Using terrestrial laser scanning technology for acquisition, processing and interpretation of spatial data from anthropogenic hazard and risk areas

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Abstract— The paper presents practical aspects for monitoring static tested constructions (bridges) and constructions subject to the current operation (dams), bringing to the forefront the possibility of using laser scanning technology.

These types of construction must be continuously monitored in order to eliminate as soon the possibility of occurrence of events that can lead to disaster.

In the case of buildings subjected to static tests confirmation of the viability of using laser scanning technology is done by performing simultaneous geometric leveling measurements to determine the arrow made by the construction elements. For the second type of constructions is shown the possibility of using laser scanning technology in the case when the known classical technologies can not be applied due to the disappearance of constructive elements of the monitoring network.

Keywords— 3D model, laser scanning, „point cloud”, sections.

I. INTRODUCTION

THE paper is devoted to practical research what is composed of two parts and covers the use of terrestrial laser scanning technology for acquisition, processing and interpretation of spatial data in areas of anthropogenic hazard and risk. Both parts of the research were carried out under two contracts made by the Technical University of Civil Engineering Bucharest [10], [11]. The first part of the research is focused on the use of laser scanner to monitor buildings subjected to static tests and the second on the use of terrestrial laser scanning to monitor the upstream face of a gravity rockfill dam.

II. THE USE OF LASER SCANNER FOR MONITORING STATIC TESTED CONSTRUCTION

Monitoring static tested construction is made by determining the arrow of the structural elements of construction, such as beams, columns, plates subjected to vertical or horizontal bending that causes them [5].

Monitored construction, in the present case, is a road bridge (Fig. 1) which has continuous beam type suprastructure, made by console casting, consisting of three openings: one central of 155 m and two marginal of 77.5 m. The total length is 310 m and width at the top of the deck is 14.75 m.

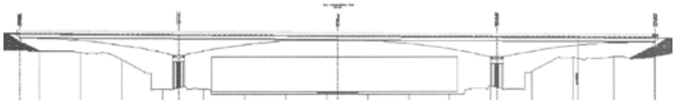

Fig. 1 – Construction studied

In order to determine structural behavior of the bridge an analysis was made using finite element method in different load assumptions.

The construction testing can be done by static or dynamic trials [4]. For the static testing are used various devices and methods for determining the arrows. From the topo-geodetic point of view, in order to determine vertical movements, most often used method is geometric leveling, and the measurements are made with high precision instruments [1]. In the case of monitored construction have been made two sets of measurements in September 2011. A set of measurements was performed using middle geometric leveling method or equal lenghts using a electronic level such as Topcon DL 101-C. These measurements will be used as a reference, with them comparing the second set of measurements made with terrestrial laser scanner Leica Scan Station 2.

For the static testing of the bridge were used three load hypotheses with 12 trucks of 34 tons located in a convoy consisting of two parallel rows, one in the central opening and the other two on the marginal openings. In the three hypotheses measurements were performed using the middle leveling method.

In order to test the laser scanning technology in the case of loading the central opening of the bridge measurements were performed also with terrestrial laser scanner, and we scanned only the central opening.

In order to have reference values, measurements were performed before loading the construction in the three hypotheses, this was considered stage t^0, the next step of measurements are performed during the loadig of the central opening hypothesis.

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At each stage, in the case of leveling measurements, readings were made on a number of 43 points, including four of them located at the two ends of the bridge were used as reference points and the remaining 39 located on the bridge structure (according to the project) have been object points that were used to calculate the arrows. The time during which measurements were made was between 60 and 75 minutes for each stage.

Level differences and distances between points obtained in each stage were processed using geodetic data processing program - SiPreG. This program uses the method of least squares to compensate measurements and obtain final results, as a reference we used a system of local altitudes. The standard deviation of the network composed of the 43 points is 0.1 mm in stage t^0 and 0.3 mm in stage t^1, the accuracy of determination for point heights fits in 1 mm minimum value required in the project and the performance of measuring devices must cover an area at least 50% higher than the expected maximum deformation.

Having available compensated heights of the points at each stage arrows were calculated and compared with theoretical data in the project (Table 1). For comparison, we kept further the corresponding values for the central opening, for which measurements have been made also using terestrial laser scanner.

Table 1 – Arrows calculated in stage "1" compared to stage "0"; Loading on the central opening; Leveling measurements

Point	Calculated arrow (cm)	Theoretical arrow (cm)	Differences (cm)
C'1	0.0	-0.3	0.3
B'1	-3.3	-4.2	0.9
A1	-6.9	-8.2	1.3
B1	-3.3	-4.2	0.9
C1	0.0	-0.3	0.3

In the case of measurements using terrestrial laser scanner it was chosen the method of stationing on the known coordinate points to make the determinations in two stages, the laser scanner allowing to be used in this way, and with two-axis compensator incorporated each measurement (determined point) have received corresponding correction. Therefore measurements from the two stages have the same reference, no longer need multiple points to make point cloud registration, bringing them to the same coordinate system.

