monitoring system is *GOCA (GOCA - GNSS/LPS/LS-based Online Control and Alarm System)* [10]. This system is intended for determining three-dimensional displacement, and it was developed at the Karlsruhe University of Applied Sciences. In this system, the measured data are sent from the base station by radio communication to rover stations, where vectors are processed. The data on the processed vectors are sent to the *GOCA* center by radio modem for further processing. For each point of the facility, displacement, velocity and acceleration are determined by applying sequential adjustment, i.e. Kalman filter. The *GOCA* system organizational scheme is presented in Figure 1.

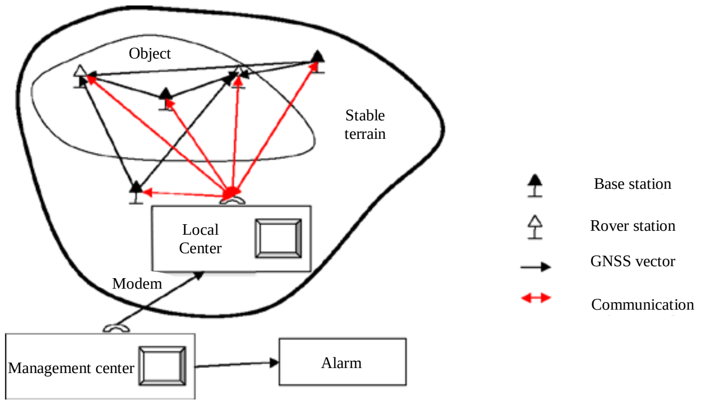

Figure 1. *Operation principles and GOCA system components* [11]

3-D TRACKER is an automated 3D monitoring program developed by the company *Condor Earth Technologies INC*. According to the manufacturer's specification, this program can simultaneously calculate 3D coordinates with millimeter accuracy for dozens of points in which GNSS receivers are located [12]. It is designed for permanent observation, and it can process data from single-frequency and dual-frequency receivers. It applies a different principle for vector processing from the standard RTK (Real Time Kinematic) method. In the RTK method, vectors are processed in a mobile station (rover), and in this program, vector processing is performed in a central station. It forms triple and double differences and epoch-by-epoch coordinate estimates are obtained using the Kalman filter.

LEICA GeoMoS is a multi-purpose automatic monitoring program. It is used for deformation monitoring of structures (dams, tunnels, bridges, tall buildings), landslides, in mines and on volcanic and geotechnically unstable terrain [13]. The program consists of the following modules:

- for monitoring, carrying out control over integrity of the sensor, collecting the measurement results for each measurement moment and analyzing the time series of measurements. Sensors that can be connected for automatic data collection are:
  - geodetic (Leica instruments only): total stations, GNSS receivers, level instruments;
  - meteorological: thermometers and barometers and
  - geotechnical: extensometers, piezometers and inclinometers.
- for analysis, analyzes the accuracy of measurements, enables a graphical display and processes the data and
- additional module, for adjustment, which has functions for epoch-by-epoch network adjustment, deformation analysis and simulation.

The communication of the device is performed using *Leica M-Com* [14] interfaces or standard communication interfaces via the Internet and mobile phone.

Some of the shortcomings of the existing geodetic systems for permanent monitoring that have been identified through research papers are:

- sensors are not located on the facility, but in its vicinity,
- the way of selecting the points that discretize the facility,
- sensor errors and increase in autocorrelation with increasing measurement frequency,
- limited manner of processing and presentation of measurement results due to online mode, etc.

3. SPECIFICITIES OF GNSS MEASUREMENT PLANNING

When planning a GNSS measurement campaign for the development of a GNSS network project, it is necessary to analyze several parameters such as:

- satellite constellations (sky plot of satellites) above the measurement area,
- number and type of receiver (single frequency, dual frequency, triple frequency) that will be used and
- economic aspects.

GNSS measurement requires different planning, implementation and data processing techniques compared to measurements with classical technologies. These requirements come from the difference between GNSS measurement and terrestrial measurement. As opposed to terrestrial measurements, GNSS measurements do not depend on weather conditions and do not require for the receivers to be within sight. The GNSS receiver requires visibility towards satellites.

The shape of the GNSS network does not play an important role as in networks in which terrestrial measurements are performed. The main reason is the mathematical model used in GNSS measurements. This brings us to the conclusion that there is a lot of freedom in designing GNSS networks.

GNSS networks can be shaped as closed (irregular) polygons: triangles, quadrilaterals or polygons. Network of quadrilaterals is recommended, since more closed polygons enable better measurement control. Additionally, it allows better reliability of the obtained results and requires fewer measurements than in the case of triangulation.

