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MODERN METHODS FOR ANALYZING THE DEFORMATIONS AND DISPLACEMENTS OF BUILDINGS

BY

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Abstract. As technology advanced the need arose for topo-geodetic methods to evolve in order to provide precise results for monitoring big engineering constructions: dams, bridges, viaducts, high altitude buildings. Structural health monitoring detects the geometric displacements of points. These displacements can be detected with the help of geodetic instruments like tahimeters, theodolites, total stations and GNSS (Global Navigation Satellite Systems) receivers. From the previously mentioned instruments only GNSS receptors are capable of determining the 3D positions of points automatically and continuously. Geodetic GNSS receptors can reach sub-centimeter, up to millimeter precision by using certain post-processing methods. GNSS satellites open new avenues for the structural health monitoring of buildings, allowing more control over the measurement process and also raising the accuracy. Another kind of less accurate monitoring uses stereoscopic images or sequences of images followed by photogrammetric processing. This implies the orientation and correlation of images that will eventually lead to a 3D point cloud similar to what would be obtained using a laser scanner. Because of this the further processing of the point cloud, needed to obtain the displacement of the building, is similar to what would be applied to a point cloud obtained from laser scanning. The images can be gathered from static cameras with an already determined image orientation (pre-calibrated) or from mobile platforms (*e.g.* unmanned aerial vehicles).This paper presents the theory of the measuring

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methods used with GNSS receivers, stereoscopic images and laser scanning. These methods will then be applied to some case studies and a comparison made between the classic methods of monitoring and these new more modern methods.

Keywords: deformations; displacements; GNSS technology; laser scanner; stereoscopic; monitoring; images.

1. Introduction

"Current monitoring of buildings applies to all buildings of any category or class, importance and form of ownership within the borders of Romania" – Normative concerning structural health monitoring of building, P-130-1999.

The monitoring of structures and large-scale engineering buildings (dams, bridges, viaducts and high altitude buildings) in regard to displacements and deformations is one of the main tasks of geodetic engineering.

The geometric displacements of points can be detected with the help of geodetic instruments like: theodolites, total stations, GNSS receivers as well as laser scanning or the use of stereoscopic images.

Structural health monitoring, as well as the analysis of deformations, have a long tradition in geodetic engineering. This is reflected in the large number of symposiums on this topic, some of the most important are: IFS (International Federation of Surveyors) International Symposium regarding monitoring measurements, that recorded numerous achievements from 1975 in Poland, up to 2003 in Greece; IAG (International Airlines Group) Symposium held for the first time in 2006; ISPRS (International Society for Photogrammetry and Remote Sensing) held in 2011, joined the series of Honk Kong symposiums then known as The International Common Symposium On Structural Health Monitoring. The last structural health monitoring symposium was held successfully in 2013, in Great Britain.

The mathematical base developed for this science was achieved by many researchers such as: PELZER (1971), NIEMEIER (1979) and CHEN (1983). Based on these mathematical discoveries, other researchers developed complete work procedures. The developed algorithms, based on statistical testing, can detected the movement o points, group of points and of whole monitoring networks.

Based on the type of deformations, geodetic monitoring methods can be classified as:

a) methods for determining horizontal displacements and deformations: the trigonometric method – micro-triangulation; the alignment method, high precision polygonal coursing;

b) methods for determining vertical displacements and deformations: high precision geometric leveling; high precision trigonometric leveling; hydro-static leveling.

The geometric leveling method is the most precise and at the same time the most used out of all the classic geodetic methods used for monitoring of vertical deformations (Nistor, 1993).

The trigonometric leveling method has a lower precision compared to geometric leveling due to the length of the sigh-line. As the sight-line is greater the influence of atmospheric refraction on the measured height difference is greater (Moldoveanu, 2002).

We can observe that the classic mathematical models used for determining deformations and displacements, together with the used instruments (theodolites and total stations) can offer very high precision.

As technology evolved a need arose to develop new, more practical, precise and fast topo-geodetic methods as a solution for structural health monitoring. As a result of this monitoring for large-scale building (dams, bridges, etc.) can now be done using the following technologies: real time GNSS, laser scanner and stereoscopic images.

