STRUCTURAL MONITORING OF A LARGE DAM BY TERRESTRIAL LASER SCANNING

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ABSTRACT:

This paper presents some first results of a project aimed to access the feasibility of monitoring deformations of large concrete dams by terrestrial laser scanning. For this purpose a test field has been established on the dam of the Cancano Lake (Valtellina, Italy). This is made up of a geodetic network materializing a local datum for georeferencing all data acquired at different times. A large number of retro-reflecting targets have been positioned and measured by a total station in the local datum. Moreover, targets have been measured also in captured scans. Some of these have been placed on the dam structure to be used as independent check points, the others in the surroundings to play as ground control point. Three measurement campaigns have been accomplished so far by using two laser scanners: a long range Riegl LMS-Z420i and a medium range Leica HDS 3000. Reported analyses are focused on two main problems: the first one is the accuracy and the stability of georeferencing, which is fundamental to make comparisons between different multi-temporal scans; the second one is the computation of deformation based on the acquired point-clouds.

1. INTRODUCTION

This paper presents some results of a research that, in the opinion of the authors, could be considered a fascinating challenge: can be used *Terrestrial Laser Scanning* (TLS) techniques for monitoring displacements of big structures, and in particular of large dams?
Monitoring the static behavior of large dams has always been a topic of great importance, due to the impact these structures have on the whole landmark where they are built. Many instruments and surveying methods have been applied so far in order to continuously access the safety of this kind of big structures. However, the common characteristics of all approaches is the possibility of measuring with high accuracy displacements of a small number of points, if compared to the size of a big dam. The number of control points is even smaller if an automatic measurement system is applied (i.e when using opto-electronic collimators or robotic total stations).
On the other hand, laser scanners are capable to acquire a very huge number of points, so that the control could be extended to the whole structure instead of being limited to a few points.
At a first look, the answer to the question introduced at the beginning of the paper would be negative. The small number of papers dealing with this subjects (see e.g. Schäfer *et al.*, 2004) confirms this finding, even though the interest of researcher on TLS in applications for deformation analysis is quickly increasing (see e.g. Teskey and Bijoy, 2005; Guarnieri *et al.*, 2006; Tsakiri *et al.*, 2006).
Although long range instruments capable to measure 3D points also at 400-500 m of distance (greater ranges are not considered because the data quality sharply decreases) have been sold by vendors for about a half decade, in concrete dam monitoring an accuracy of few mm is always required. Unfortunately, current instruments cannot satisfy these requirement.
For better exploring this possibility, a group of Italian researchers in the context of a national research program (COFIN 2004) have started an activity with the aim of checking the real possibility of using laser scanners for dam monitoring. This research has been planned in cooperation with AEM S.p.A. Production Dept.[1], which has opened one of its dams (the dam of Cancano Lake, near the well known village of Bormio, Valtellina) to setup a test field. Along this project a complete laser scanning surveying of this dam has been also accomplished, as described in Alba *et al.* (2006).
Two laser scanners have been used in tests along three measurement campaigns, in May 2005, October 2005 and May 2006. A long range instrument Riegl LMS-Z420i has been stationed on two different stand points respectively at a mean distance of 200 and 300 m from the dam surface; a Leica HDS 3000 at shorter distances. To access the measurements of displacements derived from laser scanning, a set of 68 signalized targets have been distributed on the whole front of the structure, so that their 3D positions could have been measured by multiple intersections using a total stations.
Data acquisition is performed in order to acquire a dense point cloud at the highest achievable accuracy. The concept we would like to apply for deformation analysis is to use an *area-based method* (Schneider, 2006), i.e. to make a comparison between data acquired at different times by considering mathematical surfaces fitting measured points, so that noise could be reduced (Lindenbergh and Pfeifer, 2005). The surface of the dam is divided is small homogeneous areas and for each of these an interpolating surfaces estimated. Because different point clouds have been already georeferenced into the same reference system, the comparison between interpolated surfaces allows to evaluate displacements. Unfortunately, the georeferencing is affected by errors, so that an analysis to check which part of detected displacement is really due to a structure's movement is needed. At the current stage of the project only some simpler methods have been applied to make comparisons and then to detect deformations, as presented at par. 5. More enphasis has been given so far to the analysis of georeferencing stability, which is fundamental to make comparisons between surfaces registered into the same reference system (par. 4). On the other