The GNSS network shape primarily depends on:

- required accuracy,
- the number of receivers that will be used and
- cost-effectiveness.

According to their form, GNSS networks are divided to [15]:

- radial (star-shaped) networks and
- networks of closed geometric figures.

There are two rules in designing a GNSS network, and one of them must be followed: at least two vectors should start from each point of the network or each point needs to be occupied at least two times.

One of these two rules must be followed in order to prevent blind points in the network. GNSS measurement planning for GNSS network design is most often done in GNSS measurement processing programs that also contain a planning module. Using the planning module saves time and resources in defining the project solution.

GNSS measurement planning for GNSS network design consists of the following stages [16]:

- selection of point positions,

- selection of the observation period,
- determining the duration of the measurement (session duration),
- on-site inspection,
- stabilization of points and
- organization of measurements.

4. INFLUENCE OF SATELLITE GEOMETRY QUALITY ON MEASUREMENT ACCURACY

The quality of determining the position of points using GNSS technology depends on the geometric arrangement of visible satellites. Real-time changes in geometry quality occur due to the mutual movement of the satellites. Geometry quality measures are DOP (Dilution Of Precision) factors. The lower the value of the DOP factor, the better the geometry of the satellite, and the expected quality of the positioning solution. In principle, fair satellite geometry consists of several satellites that are evenly distributed in azimuth and are located slightly above the horizon, with one or more satellites in the direction close to zenith.

Monitoring of engineering structures with GNSS technology, due to the requirements of accuracy, implies the application of the relative positioning method, which is used to obtain 3D coordinate differences between network points. Additionally, phase measurements of pseudoranges are used to determine them. For example, the wavelength of L1 signal is 19 cm, whereas L2 is 24 cm. The accuracy of measuring the phase difference is approximately 1% of the wavelength. In order to reduce or eliminate measurement errors, the following differences are applied: single (eliminating errors in satellite position, satellite clock and ionosphere), double (eliminating errors satellite and receiver clock differences) and triple differences (determining the number of complete wavelengths) [15], [16]. However, the correct estimation of accuracy based on pseudoranges obtained by phase measurements is complex and commercial software does not contain the procedure of preliminary calculation of accuracy based on them, but on the basis of pseudoranges obtained from code measurements.

Since the measurements are error-laden, the code pseudoranges measured simultaneously at time *t* from station *A* to *n* satellite can be mathematically modeled as [17]:

$$P_A^i = r_A^i + c_0 \delta t_A + \varepsilon_A^i = \sqrt{(x_A - x^i)^2 + (y_A - y^i)^2 + (z_A - z^i)^2} + b_A + \varepsilon_A^i \tag{1}$$

where the superscript *i* has the values *i=1, 2, …, n.* The coordinates of the observed satellites (x^i, y^i, z^i) are calculated from the data of the navigation message for the moment of signal transmission and represent known values. For the purposes of preliminary accuracy calculation in the process of designing GNSS networks, almanac data files with predicted satellite position can be used instead of observations and navigation messages.

In the previous model (formula 1) the majority of elements are not present because it is assumed that their values can be determined and subtracted from the measured pseudoranges. The element includes all measurement errors and unmodelled influences related to the code pseudorange, and the element with the receiver clock error is expressed for practical reasons as a value b_A in linear units of measure.

In order to determine the unknown coordinates and clock synchronization errors of the receiver, it is necessary to use a system of at least four equations, that is to measure the pseudoranges to at least four satellites. In that case, the presence of elements ε_A^i is ignored. If the number of equations is higher than four, the presence of errors is taken into account, and solutions are obtained by estimates in accordance with the least square method. Using the least squares method allows determination of estimates of measurement errors, estimates of unit weight standards and covariance matrix of unknown parameters. [17]:

$$\mathbf{C} = \sigma_0^2 (\mathbf{A}^T \mathbf{C}_P^{-1} \mathbf{A})^{-1} = \sigma_0^2 \mathbf{Q} \, . \tag{2}$$

It is clear from formula 2 that the quality of positioning primarily depends on two key factors: the quality of performed measurements and the number and arrangement of satellites (matrix **Q**). DOP factors are defined and calculated exactly using the matrix **Q** elements, as it follows:

- geometric DOP factor:

$$GDOP = \sqrt{\mathbf{Q}_{XX} + \mathbf{Q}_{YY} + \mathbf{Q}_{ZZ} + \mathbf{Q}_{tt}} \tag{3}$$

- position DOP factor:

$$PDOP = \sqrt{\mathbf{Q}_{XX} + \mathbf{Q}_{YY} + \mathbf{Q}_{ZZ}} \text{ i} \tag{4}$$

- time DOP factor:

$$TDOP = \sqrt{\mathbf{Q}_{XX} + \mathbf{Q}_{YY} + \mathbf{Q}_{ZZ}} \text{ .} \tag{5}$$

DOP factors of horizontal position and height, HDOP and VDOP, can be calculated in a similar way, but the cofactor matrix must be previously transformed so that its elements refer to the axes of the local geodetic system instead to the axes of the WGS84 system.