In each stage was performed one scanning station to measure the central opening. Station from which measurements were made it was located about 100 m from the bridge, measurements at each stage lasting about 20 minutes. If we wanted to measure the whole construction the measurements could have taken around 80 minutes. If the laser scanner could be placed under the bridge (which is impossible because of the existence of water), time could be reduced to about 60 minutes. For each scanning stage we obtained about 500,000 points in the central opening, the results can be seen in the figure below.

The primary analysis of measured data is done by overlapping the point clouds from the two stages of measurement (Fig. 2: with green point cloud resulting in stage t^0 and with red the point cloud resulting in stage t^1).

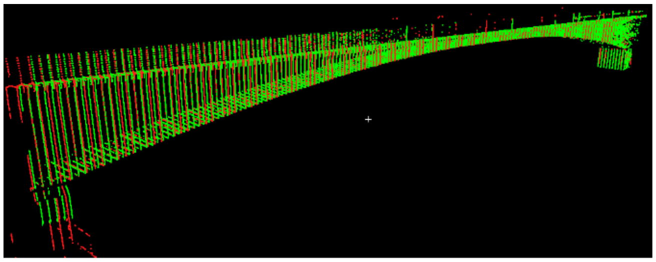


Fig. 2 – Overlapping point clouds

At a first visual analysis we can see the differences between the points determined in the two stages. In Fig. 3 the horizontal displacement of scanned points is due to initial orientation of the scanner and because the scan grid chosen that was different in the two stages, to see if this influences the final result. Vertical displacement is due to the loading of bridge.

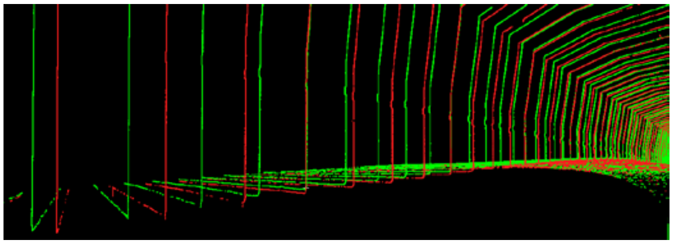


Fig. 3 – Overlapping point clouds - detail

The easiest way to determine the arrow is to create sections with the same origin, through the two point clouds using the Cyclone software [3]. The first operation to obtain sections is to create the alignment from which the sections are made. For alignment we chosen the transverse axis passing through the middle of the bridge and the sections were perpendicular to it.

With sections generated for the two stages, common areas will be selected to determine the arrow. Determination can be made in Cyclone software, measuring the value of the arrow in the same points where it was determined from the measurements of geometric leveling, or at other intervals along the length of the entire section. The results can be obtained using other CAD programs, because the generated sections can be exported in other various formats.

Fig. 4 shows measured values of the arrow, and in Table 2 the comparison with theoretical values.

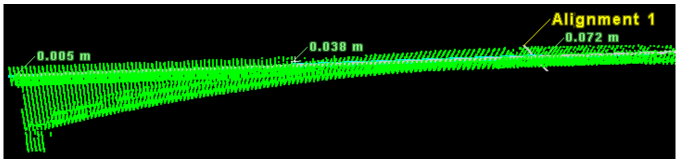


Figure V.4 – Measuring the arrow

In Table 3 are calculated the differences between the results obtained from the two measurements. As shown in table the differences between measurements fall within the tolerance of the laser scanner measurement, which confirms the viability of using this technology.

Table 2 – Arrows calculated in stage "1" compared to stage "0"; Loading on the central opening; Terestrial laser scanner measurements

Point	Calculated arrow (cm)	Theoretical arrow (cm)	Differences (cm)
C'1	0.5	-0.3	0.8
B'1	-3.8	-4.2	0.4
A1	-7.2	-8.2	1.0
B1	-3.8	-4.2	0.4
C1	0.5	-0.3	0.8

Table 3 – Differences between the results obtained from the two measurements

Point	M1- Calculated arrow (cm)	M2 - Calculated arrow (cm)	Differences (cm)
C'1	0.0	0.5	-0.5
B'1	-3.3	-3.8	0.5
A1	-6.9	-7.2	0.3
B1	-3.3	-3.8	0.5
C1	0.0	0.5	-0.5

III. Using Terrestrial Laser Scan To Monitor The Upstream Face Of A Rockfill Weight Dam

Monitoring of dams is an important aspect in ensuring their proper functioning. Monitoring can be done on several levels with physical methods or geometric methods (geodetic measurements).