[1] AEM S.p.A. (Azienda Elettrica Municipale) is currently the main facility management company of the city of Milan; it is the owner of several hidropower plants and dams in Valtellina Valley (Northern Lombardia).

hand, the first part of the paper is focused on the experimental data acquisition, dealing with the presentation of the test field (par. 2) and with the description of the acquired measurements (par. 3).

2. THE TEST FIELD

The core of this research, considering its experimental character, is the test field for laser scanning deformation analysis which has been established on the dam of Cancano Lake. In this chapter an overview on the dam, on the geodetic network established to define a permanent local datum (*Ground Reference System* – GRS) and on the materialization of targets to be used as *Ground Control Points* (GCPs) for georeferencing and as independent *Check Points* (ChkPs) during tests are presented.

2.1 The Dam of Cancano Lake

The dam of Cancano Lake (about 1900 m on s.l.) has been built up in '50 on the Adda river, generating a basin of about 124 million m^3 of water (Fig. 1). In the area there is another artificial lake (San Giacomo) bounded by another dam, resulting in two consequent basins with a difference of full supply level of about 100 m.

The dam presents an arc gravity structure featuring 136 m of height and 381 m of length at the crest. The conservation of the structure is good, thanks to the monitoring which is carried out by traditional sensors (strain gauges, inclinometers, etc.) and by periodical geodetic measurements (levelling and geodetic control networks, optical collimators). Moreover, the availability of other deformation measurements is very important to access the results obtained from laser scanning.

The morphology of the ground is really suitable for laser scanning surveying, because the valley presents the shape of a natural arena just in front of the dam. Thank to a lift, very comfortable positions for TLS stand-points can be easily reached.

Fig. 1.- Downstream face of the dam of Cancano Lake.

2.2 Geodetic network

In the nearby of the dam a geodetic network established during the dam construction already existed. However, due to the bad conservation of its monuments, a new network has been setup and measured, consisting in 11 main vertices materialized by topographic nails fixed in concrete elements on the ground (see the network layout in Fig. 3). The geodetic network is the materialization of the GRS. Because vertex 1000 belongs also to the Geodetic Regional Network of Lombardia Region, its ortometric height has been used as reference.

The measurement of geodetic network has been carried out in May 2005 by means of a Leica TCA2003 total station. The least squares network adjustment has resulted in the determination of 3D points with estimated standard deviations of ±2 mm in X-Y and ±3 mm in Z.

2.3 Materialization of control points

Control points have been used for a twofold aim. Firstly, to compare scans captured at different times, a set of GCPs finalized to give them the same georeferencing is needed. On the other hand, the deformation analysis performed by TLS data requires other independent measurements for validation. To this goal, in addition to data coming from monitoring instruments and sensors installed on the dam (see par. 2.1), a set of check points placed on the concrete front has been established (see Fig. 2).

All targets (15 GPC+ 68 ChkPs) have been materialized in May 2005 by alluminium disks (ϕ=120 mm) with a central reflecting circular shape (ϕ=100 mm), to be fixed to the concrete dam surface or to some stable rocks in the nearby of laser scanner stations 6000 and 8000.

The measurement of target coordinates into the GRS has been carried out along the determination of the geodetic network by multiple intersection from the nearest vertices. Thank to the high reflectiveness of the material covering each target, a phase-measurement rangefinder of a total station Leica TCRA 1203 could be used for all targets out of the dam. On the contrary, control points placed on the dam front have been measured from vertices 5000, 7000, 9000 and 10000 of the geodetic network by using only angular measurements. This solution has been motivated by the narrow incidence angle between the direction of collimation from the total station and the target surface, resulting in large errors in range measurement. Accuracy of measured target coordinates has resulted ±3 mm in X-Y and ±4.5 mm in Z.