Table 1 presents the values of DOP factors with the interpretation of the possibility of their use in geodetic applications. It can be concluded that the application of GNSS technology in monitoring requires DOP factor values under 3.

The selection of the observation period in defining the project solution presented in practical research was carried out using the software tool *Trimble GNSS Planning Online* [18] and further on in the paper we will present the most important steps and principle of operation of this powerful tool for GNSS measurement planning.

Table 1. Interpretation of DOP factor values

DOP value	Rating	Interpretation
1	Ideal	Highest possible confidence level to be used for applications demanding the highest possible precision at all times.
1-2	Excellent	Accuracy which allows performing highly precise work.
2-5	Good	Accuracy used in navigation and for standard geodetic works.
5-10	Moderate	Accuracy used for calculations.
10-20	Fair	Rough estimate of point position. It is used for designing, determining the approximate positions of points.
>20	Poor	Poor measurement accuracy. All measurements with a DOP factor higher than 20 should be discarded from data processing.

The first and basic thing that needs to be carefully set up is the data on the location where GNSS measurements will be performed and the elevation angle, which can be set up depending on the terrain configuration and project requirements (Figure 2). Additionally, it is necessary to select the day and period of the day for which you want to see the arrangement of satellites for the location of interest. Afterwards it is possible to enter data on obstructions in the field that can interfere with signal reception at measuring stations, setting azimuth and elevation angle (Figure 3).

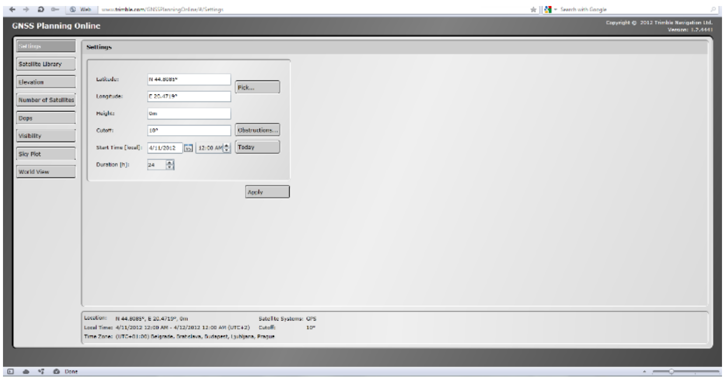

Figure 2. *Location data settings*

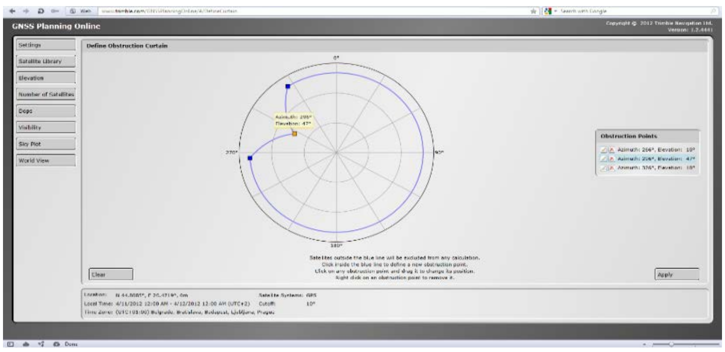

Figure 3. *Obstruction settings*

There are a total of four global and several regional navigation satellite systems nowadays, and some of them have already reached the stage of full operational capability (FOC). In practice, this means that there is a large number of satellites from which measurement signals can be received. Information on satellite correctness and status is publicly available on the official websites. Almost all planning programs provide the option of selecting systems and satellites from which it is planned receive signals, which may be important depending on the type of receiver available (Figure 4).

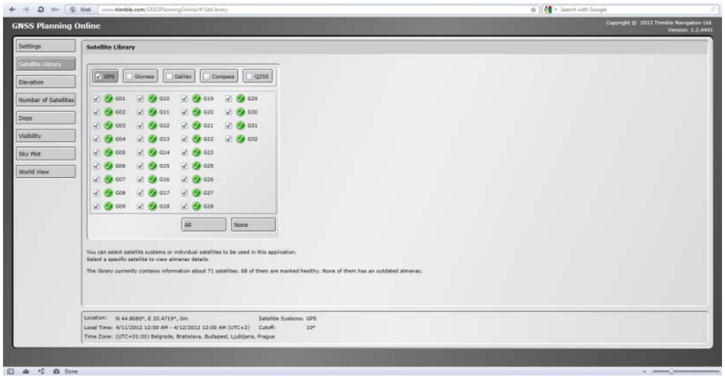

Figure 4. *Selection of satellite system and satellites from which signals will be received*

Number of satellites (Figure 5), their elevation (Figure 6), DOP factors (Figure 7), visibility above a certain location during the day (Figure 8) and sky plot of satellites (Figure 9) represent standard outputs in the process of GNSS measurement planning available in software and services for GNSS measurement planning.

