International Journal of Civil and Structural Engineering – IJCSE
Copyright © Institute of Research Engineers and Doctors
Volume 6 : Issue 2 - [ISSN : 2372-3971] - Publication Date: 27 Dec, 2019

Quantitative contrast between the methodologies for the volumetric evaluation with cross-sections and 3D models in tunnels excavated with explosives

[Julio Manuel de Luis Ruiz, Raúl Pereda García, Rubén Pérez Álvarez, Felipe Piña García, Elena Castillo López]

***Abstract*— This research aims to establish the differences that are produced when calculating the volume of the excavation of a tunnel by means of equidistant cross sections obtained from a 3D model, and the 3D model itself, which was obtained from laser scanner data. The purpose of this research intends to contrast numerically a methodology that has been traditionally applied (cross-sections), and a more recent one which is supported by the use of powerful calculation algorithms that are appropriate for 3D models.**

All this research is applied to a tunnel that is used as spillway of a large dam that serves to regulate the water of a hydraulic facility. The results of this work justify in a quantitative way that, compared to the modern approach, the classical methodology produces deviations that can reach the 10% of the total volume of the excavation, which implies very high expenses, given the costs of this kind of work.

***Keywords*—Drill and Blast Tunneling; Cubication; DTM; Crossed Sections; Laser scanner.**

I. Introduction.

Depending on the typology of excavation, many constructive systems for tunneling are available nowadays, such as drill and blasting, mechanical excavation (road headers), mechanical excavation with non-pressurized (TBMs and shields) and pressurized machines (Hydroshields and Earth Pressure Balance shields). Especially in the case of the first alternative, the drill and blasting excavation, a wide range of sub-methods are available which, according to the typology of the terrain to excavate, can be more or less effective.

Julio Manuel de Luis Ruiz. Researcher ID: B-4956-2015
School of Mining and Energy Engineering / University of Cantabria / Spain

Raúl Pereda García. Researcher ID: B-5240-2015
School of Civil Engineering / University of Cantabria / Spain

Rubén Pérez Álvarez. Researcher ID: B-8959-2015
School of Mining and Energy Engineering / University of Cantabria / Spain

Felipe Piña García. Researcher ID: B-5710-2015
School of Mining and Energy Engineering / University of Cantabria / Spain

Elena Castillo López. Researcher ID: M-1310-2015
School of Civil Engineering / University of Cantabria / Spain

Drill and blasting is one of the most applied methods, due to the advantages that it offers: it does not require high investment on the equipment, which is highly moveable, and allows developing all types of sections, it being suitable for any kind of rock. However, it has some disadvantages, such as a very significant one: the over-excavation is due to the lack of parallelism of the contour and floor holes with respect to the tunnel axis, which provides space for drilling the outer holes in subsequent blasts, without losing the practical cross-section. In addition to this, the blast is usually over-dimensioned, so as to avoid the necessity of a second one, which would, undoubtedly, increase the costs of the method in every respect.

The following figure shows a typical section of a tunnel, the section that is obtained from blasting (which is not easily predictable), and the concept of over-excavation.

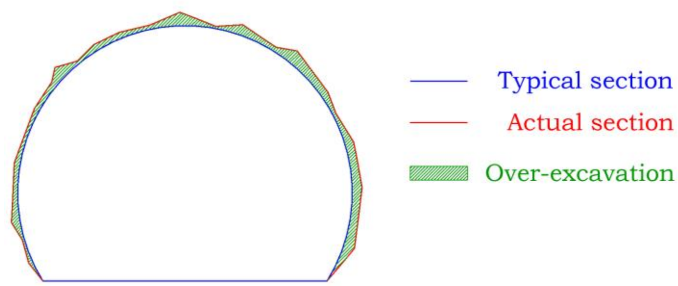

Figure 1.- Concept of over-excavation.

The over-excavation phenomenon is a source of constant discussion. The cost of this excavation is usually high: in addition to the expenses related to the transportation, those associated to the use of explosives and its pertinent operations must be considered. The excavation can be determined by the use of several alternatives, which provide results of the same order, but different. Classically, this volume was calculated by a series of equidistant cross-sections that were exclusively obtained for the volumetric determinations. It is worth noting that the over-excavation is usually reduced by the loss of volume that is due to the relief associated to the tunnel excavation (Rysdahl et al, 2015), for which a previously existing research has proposed a volumetric calculation in two sections of a tunnel (Dias and Kastner, 2013).