These targets have been used for georeferencing scans captured by Riegl LMS-Z420i laser scanner. In addition, 14 target-tape (ϕ=75 mm) have been temporarily fixed to the downstream face during each campaign for the use with Leica HDS 3000. The accuracy of measurement of this target has resulted ±4 mm in X-Y and ±8 mm in Z.

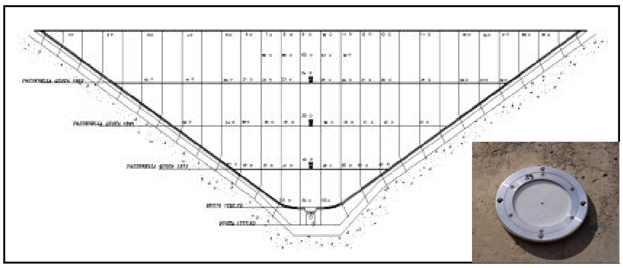

Fig. 2.- Positions of targets to be used as independent control points on the dam's front; in the window on the left, an image of a retro-reflecting target used for Riegl LMS-Z420i laser scanner.

3. DATA ACQUIRED DURING MEASUREMENT CAMPAIGNS

3.1 Adopted laser scanners

The laser scanning surveying has been carried out by adopting two *time-of-flight* instruments featuring very different properties. The first one is a *long-range* TLS Riegl LMS-Z420i, the second a *medium-range* TLS Leica HDS 3000. In Table 1 some details about both instruments and the way they have been used in the test field are reported.

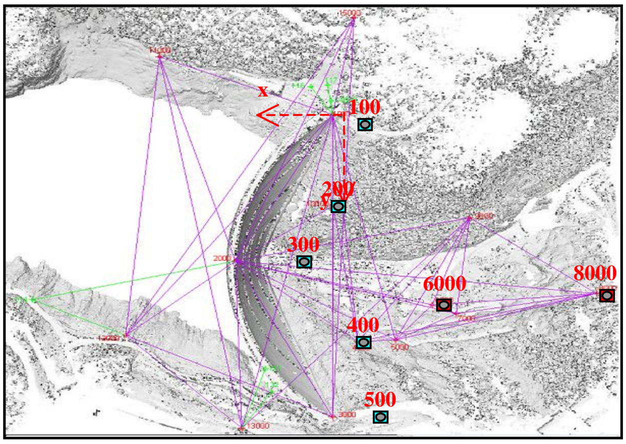

Fig. 3.- Layout of the geodetic network reporting laser scanner stand-points.

Instrument	*Riegl LMS-Z420i*	*Leica HDS3000*
Acquisition speed (points/s)	up to 12k	up to 2k
Measurement range (m)	2÷1000	1÷100
St.dev. of single range meas. (mm)	10 ± 20 p.p.m.	4 @ 50 m
Angular resolution (deg)	0.0025	0.0034
Horiz. & Vert. FoV (deg)	360x80	360x270
Laser beam-width (mm)	25 @ 100 m	6 @ 50 m
Wave-length (nm)	Near infrared	532
Size (mm)	463×210 (H×D)	165×236×215 (D×W×H)
Weight (kg)	14,5	12
Integrated CCD camera	Nikon D100	internal

Table 1.- Main technical features of TLS adopted in the deformation monitoring test; features refer to vendors documents, as reported in Ingensand (2006).

3.2 Scheduling of measurement campaigns

The measurement campaigns have been programmed to acquire data in correspondence to the highest (at the beginning of autumn) and the lowest (in latest spring) water level in the basin, and then to the maximum and minimum deformation of the dam. According to this, three measurement campaigns have been carried out so far, as reported in Table 2.
Due to the scarce snowing in winter 2005, the highest water level in the basin has kept quite low with respect to the historical maximum value, resulting in a smaller deformation of the dam. For this ground, probably new measurement campaigns will be carried out in October 2006 and May 2007.