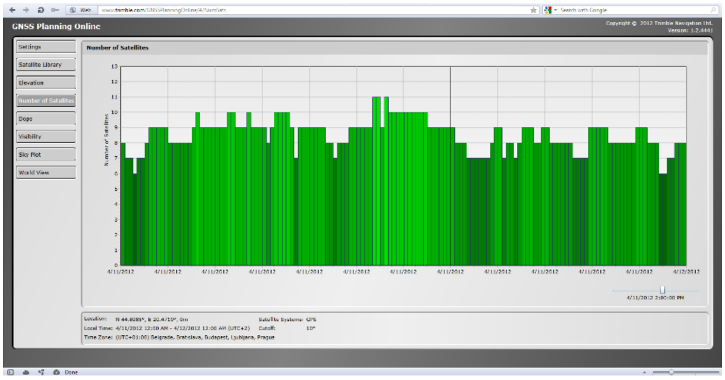

Figure 5. *Number of visible satellites above a certain location*

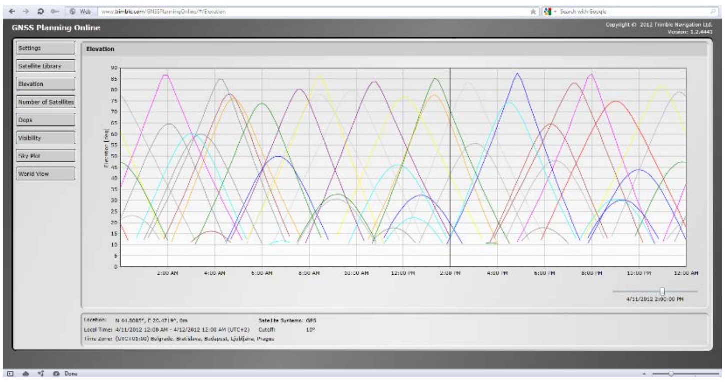

Figure 6. *Elevations of chosen GPS satellites above a certain location*

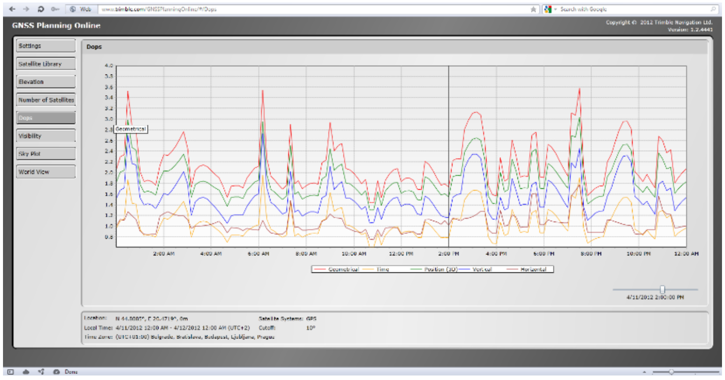

Figure 7. *DOPs for satellite geometry above a certain location*

Figure 8. *Visibility of chosen satellites above a certain location*

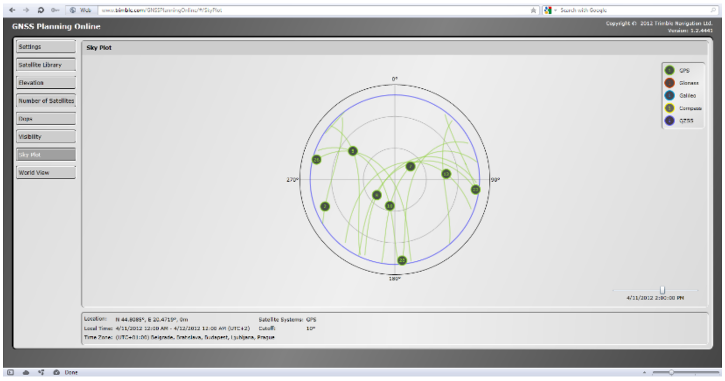

Figure 9. *Sky plot of chosen satellites above a certain location*

5. PRACTICAL RESEARCH

Practical research was presented through the project solution of permanent GNSS monitoring of the earth-filled *Soubella* dam, on the small river of the same name in *Algeria*. It is an earth-filled dam (Figure 10) with a clay core. The dam is 67 m high. The dam crest width is 10 m, and the spillway is Krieger with one spillway bay. The construction of the dam created an artificial lake with a capacity of 160,000,000 m^3, providing water for irrigation in the settlement just below the dam. Due to the settlement vicinity, it is planned to carry out continuous dam monitoring.

