INVESTIGATION OF REPEATABILITY OF DIGITAL SURFACE MODEL OBTAINED FROM POINT CLOUDS IN A CONCRETE ARCH DAM FOR MONITORING OF DEFORMATIONS

Investigação referente à Repetibilidade do Modelo Digital de Superfície obtido a partir de Nuvens de Pontos numa Barragem Abóbada de Betão para a Monitorização de Deformações

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ABSTRACT

Applicability of Terrestrial Laser Scanners/Scanning (TLS) in deformation measurement in dams is an active area of study. With the advance of modern technology, accuracy of measurements is much improved by developments in design of terrestrial laser scanners. Currently, this technology is used in large and complex engineering structures such as dams. Although TLS is a high cost technology, it is particularly used in monitoring of dam deformations, due to its speed in obtaining thousands of data points, ability to visualize the scanned object and its environment with high accuracy and ability to take long-range measurements. In order to determine the effect of change in water reservoir levels on body of the dam, TLS are used to take deformation measurements in different time intervals, where the water level was at maximum, minimum and medium levels. This paper provides an overview of terrestrial laser scanning technology for deformation monitoring. The concrete arch dam in Antalya Oymapinar, Turkey was used for case study. Four different scannings were performed in this dam in order to verify the replicability of TLS results on same water levels and equivalent

conditions. Digital Surface Models reflecting dam surface have been created. Results obtained from surface model differences were examined using surface matching method.
Keywords: Terrestrial Laser Scanners; Deformation Measurements; Concrete Arch Dams; Data Analysis; Point Cloud.

RESUMO
A aplicação dos Scanners Laser Terrestres/Digitalização (SLT) para a medição de deformações em barragens representa uma área ativa de estudo. Com o avanço das tecnologias modernas, a exatidão da medição melhorou muito graças aos desenvolvimentos na conceção dos scanners laser terrestres. Atualmente, esta tecnologia é utilizada em grandes e complexas estruturas de engenharia tais como as barragens. Embora, os SLT sejam uma tecnologia de custo elevado, são particularmente utilizados na monitorização de deformações de barragens, devido à velocidade na obtenção de centenas de pontos de dados, à capacidade para visualizar o objeto digitalizado e o seu ambiente com elevada exatidão e capacidade para medições de longo alcance. Com a finalidade de determinar o efeito das alterações dos níveis de um reservatório de água no corpo de uma barragem, os SLT são utilizados para tirar as medições das deformações em diferentes intervalos de tempo, quando o nível da água se encontra em níveis máximos, mínimos ou médios. Este documento apresenta uma visão geral da tecnologia de digitalização laser terrestre para a medição de deformações. A barragem situada em Antalya Oymapinar, na Turquia, foi utilizada para o estudo de caso. Foram realizadas quatro digitalizações diferentes nessa barragem, a fim de verificar a reprodutibilidade dos resultados dos SLT nos mesmos níveis de água e em condições idênticas. Os Modelos Digitais de Superfície que refletiram a superfície da barragem foram criados. Os resultados obtidos a partir das diferenças do modelo de superfície foram examinados utilizando o método de correspondência de superfície.
Palavras-chave: Scanner Laser Terrestre; Medições de Deformação; Barragem Abóbada de Betão; Análises de Dados; Nuvens de Pontos.

1. INTRODUCTION
    Based on the scale of past accidents that resulted in life and property loss caused by large scale engineering structures such as dams, the elements, states and processes that may cause damage to environment, humans and structure itself should be determined. In particular, hazards that cause damage to the structure should be detected and risk analysis and evaluation should be performed. The risk factor should be detected, its potential and behavior should be determined, it should be reduced by planning and structural arrangements, the early warning systems that provide efficient information and reduce the risk should be implemented, an emergency plan should be determined and precautions should be taken for aftermath (HEINE et al., 2007). In order to perform these duties and take the necessary

precautions, the structure or the object that causes the risk should be monitored persistently in specific cycles.

From the past to present, many studies were conducted on solution of problems in social environments and monitoring of engineering structures by using different geodesic and physical measurement methods (SCHROEDEL et al., 2002). There exists a vast literature on monitoring of structures and detection of deformations by using these measurement methods. Today, Terrestrial Laser Scanners are starting to emerge and they are rapidly developing for these types of applications. In order to analyze these studies, new and accurate data is needed. The data obtained from Terrestrial Laser Scanners match with the truth data. Three dimensional geometric and visual data is gathered rapidly with laser scanning systems. With TLS, it is possible to gather details on hard to reach, dangerous objects and environments in a single shot. Because of these properties, laser scanners are used for risk evaluation and analysis across different applications, in particular evaluation of deformations in structures (dams, bridges, etc.) caused in the long run by internal and external forces.

There are many references in the literature regarding TLS applications. A general overview on TLS is presented on Pfeifer and Lichti (2004), Fröhlich and Mettenleiter (2004). Lemmens (2004) compared TLS with different designs on various applications and Boehler et al. (2003) performed accuracy analysis on the data obtained from laser scanners. The study on Bitelli (2004), Hesse and Stramm (2004) examined deformations by direct comparison of numerical height models obtained by using different TLS campaigns. Schneider (2006) performed deformation analysis for a television tower by comparing different sets of data obtained on different epochs from considering mathematical surfaces related to measurement points. Guarnieri et al. (2006) presented multi sensor approaches for preserving cultural legacy using structural analysis. Alba et al. (2006) studied TLS for monitoring deformations on large concrete dams, accuracy of positioning and comparison on different scanning results. A three dimensional polynomial surface was applied to TLS point cloud for monitoring of a large dam. Another study on dams can be found in Rudig (2005). Gruen and Akca (2005) explained the surface matching method by using least squares method. Heine et al. (2007) presented a study on teaching TLS technology as a part of European Leonardo da Vinci project and detection of deformations on a hydroelectric central.