Measurement campaign	dates	Water level height (m on s.l.)	Horizontal displacement on the middle of dam crest (mm)
May 2005	2-5 May	1852	- 12
Oct 2005	27-28 Oct	1894	- 34
May 2006	8-9 May	1842	- 5

Table 2.- Details about measurement campaigns; horizontal displacements are given in x direction (see Fig. 3) with respect to a local zero.

3.3 Description of acquired scans

3.3.1 Scans acquired by Riegl LMS-Z420i

Scans have been captured from 2 stand-points, placed respectively at a mean distance of about 200 m (station 6000) and 300 m (station 8000). The scanned area is the central portion of the dam, which is the part subject to major deformations. In Table 3 some properties of scans are shown.
Georeferencing has been carried out by exploiting retro-reflecting targets described at par. 2.3, positioned in the nearby of stand-points. The measurement of control points put on the frontal face of the dam has been used only for the validation of results. The use of "multiscan" option with n=4 repetition would allow to reduce of a factor 0.5 the standard deviations of measured range.

3.3.2 Scans acquired by Leica HDS3000

Scans have been taken from 5 stand-points, placed respectively at a distance ranging from 50 to 120 m from the dam. In the map in figure 3 stations are drawn with label 100, 200, 300, 400 and 500. The whole surface of the down stream face has been scanned (in Fig. 4 the whole point cloud made up of all acquired scans is reported).
The georeferencing of data has been carried out by using its own retro-reflecting targets suppplied by the vendor, that have been positioned on the dam surface to get a geometrically stable constraint. Because these targets could be easily damnaged by wind and rain, their positioning and measurement from the geodetic network have been repeated at each campaign. A mean number of 6÷8 targets have been used for georeferencing each scan.

Scan		*6000*	*8000*
Scanning time (min)		*70*	*55.6*
# total measured points		*7.55M*	*8.22M*
Angular resolutions (deg)	**Horiz.**	*0.014*	*0.008*
	Vert.	*0.014*	*0.007*
Point density (1/cm^2)	**Min**	*0.31*	*0.25*
	Max.	*0.14*	*0.26*
Acquisition range (m)	**Min.**	*148*	*286*
	Max.	*215*	*320*
FoV (deg)	**Horiz.**	*37.4*	*22.4*
	Vert.	*41.8*	*21.9*
Laser beam spot-size (m)	**Min.**	*0.037*	*0.072*
	Max.	*0.054*	*0.080*

Table 3.- Properties of scans acquired for deformation monitoring by Riegl LMS-Z420i laser scanner.

4. ANALYSIS OF GEOREFERENCING STABILITY

In the analysis of dam deformation the definition of a stable reference system (GRS) is fundamental. In this test the reference system has been materialized through the geodetic network. To register all scans to it, some GCPs have been used. As previously said, targets used for Riegl LMS-Z420i are disk covered by retro-reflecting material, which have been positioned in stable positions all around both stand points 6000 and 8000. In case of Leica, targets have been fixed to the dam front and measured during each campaign.
The georeferencing of scans has been performed firstly by using commercial SWs, i.e. Riscan Pro in case of Riegl data and Cyclone in case of Leica. Secondly, all measured GCP and ChkP coordinate have been imported into a scientific controlled environment where 3D roto-translation have recomputed by a rigourous l.s. approach. Here some analyses about accuracy have been computed, aimed to access either the georeferencing of each scan, and to check the stability of it at different times.