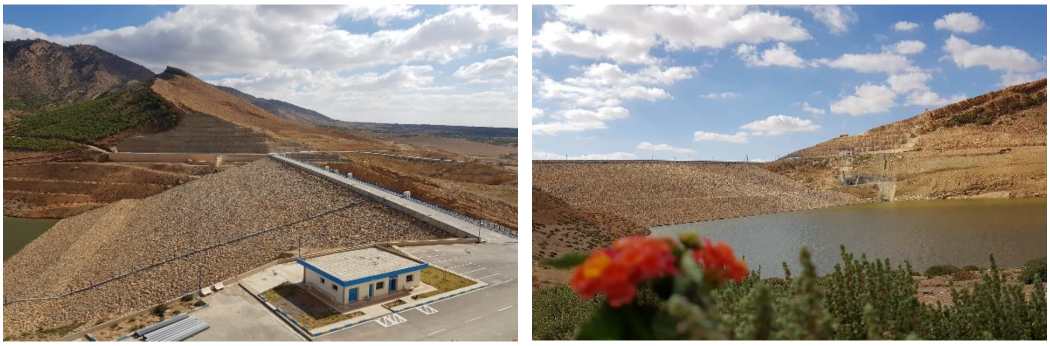

Figure 10. *Soubella dam* [19]

In defining the displacement values that must be detected, we used the standards for monitoring embankment dams shown in Table 2:

Table 2. Accuracy standards of geodetic monitoring of embankment dams [20]

Facility: earth-filled (embankment) dams	Accuracy
Stability of the slope of the dam crest	± 20 – 30 mm
Horizontality of the dam crest	± 20 – 30 mm
Dam crest subsidence	± 10 mm

5.1. SELECTION OF NETWORK POINT POSITIONS

In geodetic monitoring of earth-filled dams, the ideal place for setting the points of the geodetic basic network are the rocks, located at depths or the surrounding terrain, in which the influence of water accumulation (basin) is not felt. Basic network established in this way is a precondition for successful geodetic monitoring of the facility, of permanent assessment of absolute displacements. The *Soubella* dam monitoring network consists of four points (Figure 11). Two points represent reference network points and are located on the rock elevations upstream of the dam (GPS1 and GPS4). Two points, GPS2 and GPS3, are located on the dam crest. It was suggested to use concrete pillars in construction of the points. On top of the pillar should be a plate with a central screw, made of stainless metal, in order to install GNSS antennas. On the concrete steps of the pillars are constructed boxes, in which the installed batteries and routers would be protected from the rain, wind and sand.

WGS84 was selected as the coordinate system of the monitoring network, and in that system, in this specific case, are indicated the coordinate differences obtained by applying GNSS technology. Considering the fact that analysis of the dam stability requires comparison of the differences of estimated coordinates between consecutive GNSS measurement epochs, the transformation into the local coordinate system of the object is not anticipated.

5.2. SYSTEM COMPONENTS

The components of the system for *Soubella* dam permanent monitoring system, as defined in the project solution include:

- sensors,
- communication devices and
- control center.

The system designers had to take into account the fact that GNSS sensors for dam monitoring already existed, and they had to be included in the project solution. These include four *Leica GMX910* GNSS receivers [21]. The positioning accuracy using these sensors is:

- for static post-processing: 3 mm + 0,5 ppm (horizontal) and 5 mm + 1 ppm (vertical) and
- for RTK: 8 mm + 0,5 ppm (horizontal) and 15 mm + 0,5 ppm (vertical).