In the following I will show how a dam monitoring can be done using terrestrial laser scanning technology.

Pecineagu accumulation is located in the upper part of river Dîmbovița in the depression between massive Iezer-Păpușa, Fagaras and Piatra Craiului (Fig. 5).

Fig. 5 – Location of Pecineagu accumulation

Pecineagu dam, with a height of 105 m, the length of 267 m at the crest and a width of 360 m in the central section at the base and 10 m at the canopy is made of rocks and it is sealed with reinforced concrete mask.

Following the operation of the dam, the upstream mask suffered deformation, the maximum being about 400 mm. Repairs made during operation failed to achieve sealing of the mask, and thus it was chosen the solution of covering it with a Carpi membrane (up to 1095 m elevation). This solution led to the destruction of tracking landmarks placed on the mask and the impossibility to do the measurements using the equipment previously used. The feasible solution, which was chosen for the measurements of the mask covered with the membrane was the use of terrestrial laser scanning technology.

Terrestrial laser scanning technology allows measurement of a large number of points placed on the object monitored without the need for them to be accessible but only visible.

The measurement result is represented by a set of points that define the monitored object, generally they are called "point cloud".

For the determination of coordinates (X, Y, H) of points from which the scan was performed I used the method of geometric levelling (for altimetry measurements - H) and method of triangulation and trilateration (for planimetric measurements - X, Y).

For the determination of planimetric coordinates of the network points from wich I performed terrestrial laser scanning was used the total station Leica Builder 300RM, for determination of the point height has been used a Trimble Dini 0.3 type electronic level, and scanning the upstream face was performed with terrestrial laser scanner Leica Scan Station 2, which has the accuracy of determining the spatial position of the points of ± 6 mm to 50 m and surface modeling accuracy of ± 2 mm.

In April 2012 several tests were made to see if terrestrial laser scanning technology can be applied in case of the upstream face of concrete slabs covered with the Carpi membrane. It was first tested at the Technical University of Civil Engineering Bucharest the reflectivity of the Carpi membrane.

This was done to see if the results obtained from scanning at a distance of about 200 m (maximum distance at which the laser scanner can be placed from the upstream face, according to existing plans) can be used to generate the 3D model.

Since the the laser scanner Leica Scan Station 2 have the maximum measurement field between 134 m at a reflectivity of 18% and 300 m at a reflectivity of 90% (according to specifications) was taken into account the angle of incidence of the laser wave made with surface measured, because the sharper it is the reflected signal will be weaker [9]. The color of the membrane was not an important factor because its reflectivity is high.

Measurements were made on a type Carpi membrane, size 20 x 30 cm for three cases of the angle of incidence:

- about 90°, being measured 3098 points – Fig. 6a
- about 50°, being measured 784 points – Fig. 6b

- about 20°, being measured 41 points – Fig. 6c

As can be seen from the results of measurements incidence angle is an important factor to be taken into account when designing points from which terrestrial laser scanning will be performed. If the distance factor, reflection and incidence angle are not correlated there is a risk of not measuring the proposed objective from the station points projected.


a) b) c)

Fig. 6 – Scanned membrane

To find the optimal locations for placement of the terrestrial laser scanner for Pecineagu accumulation measurements, in May 2012 tests were carried out on the spot, being established three locations positioned upstream of the dam crest at distances between 50 and 160 m, with a good incidence angle to the upstream face and three sites located on the dam, which provides small angles of incidence, but allow covering with measurements the areas omitted from the first three stations.

The measurements were carried out on the upstream face in November 2012. In order to cover with terrestrial laser scanning measurements the uncovered upstream face (water elevation at 1052.4 m) were marked six projected points (SW1, SW2, SW3, SW4, SW5, SW6), whose coordinates (X, Y, H) were determined using the triangulation and trilateration method for planimetry and geometric leveling method for altimetry [2].

Aspects from the measurements can be viewed in Fig. 7.


Fig. 7 – Aspects during the measurements

Terrestrial laser scanning was performed from points SW1, SW2, SW3, SW5 and SW6. Scanning in each point lasted about 25 minutes, during this interval were taked first the panoramic images of the scanned area, after the effective scanning of the area was made and in final recording of sighting targets (Fig. 8).