4.1.1 Georeferencing of scans acquired by Riegl LMS-Z420i

Georeferencing of both scans has been performed by measuring 9-10 GCPs positioned out of the dam. To check the stability of georeferencing, a further estimate for each scan has been computed by fixing all ChkP coordinates. The finality of this test is to verify the possibility of materializing a stable reference system based only on points outside the structure, fact that would avoid the topographic measurement of GCPs at each data acquisition. Estimated standard deviations of georeferencing parameters are reported in Table 4, together with the same parameters estimated by fixing all ChkPs.
As can be seen, st.dev.s are quite similar with both sets of GCPs; moreover, to add GCPs does not always mean an improvement in accuracy. This fact is probably due to the presence of outliers in measured targets which should be better investigated and rejected.
Considering the effects of errors in georeferencing parameters, the variance of IRS center coordinates will directly add up to the variance of scanned 3D points (see Scaioni, 2005). They are generally limited to a few mm. The effects of errors in rotations propagates to an error in 3D point coordinates of the same order.
The analysis of differences between estimated parametes with both sets of constraints for each scan has resulted in mean absolute differences of about 3÷4 mm for X_0, Y_0 and Z_0, and 2÷3 mgon for rotations.
A further test on the quality of georeferencing has been carried out by fixing parameters estimated with only GCPs outside the dam's downstream face, and by computing residuals on ChkPs put on the structure. Statistics computed on residuals (see Table 5) show two aspects. First, their mean value are ranging from very low values (e.g. for scan 6000 in Oct 2005 and May 2006) up to larger ones, which could be due to errors in georeferencing but also to errors in topographic measurements of targets. Moreover, the behaviour of residuals is disregarding the type of coordinate, i.e. there is not a prevalent direction of errors in all scans. A more accurate analysis on geometric distribution of residuals on ChkPs has revealed that some problems exist about measurement of target coordinates in the IRS. This is probably due to the varying incidence angles of laser beam on the retro-reflecting material. These problems, which devise to be better focused, are however limited to a few mm and have been neglected in a first analysis.
Finally, st.dev.s of residuals are quite concentrate around 8÷9 mm for all coordinates, with a few mm of discrepancies with respect to these values. This fact show that, a part some small error due to georeferencing, the accuracy of target measurement is quite constant.

Scan	Camp.	GCP	σ_0 (mm)	St.dev.s of coordinates of IRS origin (mm)			St.dev.s of rotations (mgon)		
				X_0	Y_0	Z_0	ω	ϕ	κ
6000	May 2005	9	5.7	4.5	5.0	5.1	2.6	2.5	2.1
		42	*5.8*	*3.1*	*3.4*	*3.6*	*1.2*	*1.4*	*1.3*
	Oct 2005	10	9.8	4.6	4.8	5.3	4.2	2.3	1.9
		41	*6.7*	*2.5*	*2.7*	*2.8*	*1.4*	*1.2*	*1.0*
	May 2006	10	7.3	2.8	2.8	3.2	9.9	10.6	1.3
		43	*10.6*	*3.2*	*3.4*	*3.6*	*9.9*	*9.9*	*1.3*
8000	May 2005	9	6.4	2.8	2.8	3.0	3.8	1.6	1.0
		43	*8.8*	*3.5*	*3.7*	*3.8*	*1.9*	*1.2*	*0.8*
	Oct 2005	10	12.0	5.5	5.6	5.6	5.3	2.1	1.7
		40	*8.3*	*3.4*	*3.6*	*3.7*	*1.4*	*0.8*	*0.8*
	May 2006	9	6.1	2.7	2.8	2.9	3.0	1.2	0.9
		47	*8.0*	*3.1*	*3.2*	*3.4*	*1.3*	*0.8*	*0.7*

Table 4.- Estimated accuracies of georeferencing parameters considering both sets of GCPs (only points out off the dam and all points).

Scan	Camp.	Residuals on ChkPs (mm)						
		#	mean			St.dev.		
			ΔX	ΔY	ΔZ	ΔX	ΔY	ΔZ
6000	May 2005	39	-14	-7	-4	±9	±9	±9
	Oct 2005	31	3	-2	2	±6	±7	±4
	May 2006	30	-2	1	1	±8	±13	±8
8000	May 2005	34	-2	-4	-8	±6	±12	±9
	Oct 2005	30	-1	-4	9	±5	±7	±8
	May 2006	24	-7	3	-5	±8	±10	±8

Table 5.- Residuals on independent check points.