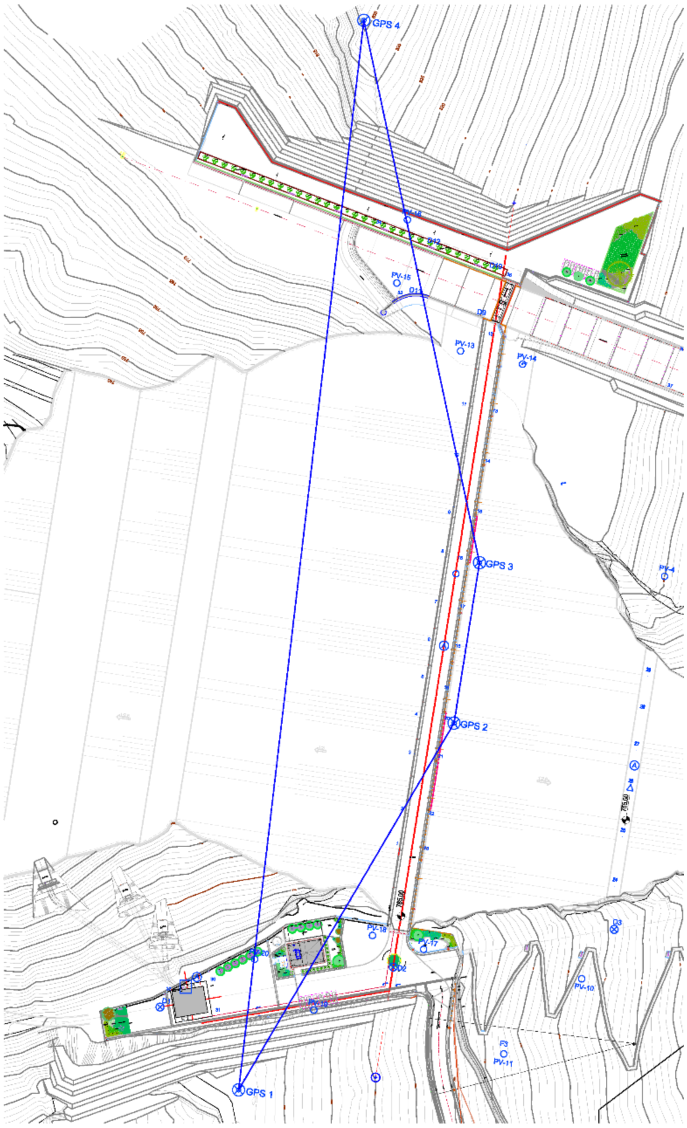

Figure 11. *Outline of the geodetic network of Soubella dam permanent monitoring*

In addition to GNSS sensors, it is planned to install the following equipment at each point (Figure 12):

- solar panel,
- charger,
- spare battery,
- radio modem and proper antenna,
- RS232 network cable for connecting chargers, receivers and radio modems [22] and
- *GEV 197* coaxial cable from *Leica* for link between radio modem and antenna [23].

Charging batteries and receivers is carried out using electric energy which is produced from solar panels on the measuring stations. The modem, chargers, battery and other accompanying equipment at the measuring station are located in a specially designed protective box next to the network pillar. The *Leica GMX910* GNSS receiver is a device with an integrated measuring antenna, hermetically sealed and resistant to external conditions, and therefore requires no additional protection.

Communication between system components is achieved in two ways: by cable connection between individual components at measuring stations and in the control center and using wireless connection between measuring stations and control center. As mentioned above, the cable connection is carried out using network and coaxial cables. Since *Leica GMX910* GNSS sensor is a device that only has an antenna and does not have a data storage unit, the Wireless Local Area Network (WLAN) radio modem continuously sends measurement data from all stations to the control center. The *Leica ComGate10* is a device designed to connect GNSS sensors to LAN (Local Area Network). The network connection to the sensors is achieved using cables that use USB or serial ports as contact or output/input units. The communication systems scheme is presented in Figure 12.

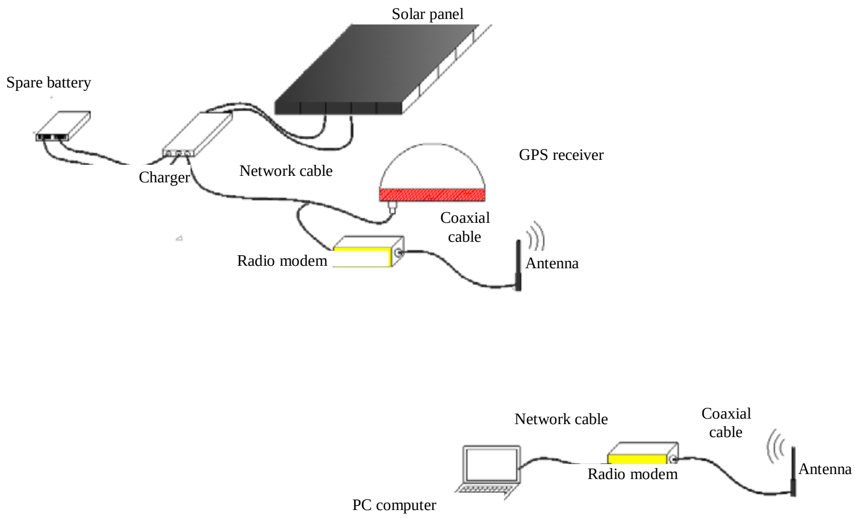

Figure 12. *Communication systems scheme: at measuring stations (above) and in the control centre (below)*

The system control center is located in the command building, and electric energy is supplied from it. It is designed for the installation of the following equipment:

- a robust PC,
- radio modem,
- RS232 network cable for connecting computers and radio modems and
- *Lieca GEV 197* coaxial cable for link between radio modem and antenna.