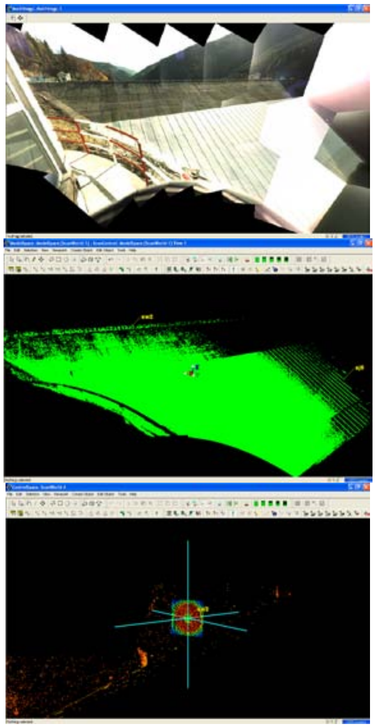


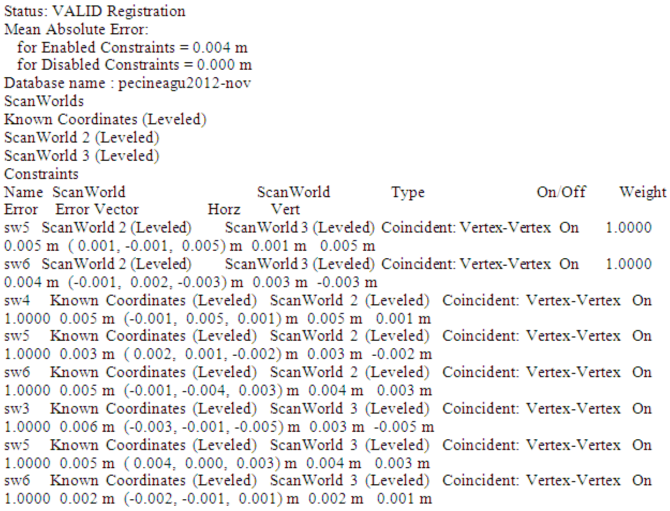
Fig. 8 – Panoramic images, point cloud and sighting target

For determining the heights for new points was used directly in the field BFFB application that allows determination of the difference levels between points and calculate their heights based on known elevation points. Thus we started on the right bank of points RND117, RND117A and level differences were determined passing through the points of unknown height, the closure (checking) being made on points T1, T2 on the left bank. The difference between the heights determined from measurements and known heights was within the measurement tolerances, thus finally obtaining the heights for new points.

For determining planimetric coordinates the measured horizontal distances and directions were rigorously processed using SiPreG program, the average standard deviation of the network was 0.39 cm.

Determined planimetric and altimetric coordinates were used further at georeferencing (bringing in the same coordinate system) the laser scanner measurements.

The mean absolute error at georeferencing has maximum value of 1 cm, the result fits within 2 cm limit accepted by the designer construction. The total individual error of the points varies between 0.2 - 1.0 cm, and the horizontal between 0.1 - 0.8 cm and the vertical between 0.1 - 0.6 cm. An extract from the resulted reports following the georeferencing can be seen below, the report contains information about: the mean absolute error, the individual errors of points, transformation parameters.