In the section 2 of this paper are discussed terrestrial laser scanner used in monitoring of structures and detection of deformations. TLS measures deformations on the object surface by the help of dense data sets (point clouds) without depending on several points. It is thought that laser scanning technology can be used in determinations of deformations of concrete arch dam with a magnitude of mm to cm level due to water level changes. This technique can determine more dense and points than conventional technique. Hence a dam surface can be accurately represented by this technique. An important advantage of this technique is that more sensible conclusion can be drawn and surface difference analysis can be done

instead of deformation analysis by point-wise. Real surface models can be generated by using TLS data. Deformation of the whole surface can be determined by comparing two or more surface models generated at different times. Aim of this paper is to detect deformations by obtaining realistic dam body surface models and performing surface comparison. For this purpose, four different scannings, which were taken at the equivalent conditions and water levels at Antalya Oymapinar Dam at April of 2008 to verify replicability of OPTECH ILRIS-3D Laser scanner results, were compared by using surface matching methods and examining distribution of surface differences (in y axis).

2. TERRESTRIAL LASER SCANNERS

A terrestrial laser scanner can rapidly measure the points of the scanned object in three dimensional x, y, z data format. The distance between the scanner and a point on the object can be determined based on the high accuracy measurement of time that passes between the dispersion of laser signal and determination of the signal that reflects back form the surface. Three dimensional point clouds can be obtained by using scanners in vertical and horizontal directions by obtaining thousands of points that spans the object surface. For each point, scanners record three dimensional coordinates (x, y, z) in a fixed coordinate frame and RGB (red, green, blue) values that is the density of the reflected laser signal.

Figure 1 - TLS Scanning Principle (Staiger 2003).
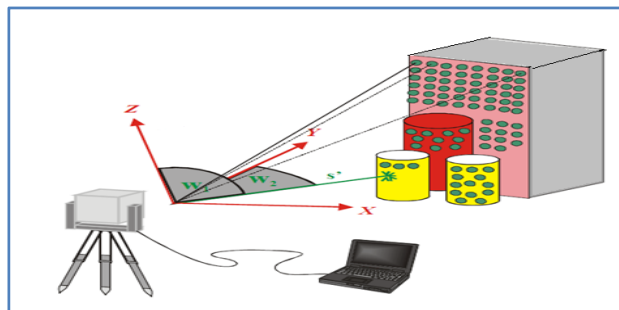
Scannings for large and complex structures are done from different overlapping points in order to get hold of the whole object geometry. These scannings are then integrated and the integrated data is transformed to a specific geodesic coordinate system in order to visualize the whole object. Visualization is done through generating a three dimensional model of the scanned object. These models can be exported to various CAD software and can be used for various applications. In TLS applications, it is important to take into consideration the conditions that affect scanning process, such as general properties of the laser scanner, geometric conditions of the scanned object (shape, size, etc.) and its

position in the environment. 3D models obtained through TLS allow indirect determination of the geometric properties of the scanned object (RESHETYUK, 2009).

In recent years, there were great developments in ease of applicability of terrestrial laser scanners and the accuracy of data obtained by them. In particular, recently developed software allows precise and accurate processing of data. These kind of scanning systems allow obtaining three dimensional positions of the points on the scanned object in a dense point cloud form, depending on the position of the scanner. For this reason, determination of such data set (the point cloud) through use of laser scanning systems is very useful for monitoring of structural deformations (GORDON et al., 2003).

Monitoring of static and dynamic behavior of the scanned object (large scale engineering structures such as dams etc.) by laser scanners became an important subject. In particular, large scale structures have important effects on their environment. Numerous measurement methods and devices are used to monitor and improve safety of such large scale structures. The common approach in technological development on this subject focuses on changes in point positions, accuracy, reliability and ease of taking measurements.

3. MATERIALS AND METHODS

3.1 Study Area (Oymapinar Dam)

Oymapinar dam is a concrete arch dam that is located on Manavgat brook, which is 18 km north of town of Manavgat, Antalya (Figure 2). Its height is double curved 185 m and its length is 360 m crest long. Construction of the dam began at 1977 and it was put into service at 1983. Dam contains 4 turbines that have 135 mwat power each and an underground hydroelectric central with 540 mwat total power. Length of the reservoir is 5 km, maximum water capacity is 185 m and the volume is 310.106 m3.