Hence, it can be stated that the earth-moving operations have one of its main exponents in underground works, given their high costs, and the capital importance of its estimation, so as to achieve the most accurate economic estimation possible. It also seems obvious that the representations of the terrain by means of virtual 3D models are the most suitable tool for the development of these calculations, as long as the

International Journal of Civil and Structural Engineering – IJCSE
Copyright © Institute of Research Engineers and Doctors
Volume 6 : Issue 2 - [ISSN : 2372-3971] - Publication Date: 27 Dec, 2019

information that is applied to obtain the model is representative enough.

Nowadays, and thanks to the new surveying devices (Terrestrial Laser Scanners, which measure millions of points in a few seconds), it is possible to obtain 3D representations of the terrain which are completely analogous to reality and have very little uncertainties (Liang et al, 2013). This new technology allows the generation of sections, such as the intersection of the solid that is generated with the surface of the tunnel, and planes that are perpendicular to its axis (Chen et al, 2013). This implies returning to the classical methodologies, although the sections are not determined in the field, but in the model itself (Lü et al, 2016). It is worth noting that, had the model been established, it is easy to define a solid between two sections, whose volume is easy to calculate with current computer tools. As it seems obvious, this model will be more accurate, and it will allow to quantify the deviation made when calculating the volume with cross sections and 3D models. This is the essential objective of this research, as there are still tunnels whose excavation is calculated by means of cross-sections, with the deviations that it implies.

II. Instrumental and Materials.

In mining industry, conventional techniques supported by the use of GPS or Survey Stations are widely used to gather data that are subsequently applied to calculate the volume of materials that are extracted (Nguyen and Liu, 2013). When the surface is very big or dynamic (Liang, et al, 2016), or in the case of collapses in tunnels (Mukhtar, 2018), the technology that offers a better representation of a 3D surface is the one related to Laser Scanner techniques, which has been properly contrasted with other techniques, such as photogrammetry (Parente and Pepe, 2018). This technique requires setting on a tripod a device that is able to measure the classical angles and distances that are observed by a survey station, but in an autonomous way, by scanning. In order to achieve this, the laser scanner counts with servomechanisms that incrementally rotate the direction of a laser-type beam both in horizontal and vertical. This beam allows defining the distance by means of electromagnetic methods, as it happens in the case of robotic survey stations, but without prism and in a totally autonomous way.

In most cases, a single scan cannot produce a 3D model of the surface. In order to get it, multiple scans are obtained with many different directions, and they must be included within a common system of reference. This process is usually known as alignment, and it implies the junction of the different scans to create the whole model, which allows measuring convergence and 3D viewing (Szafarczyk and Gawałkiewicz, 2018). Post-processing work permits adding models (different point-clouds), refining and managing spatial information, modeling and obtaining graphic outputs or alpha-numeric information. The laser scanner provides a mm-level relative accuracy, in an autonomous, fast and convenient way, thus reducing the time required for field-work.

Very manageable devices are available nowadays, with weights within the range of 4-5 kg, and therefore ideal for the types of environments where underground measurements are developed. They are very fast, as they are able to observe a million points per second, with ranges up to 350-400 m. The following figure shows the device that was applied for the development of the analysis.

Figure 2.- Device set for observation..

III. Methods.

The calculation of the actual volume of excavation of a tunnel, defined with surveing methods, can be held with two different techinques.

A. *Tunnel cubication with cross-sections.*

The determination of the actual volume of excavation of a tunnel with cross-sections requires adquiring in the field the observables that are needed to represent the real sections with a certain equidistance. Had de transverse sections been established, the average actual section is calculated. This average value, along with the tunnel length, allows determining the actual volume of excavation of the tunnel. As it is obvious, considering a same portion of tunnel, an increase in the number of sections, or a reduction in the distance between them, will improve the proximity between the obtained volume and to the real one.

The determination of cross-sections can be done with the adquisitions of data in the field, with a surveying station and the usually applied techniques. As this alternative is developed enough, it is well explained by conventional literature, and it will not be justified. It is worth noting that the transverse sections can be generated from the model obtained from any other device, even laser scanner, as it has been done for the development of this research: the contrast will provide information related to the incidence of the distance between the cross-sections and the volume calculation (Luo, et al, 2014).

International Journal of Civil and Structural Engineering – IJCSE
Copyright © Institute of Research Engineers and Doctors
Volume 6 : Issue 2 - [ISSN : 2372-3971] - Publication Date: 27 Dec, 2019

B. *Tunnel cubication with Digital Terrain Models.*

The determination of the actual volume of excavation of a tunnel by the generation of a Digital Terrain Model (DTM) requires a quasiautomatic observation with laser scanner to generate a model that is as close to the reality as possible, and the accuracy of calculations. So far, the procedure to develop this kind of observations is still open, without rules or preset standars. However, as it happens with any kind of measurement, it requires a previous scheduling that allows capturing the required information of the surveyed object.