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Status: VALID Registration
Mean Absolute Error:
   for Enabled Constraints = 0.004 m
   for Disabled Constraints = 0.000 m
Database name : pecineagu2012-nov
ScanWorlds
Known Coordinates (Leveled)
ScanWorld 2 (Leveled)
ScanWorld 3 (Leveled)
Constraints
Name  ScanWorld                    ScanWorld          Type                     On/Off     Weight
Error   Error Vector             Horz      Vert
sw5  ScanWorld 2 (Leveled)      ScanWorld 3 (Leveled) Coincident: Vertex-Vertex  On      1.0000
0.005 m  ( 0.001, -0.001,  0.005) m  0.001 m   0.005 m
sw6  ScanWorld 2 (Leveled)      ScanWorld 3 (Leveled) Coincident: Vertex-Vertex  On      1.0000
0.004 m  (-0.001,  0.002, -0.003) m  0.003 m  -0.003 m
sw4    Known Coordinates (Leveled)   ScanWorld 2 (Leveled)   Coincident: Vertex-Vertex   On
1.0000  0.005 m  (-0.001,  0.005,  0.001) m  0.005 m   0.001 m
sw5    Known Coordinates (Leveled)   ScanWorld 2 (Leveled)   Coincident: Vertex-Vertex   On
1.0000  0.003 m  ( 0.002,  0.001, -0.002) m  0.003 m  -0.002 m
sw6    Known Coordinates (Leveled)   ScanWorld 2 (Leveled)   Coincident: Vertex-Vertex   On
1.0000  0.005 m  (-0.001, -0.004,  0.003) m  0.004 m   0.003 m
sw3    Known Coordinates (Leveled)   ScanWorld 3 (Leveled)   Coincident: Vertex-Vertex   On
1.0000  0.006 m  (-0.003, -0.001, -0.005) m  0.003 m  -0.005 m
sw5    Known Coordinates (Leveled)   ScanWorld 3 (Leveled)   Coincident: Vertex-Vertex   On
1.0000  0.005 m  ( 0.004,  0.000,  0.003) m  0.004 m   0.003 m
sw6    Known Coordinates (Leveled)   ScanWorld 3 (Leveled)   Coincident: Vertex-Vertex   On
1.0000  0.002 m  (-0.002, -0.001,  0.001) m  0.002 m   0.001 m
```

Georeferenced point clouds were put together in the same file, thus obtaining the upstream face unfiltered 3D model containing 2807094 points. The next step involves filtering (removing) the points that do not belong to the study area, resulting the 3D model filtered wich contains 2312922 points after filtration (Fig. 9, 10).

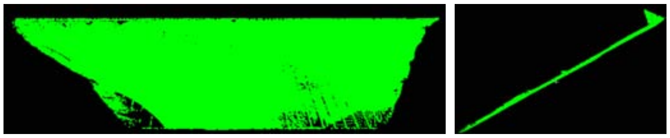


Fig. 9 – Filtrate 3D model, upstream and right view

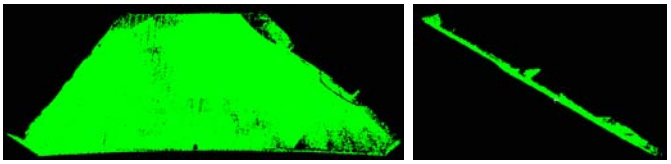
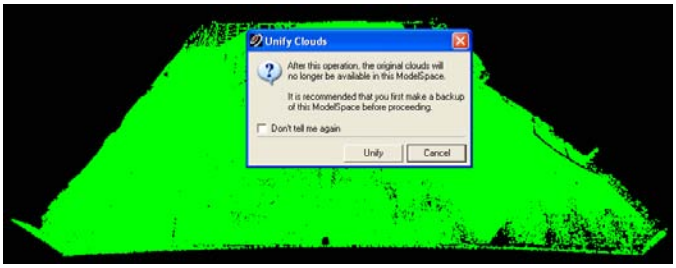


Fig. 10 – Filtrate 3D model, top and left view

The final step in managing the point clouds is to unite and uniform them (Fig. 11), obtaining the final 3D model of the area, wich contains 1889076 points.



After this operation, the original clouds will no longer be available in this ModelSpace.

It is recommended that you first make a backup of this ModelSpace before proceeding.

☐ Don't tell me again

Fig. 11 – Unification of point clouds and obtaining the final 3D model

The final 3D model (nov 2012) can be managed in several ways and can generate from it sections in any desired direction, which can be compared with the generated section on the same lines for models made at different times or with sections generated from the theoretical model. Another way for the management is to create a "mesh" (that best approximates the measured object) on the entire model or parts of the model. Then by overlapping with theoretical model or "mesh" generated at different times the deformations can be observed.