Figure 2 - Oymapinar Dam Body and Crest (Right and Left views).
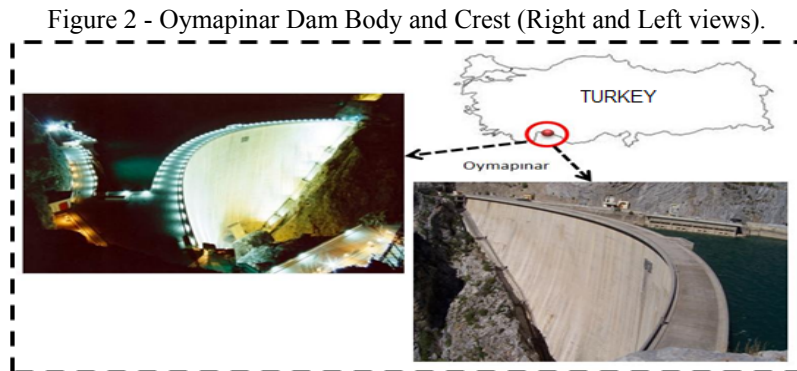
A study conducted at 1985-86 by Geomatic Engineering department of our university on geodesic study of deformations detection on this dam, was examined in order to obtain information on structure of the dam and its surroundings, before starting to take TLS measurements (ERKAYA et al., 2009). Preliminary information on changes of water levels on dam body was obtained by investigating measurement campaigns that spans 17 measuring periods. Current geodesic network points were checked to see if they can be used as scanning points. A geodesic control network, which was implemented in order to detect the changes on the dam body, was formed by 25 objects on five different altitude levels (182 m, 150 m, 125 m, 100 m and 75 m) that represent 6 reference points (1001, 1002, 2001, 2002, 2003, 2005) that represents the dam body at 1983 when the dam was put into service. 4 new reference points (3005, 3007, 3011, 3012) were added to the well side at 1985 and 2 new reference points (3008, 3010) were added at 1986 in order to detect erosion on slopes on the well side (Figure 3). At 1996, geodesic control network became a 13 point network with the addition of a new point on crest wall for reinforcing the river mouth-well connection (Erkaya et al., 2009). All the reference points are displayed at Figure 3.

Figure 3 - Geodesic Network at Oymapinar Dam.

Topography of Oymapinar dam is mountainous and surrounded by forests. Access to these reference points is pretty difficult. In the beginning, the 2001, 2002 and 2003 reference points were decided to be appropriate for TLS setup. However, due to difficulty in accessing 2001 and 2003 points and their limited view of the dam body, only 2002 point was selected to be the scanning point. Additionally, this point has a field of view that spans the body of the dam and its natural surroundings in great detail.

3.2 Equipment's

In this application the ILRIS-3D terrestrial laser scanner manufactured by OPTECH Company, was used (Figure 4). This laser scanner has properties such as, 2000 point shot per second, scanning range up to 1500 m, 0.0015 degree angle precision, operability with computer or hand-held computer, remote connection with Ethernet or wireless connection, 7mm precision at 100 m, 360^0 x 360^0 scanning area, no damage to human health due to use of first class laser, internal 6.6 mega pixel digital camera support and light compact design. The 2002 named point is compatible with maximum/minimum distance limits of the OPTECH ILRIS-3D (Figure 3). In this study, the editing, filtering, registration and georeferencing of point clouds for each scanning was applied by PolyWorks V10.1 and Surface Matching were performed by Surfer 9.0.
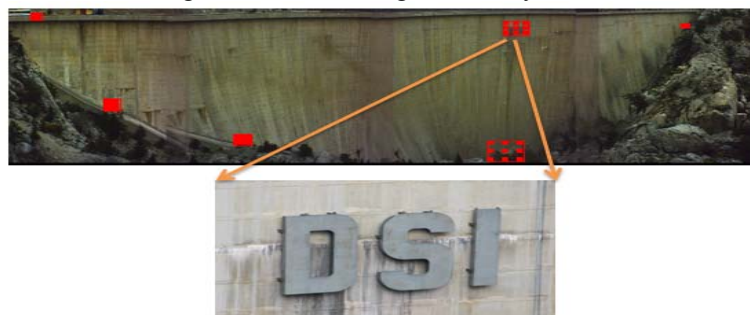
Figure 4 - OPTECH ILRIS-3D scanner.

3.3 Data Description

Since the scanner that we used to integrate different scannings and connection and control points for positioning does not have specific target type, dam body object points were used for this purpose. The position of the object points could not be accurately determined from the point cloud obtained from experiments, due to scanning time, resolution of point clouds, scanning distance and the resolution of the camera on the scanner. Plain paper targets in A3 format were fixated appropriately on the dam body surface to replace these object points as connection and control points. Center of these targets could not be accurately determined due to resolution of the camera. Then fixations of special targets, which reflect the laser signals, with the help of a crane were considered, but this option was discarded due to safety issues related to moving the crane on the crest of the dam. Finally, natural points with specific positions and good visibility in the point cloud was selected as connection and control points. The most appropriate scanning configuration for viewing these natural targets up to every detail was determined. An example of a natural target on the body dam is displayed on Figure 5.

Figure 5 - Natural Targets on Body Dam.

The OPTECH ILRIS-3D scanner was setup with a pan-tilt on reference point 2002 on Oymapinar dam. Pan-tilt is a device that enables scanner to take measurement on different angles on vertical and horizontal directions. Scanners batteries were used as the power source. The view of the dam body on the scanner control software within the field of view is displayed on Figure 6. The dam surface is divided into different frames in order to provide the most appropriate resolution based on the distance to point cloud that represents the dam surface (Figure 6). For each frame, the distance between the scanner and the dam surface was calculated with the software and the appropriate resolution was determined. This is because the distances from point 2002 to dam body varies between 40 m to 300 m. Scanning the dam body using only one frame results in denser point sets in close distance and sparser point sets in longer distance. Due to properties of the scanner we used, the distance between two points in the point cloud is determined based on the variation of angles.