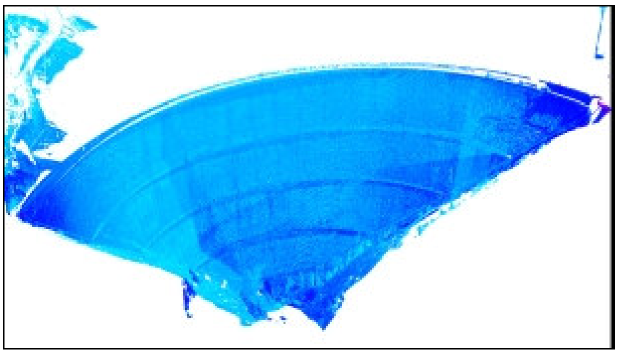

Fig. 4.- Point-cloud resulting from data fusion of all scans capturing dam downstream face acquired by Leica HDS 3000.

5. FIRST RESULTS OF MONITORING

The final goal of this project is to evaluate the possibility of performing a deformation analysis by means of laser scanning data. Currently, this stage is work-in-project and only first results are shown here.
Thank to TLS technique is possible to acquire a dense and accurate point cloud describing the external surface of a dam. Unfortunately, even though different scans would be georeferenced into a stable reference frame, the deformation

analysis cannot be carried out by directly considering points. This is due to the impossibility of scanning the same point in different measurement sessions, because of the unperfect repositioning of the instrument and because of the laser beam-width (Lichti and Gordon, 2004). Moreover, the use of “area based” techniques to evaluate deformations could allow to partially filter measurement noise.

Some tests have been carried out with a pair of scans captured form stand-point 8000 in Oct 2005 and May 2006 by the scanner Riegl LMS-Z420i. Yet this station is the farest from the dam, the angles of incidence between laser beam and surface are generally closer to the normal to this, so that the noise in 3D point measurement has appeared more reduced than in scans from station 6000.

The first processing stage has been a resampling of both original point-clouds to a regular bidimensional grid of step 2 cm along a direction tangent to the dam surface in its middle section. This task is also required by the adoption of “multi-scan” technique to get a unique regularized point-cloud. Points featuring a st.dev. of range measurement larger than ±1 cm have been discarded.

Then two different kinds of surfaces have been interpolated (see Remondino, 2004 for a review on this subject). The first one is a *triangular mesh*, which has been computed on both resampled point-clouds. As a further step, from this mesh a regular *polynomial 3D surface* has been interpolated. In Table 6 an overview about computed interpolations is reported. A significant mean difference appears only in the passage from the resampled “multi-scans” to the triangular meshes. Elsewhere interpolations contributes only to increase st.dev.s. of differences due to the low-pass filtering.

Finally, four different comparisons have been tried:

1. mesh from (Oct 2005) *vs* resampled point-cloud (May 2006);
2. polynomial surface (Oct 2005) *vs* resampled point-cloud (May 2006);
3. mesh from (Oct 2005) *vs* mesh from (May 2006);
4. polynomial surface (Oct 2005) *vs* polynomial surface (May 2006).

In both cases 1 and 2, deformations have been computed with the criterium of the *shortest distance* between each point of a scan and the considered surface of the other one. In cases 3 and 4 they have been computed in correspondece of nodes of a regular grid.

Compared datasets	8000 Oct 2005		8000 May 2006	
	Mean (mm)	St.dev. (mm)	Mean (mm)	St.dev. (mm)
Resampled “multi-scan” - triangular mesh	6	±3	4	±2
Triangula mesh – 3D polynomial surface	0.5	±3	0.4	±5
3D polynomial surface - resampled “multi-scan”	1	±8	2	±8

Table 6.- Statistics on differences computed between different interpolations tried on scan 8000.

In Fig. 5 some colour maps showing deformations on the portion of the dam scanned from station 8000 according to different comparisons are shown. The evaluated deformations in the middle point of the dam crest correspond to values measured by total station and reported in Table 2. Moreover, surface deformations in the remaining portion fo the downstream face are according to the expected structural behaviour of the dam[2].