Having the coordinates file of the 3D model this can be imported into any CAD environment and thus being able to generate sections. As the volume of data is huge, their management is done efficiently with specialized software installed on powerful computing environments. If you do not have the necessary hardware and software resources, a solution is that the sections to be generated from the 3D model directly from the Leica Cyclone application, which was used for field data acquisition and later processing. Then the sections can be exported individually or grouped, the resulting files are small and can be handled easily.

For the 3D model of the upstream face two horizontal alignments (at elevation 1118 m) were created (Fig. 12) parallel with the planimetric coordinate axes (X, Y). The alignment parallel to OY was chosen so that the points which shall generate the sections to cover the whole upstream face from one side to the other and the alignment parallel to OX was chosen so that the sections generated to cover the entire length of the upstream face.

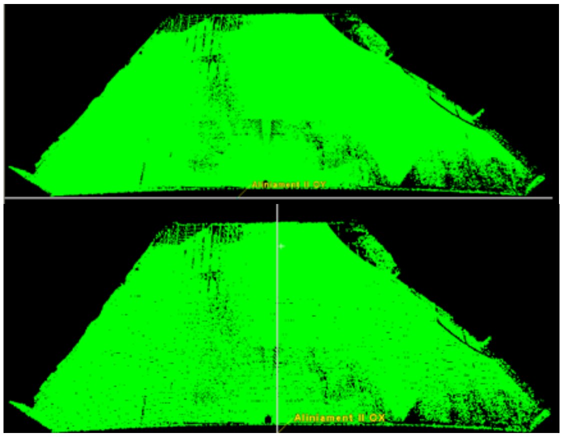


Fig. 12 – Horizontal alignments

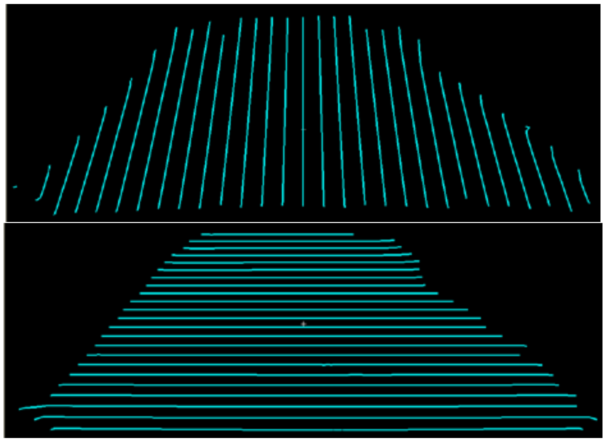


Fig. 13 – Generated sections on alignments

The interval between the sections may vary according to the needs. In order to not have a huge number of sections generated on the two directions was established an interval of 10 m for alignment OY and 5 m for OX, the other limits beeing set up as to not omit points from the model (Fig. 13).

Sections can be easily managed using implemented functions, can be viewed, adjusted on the directions left, right, top, bottom and depth, according to the needs. For the exportation of sections can be used as a reference system the general model system or system specific to each section.

Generating mesh surfaces can be made on whole model or parts of this. Cyclone application can generate mesh surface in three ways: basic meshing, complex meshing, TIN meshing [3]. The first two use simple functions and can be used on models composed of a single point cloud, and the last method uses complex functions based on a network of 3D triangles that are created according to the Delaunay algorithm and can be used on the models composed of several clouds points. For generating the mesh surface for the upstream face the last option was used (Fig. 14).

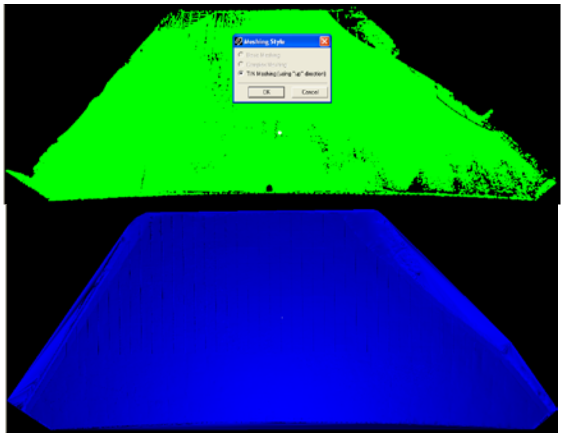


Fig. 14 – Generation of mesh surface (with blue)

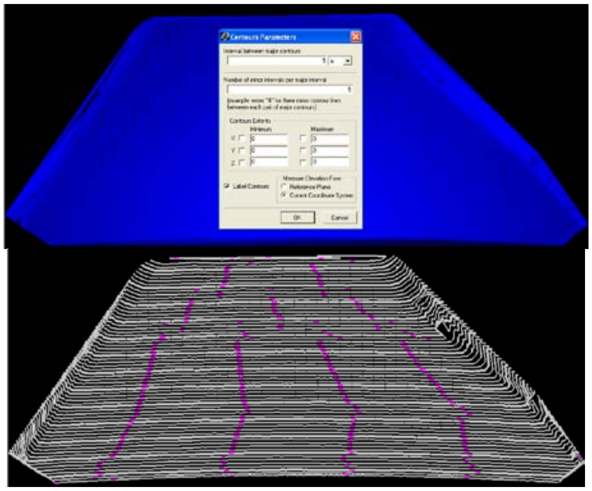


Fig. 15 – Generating contours

Imperfections (gaps or spikes) that appear when creating mesh surface, because the low density of points in some areas, due to shadows when scanning, due to erroneous points generated by objects in motion at the time of scanning, can be corrected with the editing tools of the model. In order to eliminate the spikes is possible to delete by marking their area and the results or existing gaps are filled by interpolating the triangles located closest to the defect area.

One advantage of using mesh surface is enabling automatic generation of level curves (Fig. 15) that can be compared with previously existing situations.

After initial tests at Pecineagu in May 2012 I generated a model (Fig. 16) of the upstream face for which at the time the membrane Carpi was installed up to the level of 1060 m, and the water level was at 1056.7 m.