Figure 6 - TLS field of view from reference point 2002 and scanned areas.
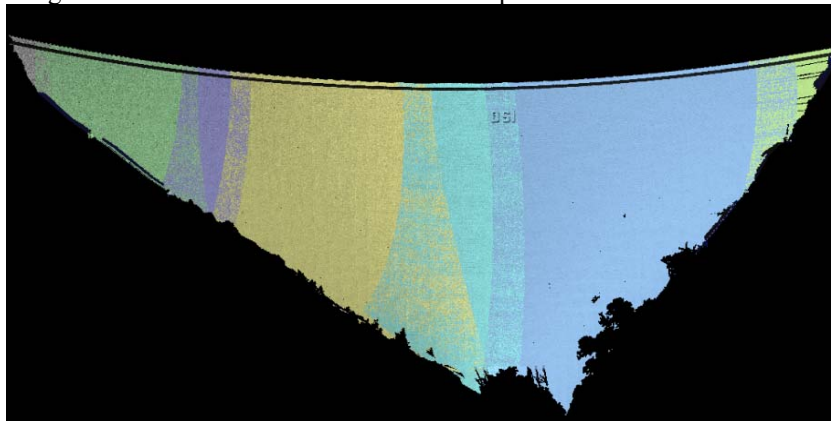
Based on scanning time, size of the dam and smoothness of the surface, general scanning resolution was set to 5 cm for accurately obtaining the surface of the dam body. Also, for verification of the surface model, scannings with fewer points and lower resolutions was performed by setting the scanning resolution o 10 cm, 15 cm, 20 cm, 25 cm and 30 cm. These additional scannings were performed at every scanning period. Redundant points were filtered based on distance and reflection values provided by the software.

3.4. Data Analysis

Integration of different scanning surfaces and transformation to geodesic network coordinate system was performed with indirect integration and positioning method. Since scannings were performed from a single point, all the points that represent the dam body surface were in scanners coordinate system initially. Sequential and overlapping scanning areas that form the whole dam body surface were displayed on Figure 6. Integration of these overlapping areas was performed by the ICP (iterative closes point) module in PolyWorks V10.1 software based on the distance between the points. The dam surface data that was integrated in scanners coordinate system were transformed to geodesic network coordinate system in mm precision for every period with the help of LEICA TPS 1201 Total Station (2 mm + 2 ppm (distance accuracy), 0.3 mgon (angle accuracy)) measurements performed on point 2002 and the distinct targets on dam surface.

The point cloud that represents the whole dam body surface was obtained after the integration and positioning process (Figure 7).

Figure 7 - Point cloud set that represents the dam body surface.
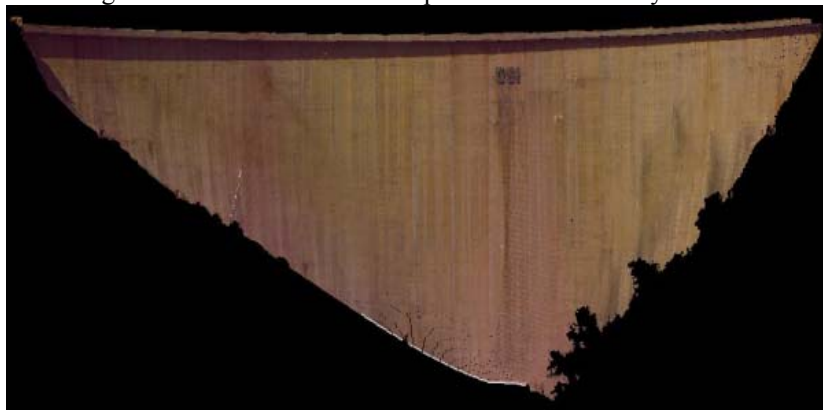

Irregular and redundant points on the back and front of the point cloud were detected. These points were removed from the set. Generally, product of 3D model

processing is a surface consisting of meshes. Meshing is formed by connecting all the points in the point cloud with little triangles. Generating a high quality mesh needs cleaning the data (noise reduction, removal of rough points), sampling (number of points), meshing, filling of empty spots on the surface and mesh optimization. After regularizing the point cloud obtained from scanning process, the critical part is generating a 3D model from the regularized point set. If the scanned object has a simple geometric structure, then 3D model can be obtained by drawing simple drawings with a CAD software. If the object has a complex geometric structure, then surface network model needs to be formed. This surface network is obtained with meshing by using software. Since meshing is performed automatically by the software, no meshes and/or redundant meshing may be formed in some places, and there may be errors in meshing in some places. Regularization of these meshes and filling of empty spots can be performed by the software user by using the software modules.

Solid model of the scanned object or area may be formed from the surface model. For visualization of the object, texture, image and etc. can be embedded into surface network. With these processes, realistic 3D models of the scanned objects can be obtained. Additionally, coordinates, distances and angles, RGB values of the point clouds can also be obtained from the software after the scanning. Obtained models can exported in DXF format for using in CAD software, in ASCII format for surface modeling and VRML format for visualization. Realistic data can be obtained from the final product model. 3D surface model obtained from all these processes is displayed in Figure 8. Position of the points, objects size, surface, area and volume can be obtained from the generated model. The generated model can be exported to other software by saving it in different file formats.