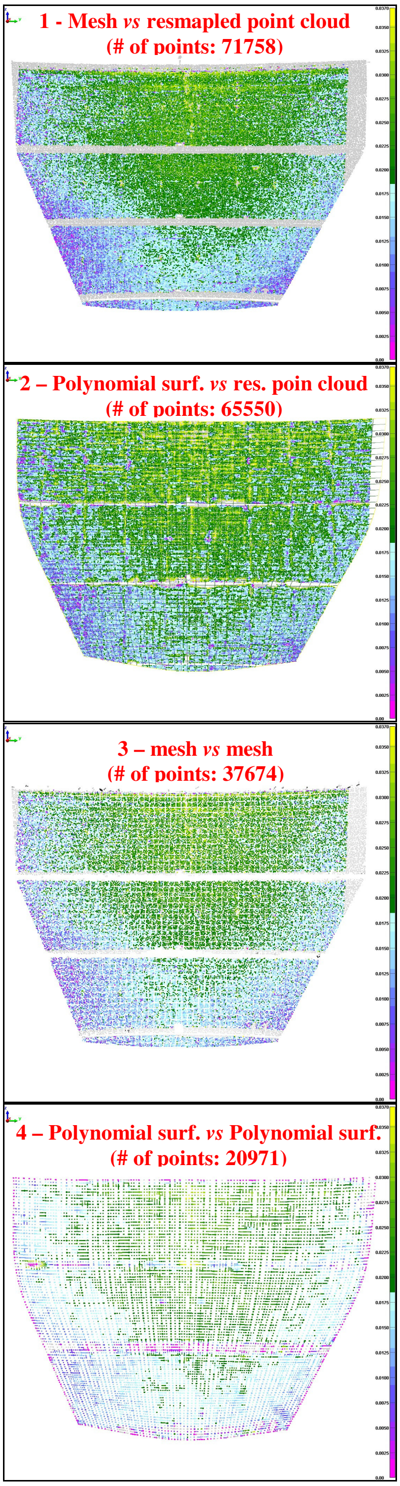

Fig. 5.- Maps of deformations evaluated by comparing different kinds of surfaces derived from scan acquired from station 8000 in Oct 2005 and May 2006.

[2] Values corresponding to scale colour bars drawn in figure 5 have been hidden for reservation.

6. FINAL CONSIDERATIONS AND FURTHER ACTIVITIES

Results reported at par. 5 clearly show that the use of TLS technique may give an important contribute to the deformation analysis of large dams. The first results obtained from data processing which has been carried out so far are dense and accurate maps of deformations of the dam downstream face. In figure 5 some maps of deformations derived from comparison of two laser scanned point clouds captured at different times can be seen. This finding is something new with respect to that could be obtained from traditional geodetic methods, which give the measurement of displacements limited to a very small number of points. For the sake of completness, similar deformation maps could be obtained from *Ground Based SAR* techniques (Tarchi *et al.*, 1999), even though the use of TLS is more operational. If terrestrial radars would allow to get more accurate measurement of deformation (accuracy even less than ±1 mm from a range of some hundreds meter), they require a permanent stationing of the instrument. In case data acquisition is interrupted, the best accuracy in deformation measurement will be consequently lost. On the contrary, TLS technique can be use without continuity, if a stable set of GCPs has been established to allow the repositing into the same local datum. This task can be obtained by materialization of permanent targets (as in case of Riegl LMS-Z420i in this project) or by positining new targets at scanning time to be measured from a geodetic network. To be noticed is the large distance of acquisition from the scanner, which reaches even more than 300 m without a particular loss of accuracy. This fact is particularly important, because in many sites to find some stand points for the instruments might be very complex due to local topography of the ground.

A part completing the processing including data acquired by scanner Leica HDS 3000 as well, two main problems have to be cope with in the sequel of this research. The first one is to improve the accuracy of scan georeferencing, which depends on the geometric distribution of GCPs as well as on the accuracy of their measurement in both GRS and IRS. Results reported at par. 4 show a large variability in georeferencing stability, which apparently disregards external influencing factors. The measurement of targets is an aspect which should be investigated again, because probably it depends on the incidence angle between laser beam and target surface. Also the reponse of retro-reflecting material is a problem which must be analyzed in details by scheduling specific experimental tests. However, the strategy of increasing the number of targets to improve the reliability of georeferencing could be a good operational solution.