The two models (may 2012 and nov 2012) can be compared using the sections or the mesh determined previously.

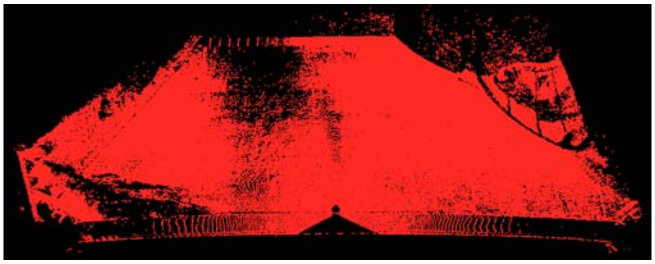


Fig. 16 – 3D model, may 2012

Comparing the sections generated on the same alignment can be done visually in Cyclone application, where you can see the difference between them. In Fig. 17 we have the green profiles generated from the model in November 2012 and with red profiles in May 2012.

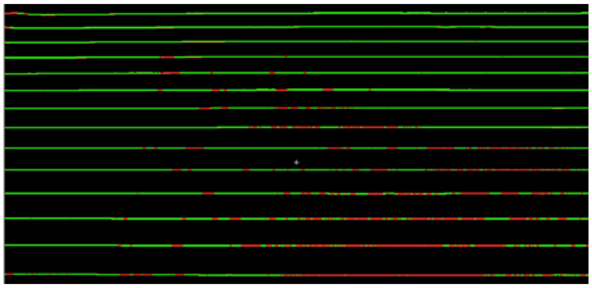


Fig. 17 – Overlapping profiles

From the overlap between them we can see the areas where the models is intersecting (alternating red-green) and areas where a model is above the other (a single predominant color). In general for areas between 1056.7 m and 1060 m elevation and between 1095 m and 1117 m elevation the two models intersect, there having the same elements measured in the two stages (upstream face covered by membrane - down and uncovered area of upstream face - up), the differences being due to measurement error. In the area between 1060 m and 1095 m elevation the model from November 2012 is above the model from May 2012, this area was covered during this time with the membrane. An example of the values determined in the vertical plane between the two models can be seen in Fig. 18, where there is a difference of 28 mm for the flat area and 110 mm for the channel separation.

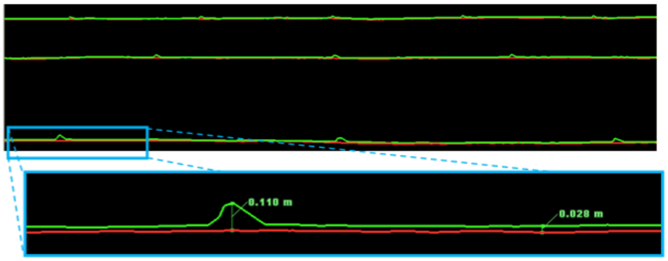


Fig. 18 – Measuring the differences between models in Cyclone application

Comparisons can be made also if sections are exported to other CAD environments. For example, in Fig. 19 I generated two profiles for which length scale is 10 times smaller than the scale of heights, here we can notice more clearly the difference between the two sections. The measured values vary between 17 mm and 30 mm for the area between two separation channels, and for two consecutive separating channels the values are 104 mm respectively 91 mm.

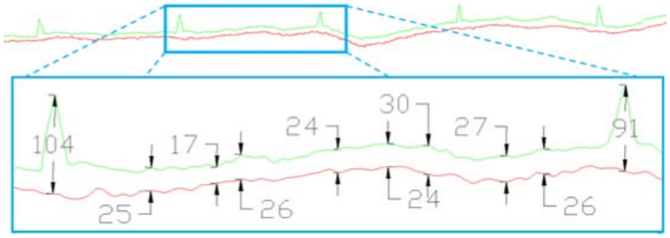


Fig. 19 – Measuring the differences between models in CAD environment

Working with sections can be time consuming unless there is the posibility for automated creation of results and allow only comparisons for sections generated through the same point.

If you want to compare largest areas solution would be to use mesh surfaces, but this mode requires powerful computing equipment and specialized applications.

Comparison of mesh surfaces can be made visually (Fig. 20) and automatically using the function of surface deviation calculation, this function can determine the deviation from a reference plane or between two surfaces [7].

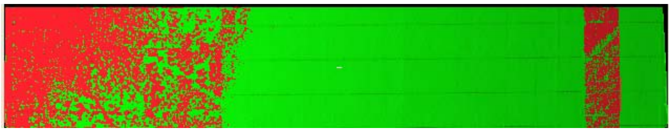


Fig. 20 – Overlapping of mesh surfaces

The result closest to reality is to generate directly the level curves (Fig. 21) which will have zero value at the intersection of surfaces, the + sign if the reference surface is below and - sign if the reference surface is above.

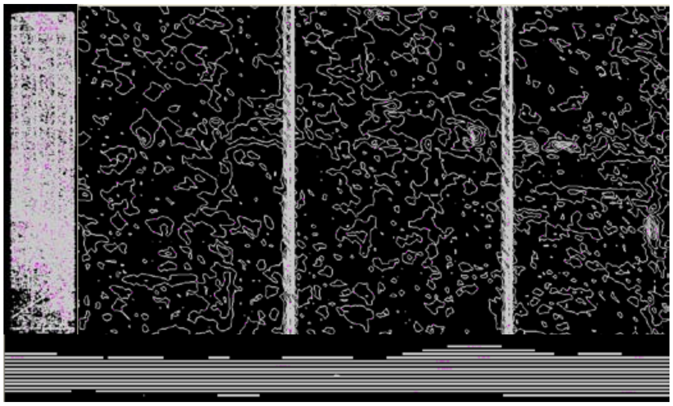


Fig. 21 – Level curves generated from the deviation between two mesh surfaces

If they are exported to different working environment the curves can be selected independently and you could assign a color for them to be highlighted or they can be selected in groups, assigning to the curves with zero value a color and to those with the + and - sign other two colors, as can be seen in Fig. 22.