Figure 8 - 3D Model of Dam Surface.
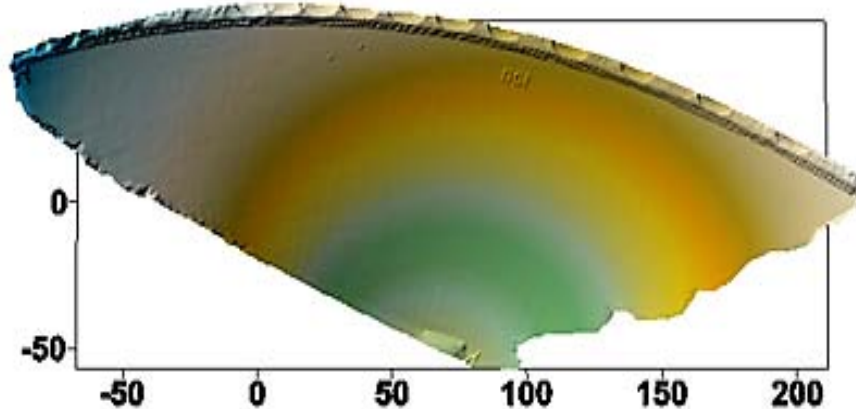
As it was discussed in Schäfer et al. (2004), structural monitoring by TLS is done by comparing surfaces to methods based on scanned objects surface (area). Deformations and translations can be detected by comparing the data obtained from different epochs, where mathematical surfaces related to measured points were taken into consideration. When the different point clouds in different reference systems are positioned, comparison between the interpolated surfaces allows computation of translations on the object surface. Detection of transformations on the scanned object or area is done with in different steps by surface differences. In the first step, points are transformed to surfaces by Delaunay triangulation algorithm. With the help of these triangles, an equivalent grid (for x and z coordinates) for each point cloud can be computed (Figure 9). Later, for each sampled point a new value interval (y) can be found. In other words, the difference in y direction for two surfaces that overlap in x and z directions yields the amount of deformation.

Figure 9 - Transformation from point cloud to surface and detection of deformations between two different time intervals (Schäfer et al. 2004).
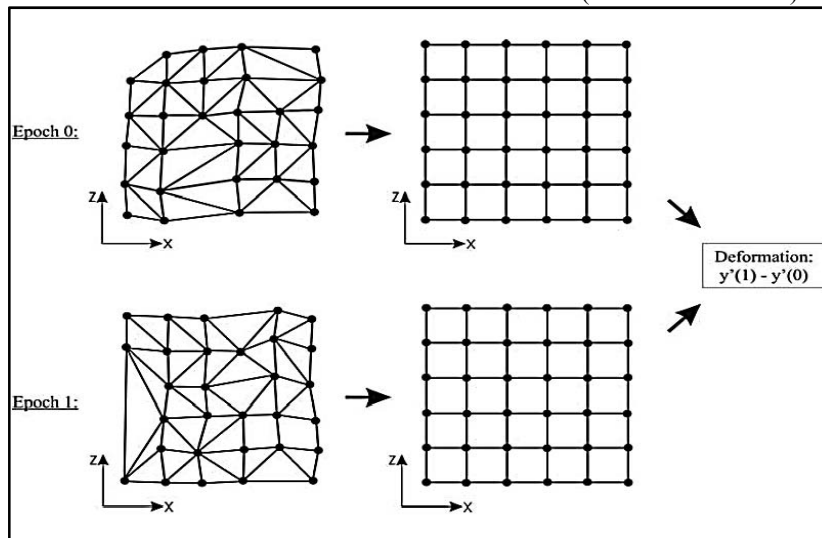

4. RESULTS AND DISCUSSION
Based on the theoretical and practical discussion above, four different 3D surface model of the dam was generated based on point clouds obtained from four different scannings performed in this study. Accuracies of point positioning which are obtained by Laser scanning technique depend on various factors. These are atmospheric and environmental conditions, distance to scanned area, structure of the

scanned surface, the accuracy of the laser scanner being used, accuracy of georeferencing and registration in data assessment, data editing, filtering, steps in 3-D modeling etc. All these factors deteriorate the accuracy of point positioning. In practice, analysis of point cloud data by laser scanning is difficult. In this study, a procedure was followed by checking the repeatability of laser data which were calculated by comparing the data obtained in similar conditions. The accuracy of the laser scanner being used is 7mm for per 100m and the accuracy of surface model from the results of the repeatability analysis is about few cm levels. The results were presented in detail in the figures 11, 12, 13, 14, 15, 16.

Aim of this study is testing the replicability of data obtained with OPTECH ILRIS-3D, generating a realistic 3D model of the dam body surface and checking if there is a significant difference between the surfaces by using surface different methods. For this reason, 4 measurements were performed on 4 different time intervals where the water level in the reservoir was the same (175 m). Aim of the future work is to examine the effect of changes in the water levels on the dam by using terrestrial laser scanners.

Based on the models generated from equivalent conditions and water levels, determination of translations on the dam was done by comparing the differences in y direction. Initially, only the difference between first and second surfaces was considered. Obtained differences (difference between surface 1 and 2) were classified within itself. Figure 10 shows which intervals maximum and minimum differences belong and the percentage of this difference on total difference on that interval.

Figure 10 - Surface Differences in Dam Body (1st and 2nd Surface) and Distribution of Differences (cm)..