The second aspect to be investigated is the technique to make the analysis of deformations. At current stage, only solutions based on functions offered by commercial softwares have been tried, but the use of more refined interpolation method would be worthwhile.

Finally, the use of this kind of data by structural engineers is aspected to influence the future of this applicationand to draw new experimentations. The laser scanner technique could be useful exploited for periodical monitoring, not for continuous, where current sensors are enough to control a small set of critical points. On the contrary, the availability of seasonal deformations of a dam would refine the computational analysis, which currently are performed by considering only the design geometry of the structure.

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REFERENCES

References from Other Literature:

Alba, M., Giussani, A., Roncoroni, F., Scaioni, M., Valgoi, P., 2006. Geometric Modelling of a Large Dam by Terrestrial Laser Scanning. In Proc. of *FIG Mondial Congress*, Munich, Germany, Oct. 8-13, pp. 15, unpaginated CDROM.

Guarnieri, A., Pirotti, F., Pontin, M., and A. Vettore, 2006. 3D Surveying for Structural Analysis Applications. In: Proc. of 3rd IAG/12th FIG Symp., Baden, Austria, May 22-24, pp. 6, unpaginated CDROM.

Ingensand, H. 2006. Metrological Aspects in Laser-Scanning Technology. In: Proc. of 3rd IAG/12th FIG Symp., Baden, Austria, May 22-24, pp. 10, unpaginated CDROM.

Lichti, D.D., and S.J. Gordon, 2004. Error Propagation in Directly Georeferenced Terrestrial Laser Scanner Point Clouds for Cultural Heritage Recording. In Proc. of *FIG Working Week*, Athens, Greece, May 22-27, pp. 16.

Lindenbergh, R., and N. Pfeifer, 2005. A statistical deformation analysis of two epochs of terrestrial laser data of a lock. In: Proc. of Optical 3D Measurement Techniques, Vol II, Vienna, Austria, pp. 61-70.

Remondino, F., 2004. From point cloud to surface: the modelling and visualisation problem. Int. Arch. of Phot., R.S. and Spatial Information Sciences, Vol. 34(5/W10), unpaginated CDROM.

Tarchi, D., Rudolf, H., Luzi, G., Chiarantini, L., Coppo, P., and A. J. Sieber, 1999. SAR interferometry for structural changes detection: A demonstration test on a dam. In: *Proc.of IGARSS*, pp. 1522–1524.

Scaioni, M., 2005. Direct Georeferencing of TLS in Surveying of Complex Sites. Int. Arch. of Phot., R.S. and Spatial Information Sciences, Vol. 36(5/W17), Mestre, Italy, pp. 8, unpaginated CDROM.

Schäfer, T., Weber, T., Kyrinovič, P., and M. Zámečniková, 2004. Deformation Measurement using Terrestrial Laser Scanning at the Hydropower Station of Gabcikovo. In Proc. of INGEO 2004 and FIG Regional Central and Eastern European Conference on Engineering Surveying, Bratislava, Slovakia, Nov. 11-13.

Schneider, D., 2006. Terrestrial Laser Scanning for Area Based Deformation Analysis of Towers and Water Dams. In: Proc. of 3rd IAG/12th FIG Symp., Baden, Austria, May 22-24, pp. 10, unpaginated CDROM.

Teskey, B., Bijoy, P., 2005. New Instrumentation and Methodology for Deformation Monitoring. In: Proc. of Optical 3D Measurement Techniques, Vol II, Vienna, Austria, pp. 103-111.

Tsakiri, M., Lichti, D., Pfeifer, N., 2006. Terrestrial Laser Scanning for Deformation Monitoring. In: Proc. of 3rd IAG/12th FIG Symp., Baden, Austria, May 22-24, pp. 10, unpaginated CDROM.