2. Monitoring with Real Time GNSS Technology

The real time GNSS method started being applied to various engineering structures as the associated hardware and software improved.

The GNSS system, includes, in general, the GNSS receiver as well as other auxiliary equipment necessary for the transmission, collection and classification of data as well as equipment necessary for real time display of the results.

An important component of classic methods of monitoring deformations is breaking up the task in different time and space components. The definition of the epoch, points to be measured as well as measurement time intervals are strictly necessary for the network points.

Every objects from the surrounding environment reacts dynamically, because it has been influenced by time. In the process of monitoring the deformations and displacements of engineering structures, simplifications are made because some data is not available. From the simplification of time we can derive different different models: the congruence model, the cinematic model, the static model and the dynamic model.

The geodetic network used for monitoring needs to cover a large area and allow long term measurements of the deformations of the dam and surrounding areas, and also allow the possibility to control the likely displacements of reference points with other measuring instruments (redundancy). High precision measurements, which can only be achieved with large time intervals, need the to have the possibility to do limited measurements in order to evaluate deformations (Fig. 1).

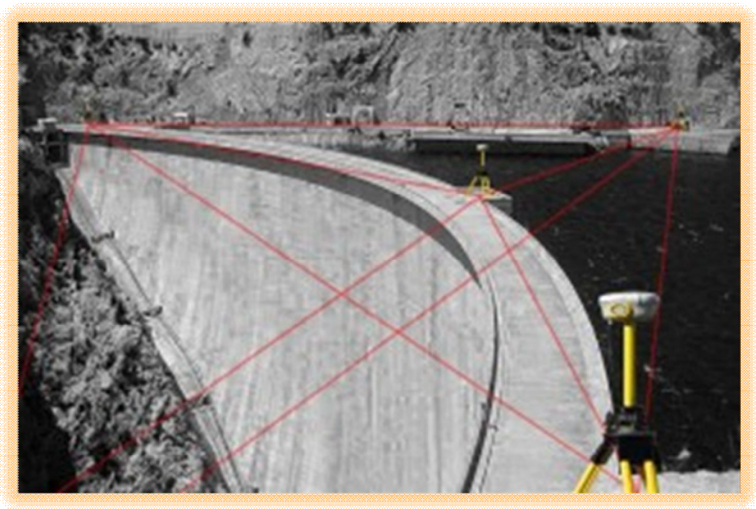

Fig. 1 – The real time GNSS monitoring network of a dam.

3. Monitoring with Laser Scanner Technology

3D Laser Scanning is an advanced technology, discovered at the middle of the 20-th century that is a also a new discovery in measurement technology that has appeared after the GPS system. Through laser scanner measurements we can obtain a high 3D resolution of the points measured on the surface of an object as the scanner can collect a very large amount of spatial information and can offer new technical means for creating the dynamic 3D model of the object.

The optical system of the scanner projects the surface, after some advanced 3D processing we can determine the 3D coordinates (X, Y, Z) and color (R,G,B) for each pixel on the screen, which will eventually generate a digital 3D color image.

The measuring technique offers all the advantages of GNSS, geotechnical and meteorological sensors (Fig. 2).

High speed of the measurements, dense and high number of points and the high precision are the advantages offered by TLS compared to other monitoring technologies.

Compared to technologies that use fixed point monitoring techniques, where the detection of deformations is affected by specific reference point values, TLS offers high data redundancy.

Together with appropriate software products, this technology offers the possibility of precise surface detection, generating millimeter precision.

Because TLS is a long distance measurement technology, the impact on the observed points and on the monitoring network is reduced to a minimum.