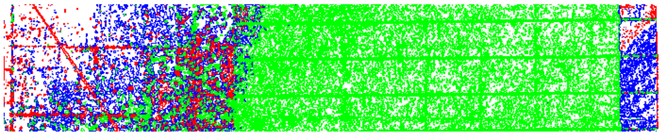


Fig. 22 – Color-coded level curves (blue - zero value curve, green - positive value curves, red - negative value curves)

Similar results are obtained using a dedicated application to compare point clouds (CloudCompareV2 - Fig. 23). This has the advantage that it is an open source application (free) that has implemented various advanced algorithms which allow working with point clouds [8]. It can compare the point clouds, mesh surfaces generated for this, obtaining a map of the deformation.

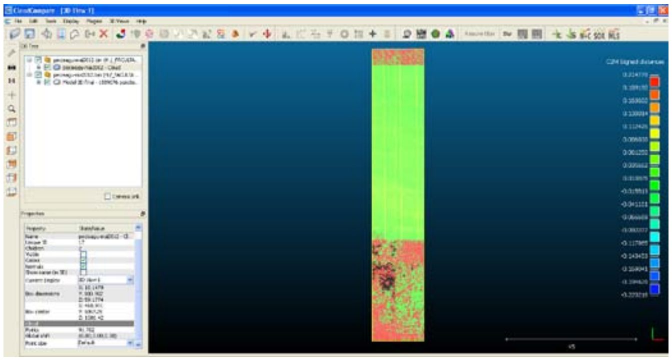


Fig. 23 – Determination of displacements using the application CloudCompareV2

Similar to the use of sections can be compared the level curves generated for each mesh surface in part, the results beeing similar (Fig. 24), since for this case the values are determined in the horizontal plane and for sections in a vertical plane.

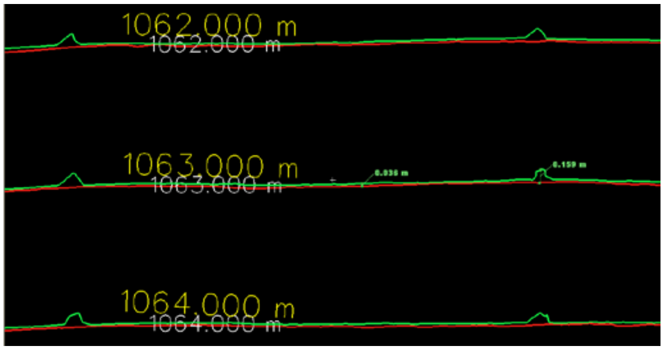


Fig. 24 – Measuring the differences between the level curves

IV. CONCLUSION

The aim of this paper was to bring to the forefront the use of new geodetic technologies to the monitoring of hazard and risk anthropogenic areas.

Thus was presented the new trends in the field of geodetic work and adjacent areas, which in some cases can supplement or replace conventional technologies already consecrated.

Analyzing all the data obtained from practical research I can draw the following conclusions:

- Using new technologies at realization of the monitoring of hazard and risk anthropogenic areas should be considered as they can bring more benefits than traditional technologies;
- It can collect a large number of data and obtaine the final results in a short time;
- If all the right conditions for making measurements using terrestrial laser scanning technology are respected, the accuracies obtained are of the order of mm - cm;
- An initial disadvantage of terrestrial laser scanning technology is related to the high cost of purchasing and training, but subsequently can be recouped by reducing the time taken to obtain the final results;
- If different applications are combined (some already purchased) to obtain the final results some acquisition costs for specialized applications can be reduced;
- For the case of buildings subject to static tests laser scanning technology adds more information, but can not yet reach the level of accuracy obtained by using the method of precise geometric leveling;
- If access to the monitored object is impossible then terrestrial laser scanning technology can be successfully used to obtain accurate results;
- In the case of monitoring the upstream face covered with sealing membrane laser scanning technology is the only viable method as long as the upstream face is discovered and cleaned of household waste;
- In the future presented methods can be improved by developing equipment and increasing the distance until which you can perform high precision measurements;
- If new specialized applications are being developed that will have lower acquisition costs, will allow multiple users access to new technologies.

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