The minimum computer requirements are 16 GB of RAM, serial and network ports, in order to install *Leica GNSS Spider* [24] and *Leica GeoMoS*, which will process and analyze the collected measurements. *Leica GNSS Spider* is an integrated software package with a primary purpose for centralized control and operation of reference stations and networks. The software is modular and flexible, with new advanced solutions for large high-precision RTK networks and centralized data distribution (*SpiderNET Module*). The *Spider Business Center* module provides efficient management and reporting using an open interface. *Leica GeoMoS* is a multi-purpose software package, which can be used for automatic monitoring of deformations of artificial structures (dams, tunnels, bridges, tall buildings and constructions), as well as for monitoring displacement, subsidence and deformation of natural features. The software is flexible, allowing extension with additional functionalities, and modification depending on the type and number of sensors. All data is stored in an open SQL database, and can be accessed remotely and locally. The project solution considered using both software. In the first step, *Leica GNSS Spider* software will be used for geodetic monitoring of horizontal displacements. In the second step, *Leica GeoMoS* will be installed in order to allow the bodies responsible for monitoring the facility to upgrade the system with non-geodetic sensors and expand it to the SHM monitoring system.

It is planned to perform processing of measurements every hour. In the first step, when using *Leica Spider* software, data post processing will be performed. If the investor decides to use *Leica GeoMoS* software, data processing will also be performed every hour, which will be harmonized with the operation of geotechnical sensors.

5.3. SELECTION OF OBSERVATION PERIOD

The selection of the observation period in defining the project solution was performed using the *Trimble GNSS Planning Online* software tool, as described in Chapter 4. Receivers that will be placed at points on the dam crest (GPS2 and GPS3) cannot receive signals from the entire horizon. Obstructions come from the left side where elevations are located, about 120 m from the points. The receiver at point GPS2 has to receive signals from satellites with elevation angles higher than 18˚, and the receiver at point GPS3 has to receive signals from satellites with elevation angles higher than 23˚. All these obstructions were taken into account when defining the measurement period and calculating the quality of DOP factors. Also, it is planned that all receivers will receive GLONASS signals.

After defining the input parameters, we determined the values of the characteristic elements of the observation plan. The results showed that the number of visible satellites during the day is from 8 to 16. After calculating the DOP factor for the selected parameters, the least favourable values were:

- GDOP 3.15,
- PDOP 3.01,
- HDOP 1.31 and
- VDOP 2.88.

and based on this it was concluded that measurements at the subject location can be carried out throughout the day.

5.4. CALCULATION OF THE PROJECT SOLUTION ACCURACY

Accuracy of the network quality criteria was calculated for the selected network geometry and vector measurement plan. For the purpose of calculation, the declared values for the measuring equipment to be used were adopted for the accuracy of vector measurement. It is suggested that the point GPS1 is the one that defines the network date. It is planned to measure six vectors, therefore the number of unknown parameters is 9 (three coordinates for three points). For the a priori standard unit of weight, the value 3 was adopted. In calculation was used the value of the level of statistical significance 0.05. The predicted values of specific criteria for the measured values are displayed in Table 3.

Table 3. Quality criteria of measured values obtained by calculation

Coordinate difference	$\mathbf{Q}_{v_{ii}}$ [mm^2]	$\mathbf{Q}_{l_{ii}}$ [mm^2]	r_{ii}	G_{ii}
$\Delta X_{GPS1-GPS2}$	0.5	0.5	0.5	11.9
$\Delta Y_{GPS1-GPS2}$	0.5	0.5	0.5	11.9
$\Delta Z_{GPS1-GPS2}$	10.0	10.0	0.5	53.9
$\Delta X_{GPS1-GPS3}$	0.5	0.5	0.5	11.9
$\Delta Y_{GPS1-GPS3}$	0.5	0.5	0.5	11.9
$\Delta Z_{GPS1-GPS3}$	10.0	10.0	0.5	53.9
$\Delta X_{GPS1-GPS4}$	0.5	0.5	0.5	11.9
$\Delta Y_{GPS1-GPS4}$	0.5	0.5	0.5	11.9
$\Delta Z_{GPS1-GPS4}$	10.0	10.0	0.5	53.9
$\Delta X_{GPS2-GPS3}$	0.5	0.5	0.5	11.9
$\Delta Y_{GPS2-GPS3}$	0.5	0.5	0.5	11.9
$\Delta Z_{GPS2-GPS3}$	10.0	10.0	0.5	53.9
$\Delta X_{GPS2-GPS4}$	0.5	0.5	0.5	11.9
$\Delta Y_{GPS2-GPS4}$	0.5	0.5	0.5	11.9
$\Delta Z_{GPS2-GPS4}$	10.0	10.0	0.5	53.9
$\Delta X_{GPS3-GPS4}$	0.5	0.5	0.5	11.9
$\Delta Y_{GPS3-GPS4}$	0.5	0.5	0.5	11.9
$\Delta Z_{GPS3-GPS4}$	10.0	10.0	0.5	53.9