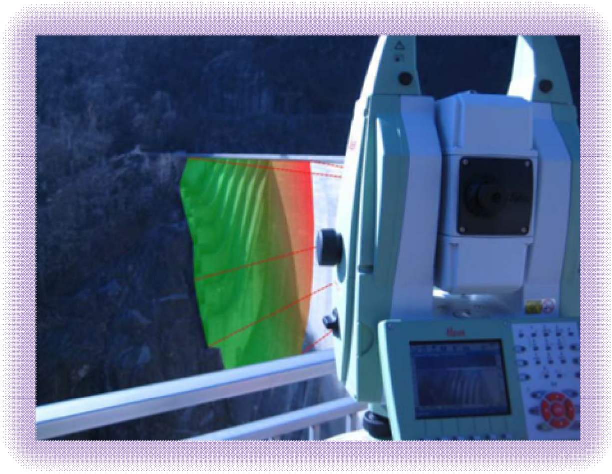

Fig. 2 – The laser scanner monitoring network of a damn.

4. Monitoring with Photogrammetric Methods

Monitoring using photogrammetric methods is defined by generating images at certain fixed positions, selected around the building.

This type of less accurate monitoring uses stereoscopic images or sequence of images, followed by photogrammetric processing, which implies the orientation and correlation of images that will eventually lead to a 3D point cloud, similar to what would be obtained using a laser scanner. Because of this, the further processing of the point cloud, needed to obtain the displacement of the building, is similar to what would be applied to a point cloud obtained from laser scanning. The images can be gathered from static cameras with an already determined image orientation (pre-calibrated) or from mobile platforms (*e.g.* unmanned aerial vehicles).

5. Conclusions

The geometric leveling method is the most precise geodetic method for monitoring vertical deformations. However in certain special conditions, when the area has a sharp slope or when there are discontinuities that can impede the forming of a leveling line, the solution is to apply trigonometric leveling.

Trigonometric leveling has limited precision due to the length of the sight-line, as it increases, the measured level difference is strongly influenced by atmospheric refraction.

Geodetic GNSS receptors can reach sub-centimeter and up to millimeter precision by using certain post-processing methods.GNSS satellites open new avenues for the monitoring of buildings, allowing more control over the measurement process and also raising the accuracy.

Other, less accurate monitoring methods are the ones using laser scanners and photogrammetric images.

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METODE MODERNE DE ANALIZĂ A DEFORMAȚIILOR ŞI DEPLASĂRILOR COSTRUCȚIILOR

(Rezumat)

Odată cu evoluția tehnologiei a apărut necesitatea dezvoltării metodelor topo–geodezice pentru a asigura rezultate precise în monitorizarea construcțiilor inginereşti de mare amploare: baraje, poduri, viaducte, imobile cu înălțimi mari.

Urmărirea în timp a construcțiilor conturează modificări geometrice ale punctelor, ce pot fi detectate cu ajutorul unor instrumente geodezice, cum ar fi tahimetre, teodolite, stațiile totale şi receptoarele GNSS (Sistemul global de navigație prin satelit). Pe lângă instrumentele prezentate anterior, numai receptoarele GNSS sunt capabile să măsoare pozițiile tridimensionale în mod automat şi continuu. Receptoarele GNSS geodezice pot obține o precizie în intervalul sub-cm până la mm, prin metode de post-procesare. Sateliții GNSS deschid noi oportunități de monitorizare a structurilor, a obiectivelor inginereşti, permițând controlul măsurătorilor şi dezvoltând acuratețea acestora. Un alt tip de monitorizare, mai puțin fidelă, este cea a utilizării imaginilor stereoscopice sau a secvențelor de imagini, urmate de procesarea fotogrammetrică care implică orientarea imaginii şi potrivirea imaginilor, ducând la un nor de puncte 3D similar cu cel al scanării cu laser. Ca o consecință, prelucrarea ulterioară a acestui nod de puncte pentru a determina mişcarea obiectului este foarte asemănătoare cu cea pentru norii de scanare cu laser. Acumularea de imagini poate fi realizată de la camera statice cu orientare de imagine cunoscută (pre-calibrată) sau de la platforme mobile, de exemplu vehicule aeriene fără pilot (UAV). În lucrare se prezintă partea teoretică a metodelor de urmărire în timp cu receptoare GNSS, imagini stereoscopice şi scanare laser, care urmează să fie aplicate pentru unele studii de caz (baraje), făcându-se astfel comparaţie între aceste metode moderne şi metodele clasice.