Surface Differences	Distribution	%
		100

		99
		98
		97
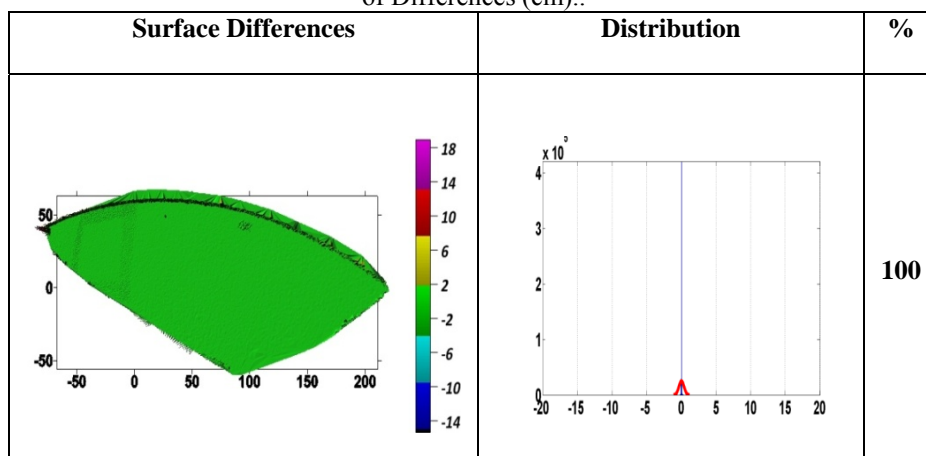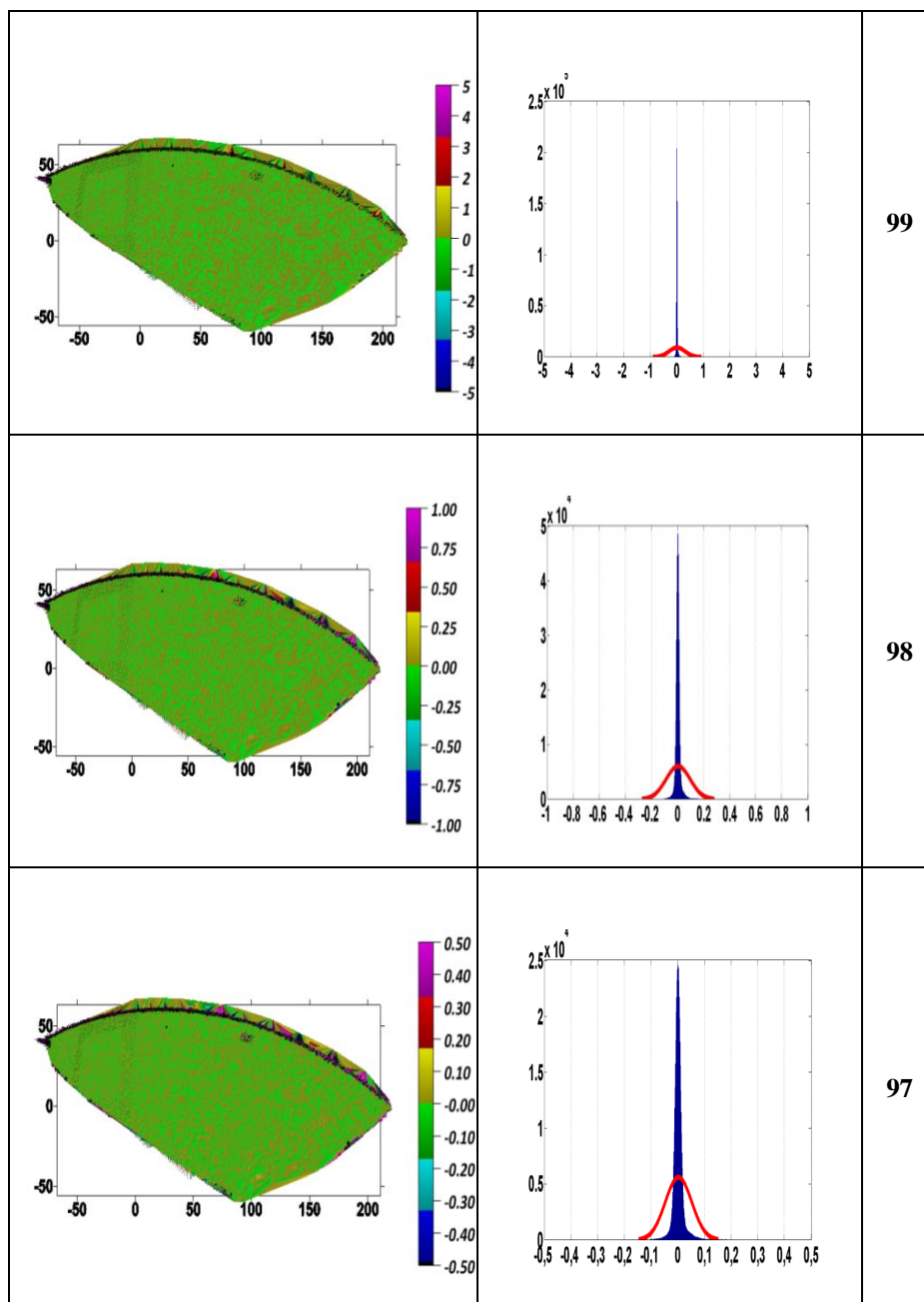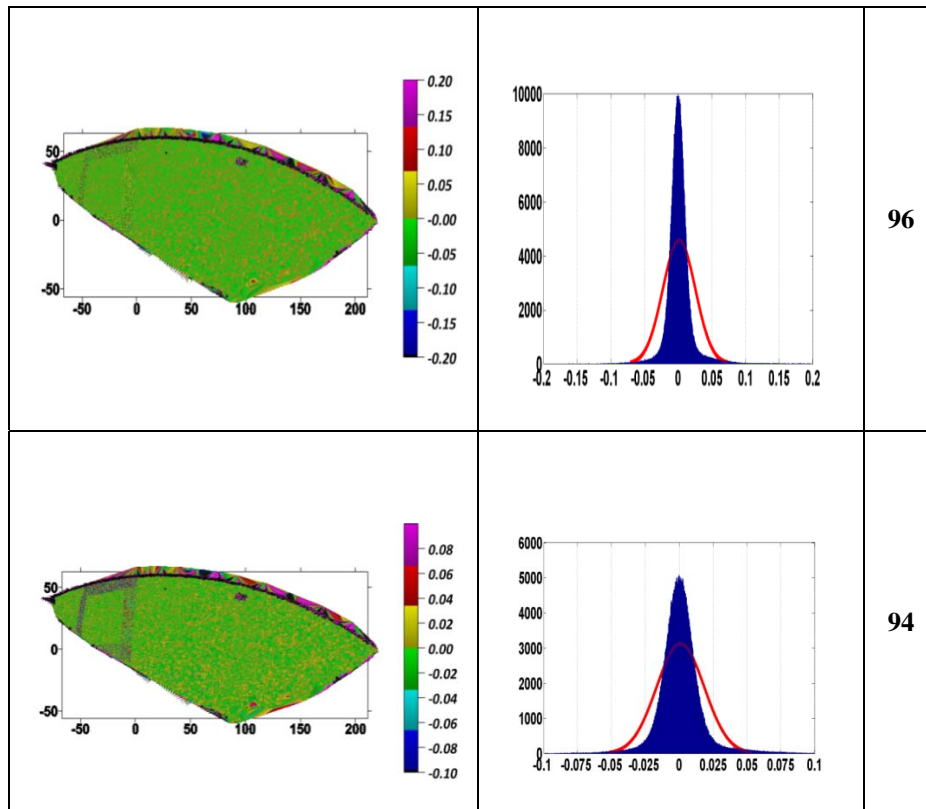
Distributions of points were examined to determine which intervals the big differences belong. Examination of colored scale surface differences above clearly shows that 94% of the data is between -0,1 mm and 0,1 mm. Distribution of the remaining points is presented on Table 2.