Table 4 shows the values of the quality criteria of unknown parameters that can be obtained for the proposed project solution. We calculated the value of standard deviations in the coordinate axes and the displacement values that can be detected from the coordinate estimates, when selecting the power of a test 0.8.

Table 4. Calculation of the accuracy of unknown parameters with the calculation of displacement values that can be detected from coordinate estimates

Point	standard deviations in coordinate axes [mm]			displacement value [mm]		
	σ_X	σ_Y	σ_Z	dp_X	dp_Y	dp_Z
GPS2	2.1	2.1	9.5	8.5	8.5	37.6
GPS3	2.1	2.1	9.5	8.5	8.5	37.6
GPS4	2.1	2.1	9.5	8.5	8.5	37.6

Pursuant to the accuracy calculation for the proposed project solution, it can be concluded that after the network adjustment, the displacement values in the coordinate axes in the horizontal plane below 10 mm can be detected, which meets the required criteria for monitoring horizontal displacements of the Soubella dam.

6. CONCLUSION

Monitoring of engineering structures depends on the type of deformations to be detected and the characteristics of the structure. The diversity of structural materials is one of the key factors for the occurrence of structural deformations. In the case of earth-filled and embankment dams, or other similar structures, deformations occur as a consequence of the dam weight and the hydrological influence. The embankment is filled with water causing vertical subsidence. Also, the influence of water level in the accumulation leads to permanent deformations in the horizontal plane. Deformations of such structures can also be a consequence of adaptation to new water waves, aging of the embankment or fatigue of the rock mass in which the structure is built in. Of course, such deformations are not considered significant if they do not pose a threat to the structure safety. In order to determine the stability and safety of the structure, it is necessary to carry out geodetic monitoring of the structure and, if necessary, the surrounding terrain. For a complete insight into the trends of displacements of specific structure points, it is necessary to perform permanent measurements using modern measuring technologies. It is particularly suggested to carry out permanent monitoring, and sometimes it is even requested, on all structures that pose direct threat to settlements, such as the case with the Soubella Dam.

Geometric deformation models were applied in the past, and these did not take into account explicit time, and the forces acting on the structure were not taken into account (congruence model and kinematic models). In the 1990’s we started using cause-and-effect models, taking into account time and forces (static and dynamic models). Additionally, the development of new geodetic instruments enabled the possibility of permanent monitoring of critical structures. The application of GNSS technology also enabled special possibilities and advantages in the field of permanent monitoring. Certainly, efforts are being made to optimize its application both in technical and economic terms, as well as in the application of terrestrial measurement technologies. To make this possible, it is necessary to understand the positioning methods and sources of errors affecting the accuracy of their application.

The quality of satellite geometry is characterized by their mutual position in relation to the observation location and has significant effect on measurement accuracy. DOP values are in high correlation with satellite geometry that changes over time due to the relative motion of the satellites. Therefore, DOP values depend on the number of visible satellites. These values are an indicator of the quality of satellite geometry. Good geometry means that the satellites are evenly distributed in all four quadrants.

There were many published scientific and expert papers on the topic of continuous monitoring of individual structures. This paper is a presentation of one view on resolving the problem of designing permanent monitoring using GNSS technology. On the basis of DOP factors, we can evaluate the accuracy of the planned pseudorange measurements and select an appropriate observation period. Application of GNSS model of relative positioning and calculation of the network accuracy allows us to obtain the network quality criteria, and we can see if the suggested geometry and observation plan (functional model) and measurement accuracy (stochastic model) meet the criteria for determining the displacement values of characteristic points and permanent monitoring of the structure in general. It can be concluded from specific practical research that GNSS technology can be used to monitor horizontal displacements even in challenging environments.

However, determining vertical displacements using GNSS technology is still questionable. Certainly, possible improvements in positioning methods, integration with other measuring technologies and sensors of other professions in order to achieve better accuracy in determining vertical displacements are possible directions for further research.

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