Table 2 - Distribution of points based on maximum and minimum surface differences (%).

Maximum (mm)	Minimum (mm)	Point Distribution (%)
18	-14	100
5	-5	99
1	-1	98
0.5	-0.5	97
0.2	-0.2	96
0.1	-0.1	94

Next, computability of 4 different surface models obtained from 4 different scannings was examined. Surfaces of these models were matched and differences were compared statistically. Point distributions and matching of object surfaces are critical processes for analysis of the data obtained from different scannings, where the water level as high, low and medium.

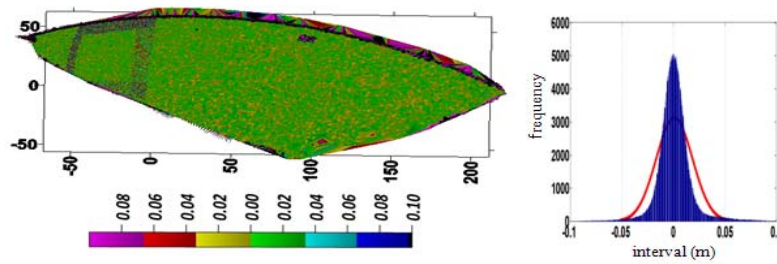Figure 11: 1st Surface- 2nd Surface (Y direction) Differences (cm)

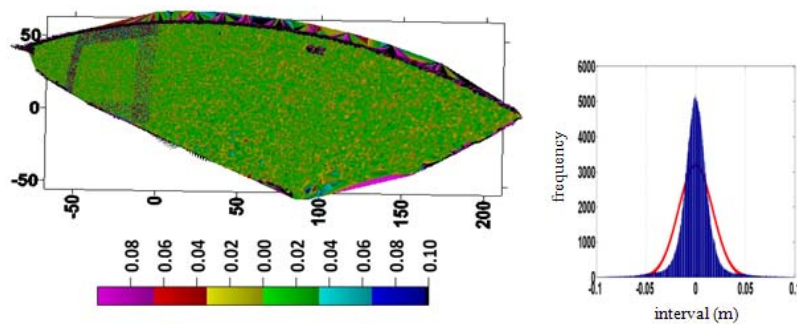Figure 12: 1st Surface- 3rd Surface (Y direction) Differences (cm)

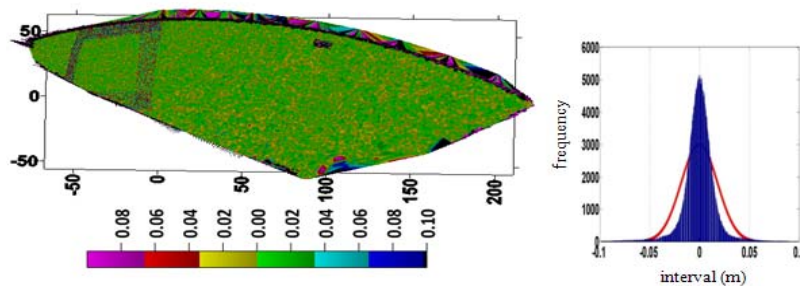Figure 13 - 1st Surface- 4th Surface (Y direction) Differences (cm).
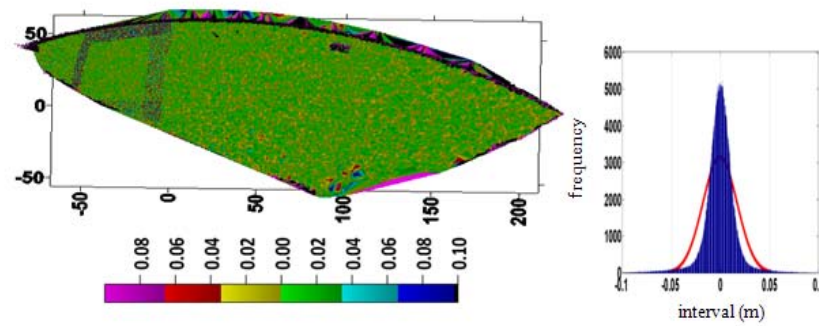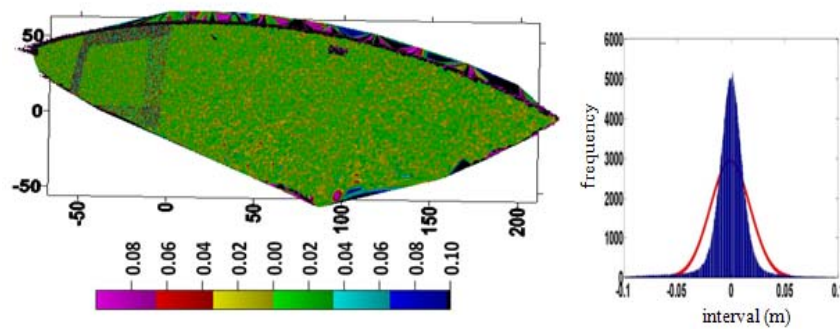
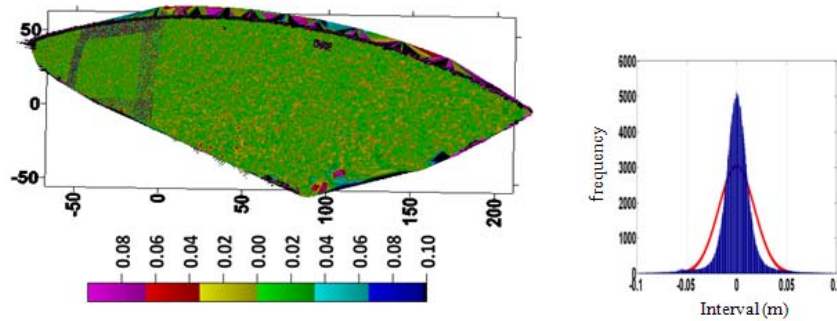Figure 14: 2nd Surface- 3rd Surface (Y direction) Differences (cm).

Figure 15 - 2nd Surface- 4th Surface (Y direction) Differences (cm).

Figure 16 - 3rd Surface- 4th Surface (Y direction) Differences (cm).

Surface differences displayed on the above figures show that similar results were obtained and the irregularities at dam surface and multiple reflection of the

laser signal on the corners was the source of differences and errors. Statistical results obtained from surface differences also provide similar results (Table 3).

Table 3 - Statistical Results (meter) Obtained from Surface Differences (within $\pm$ 10 cm)

	1st SURFACE – 2nd SURFACE	1st SURFACE – 3rd SURFACE	1st SURFACE – 4th SURFACE
Number of Points	2474611	2470044	2472713
Mean	0.00085	-0.00018	-0.000416
Median	0.00021	-0.000103	-0.000148
Variance	0.000308	0.000294	0.000332
Standard Deviation	**0.01757**	**0.017144**	**0.018207**
	2nd SURFACE – 3rd SURFACE	2nd SURFACE – 4th SURFACE	3rd SURFACE – 4th SURFACE
Number of Points	2470058	2469699	2468555
Mean	-0.000583	-0.001004	-0.000215
Median	-0.000214	-0.000256	-0.0000347
Variance	0.000302	0.000345	0.000323
Standard Deviation	**0.017375**	**0.018587**	**0.017968**

5. CONCLUSIONS AND SUGGESTIONS

In terms of determination of deformations on engineering structures, dams in particular, use of terrestrial laser scanning technology is a new measurement method. Specification of the scanned object in these applications is important. Geometry of the object and regularity and smoothness of the scanned object is important for analysis. Points where the scanning is performed should be related to geodesic control network present in the environment for comparison purposes. Integration of different scanning results and use of objet points on the dam body instead of target points for coordinate transformation is also important for the results. In particular, applicability of the scanner in deformation measurements relies on properties of the scanner, geometry of the scanned object, selection of the points where scanning is performed, scanning configuration, environmental conditions, experience of the scanning team, reliability of the geodesic network present in the environment and proper use of the software used in data analysis. In order to obtain realistic 3D models with TLS, to properly collect millions of points that generates these surfaces and to detect deformations, these factors should be taken into consideration during scanning and analysis stages.

In this work, deformation measurements obtained with TLS under the same water levels on Oymapinar dam was examined. There dimensional models of the Dam body were obtained from four different scans. For repeatability, six surface model differences (1-2, 1-3, 1-4, 2-3, 2-4, 3-4) were produced from the comparison of 3D surface models. Standard deviations from these comparisons vary between 0.0171 and 0.0186. Similar results were also obtained from the comparisons of colored surface difference scales drawn by ±10 cm intervals. The differences showed that they were normally distributed and their range in general (94% of them) were between -0,1mm and 0.1mm. Statistics obtained by the comparison of surface difference indicated that they contain similar results and compatible with them. There is no difference between the surfaces acquired from four different scans done at the same conditions and at the same water level. The surface differences produced by repetition of the application of TLS possess almost the same precisions and accuracies. The accuracies of surfaces acquired from the scans at different times at different water levels (min, max, etc.) are important in the assessment of effects and its deformations of water level changes on dam body.

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