Considering the case that has been analyzed in this work, the management of data started with an alingment (re-arrangement of the space of the single point-clouds under a same system of reference by means of Helmert Transformation, keeping each point cloud its character of single element yet) with the software Leica Cyclone (Xu, et al, 2017). Althought the observation was made with a Faro Focus 3D device, this option of sofware was adopted given the possiblity to work with point-clouds acquired with devices developed by other manufacturers that it offers, and its robustness and functionality. The point-cloud was exported to *.pts format for its subsequent treatment with freeware, increasing the options to generate meshes.

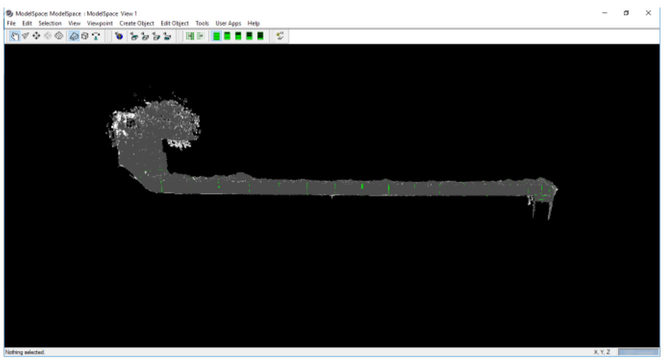

Figure 3.- Elevation view of the tunnel in Leica Cyclone.

After generating the model with Leica Cyclone, in order to reduce the potential uncertainties associated to non-linear segments, the portion of tunnel comprised between the sections 0+050 and 0+140 was adopted for the comparison, being both of them included. Hence, any problem related to segments with varying slopes or curves, which can be found at the beginning and the end of the tunnels that has been studied, was avoided. .

Had the segment in which the research was developed chosen, the cross-sections that would be applied for the subsequent sections were firstly obtained. To define these sections, the trajectory of the tunnel was defined, and a 10-meter spacing between them was set. 10 sections were thus obtained. As Leica Cyclone does not allow developing volume calculations from cross-sections, they were exported to *.dxf format.

Nowadays, there is a wide range of software with different workflows to obtain the modelled volume from the point-cloud obtained with laser scanner. These processes imply the initial generation of a watertight surface, and the calculation of the volume that is enclosed by it (Xu, et al, 2017). In this research, the sections and the point-clouds were both imported to the freeware CloudCompare. This software was adopted due to the possibility to overlap the sections and the cloud that it offers. It is worth noting that this overlap allowed an accurate severing of the cloud, to exclusively work with the segment of interest.

After setting the portion of interest for the development of the contrast, the software MeshLab was applied to obtain the mesh and the subsequent volume calculation. In this regard, it is worth mentioning that CloudCompare allows exporting to *.ply format, which is perfectly recognizable for this second tool, and translating in an automatic way the point-cloud. It must be taken into account that the latter was referred according to its UTM coordinates, it being impossible for many programs of point-cloud management and/or meshing to work with values with so many significant digits, as they are commonly developed to work with 32-bit float variables.

Had the point-cloud been imported with *.ply format in MeshLab, a watertight surface was developed with the "Screened Poisson Surface Reconstruction" algorithm (Kazhdan and Hoppes, 2013). Compared to other possible alternatives, this algorithm smoothes the mesh, but guarantees the absence of gaps in the mesh, and allows the application of computers with more modest features.

IV. Results.

As it has been previously mentioned in the methodological section, the first calculation of the real volume of excavation implies the use of actual sections which were set each 10 m along a total segment of 90 m. The following figure shows the result of the 10 cross-sections, with a resulting value for the average cross-section area of 32.58 m^2.

Figure 4.- Cross-sections each 10 m.

Given the fact that the average section of excavation of the tunnel through the 90-m-long segment is 32.58 m^2, it can be deduced that the actual volume of excavation for that portion of tunnel is 2932.2 m^3.

As previously described, the second procedure to calculate the volume of the actual excavation of the tunnel requires the importation of sections and the point-cloud in CloudCompare, so as to overlap the them and define the strict area for which the contrast will be developed. It is worth highlighting that the segment of the tunnel that is subject to this contrasts counts with a point-cloud that comprises about 21.5 million points, with provides an idea of the level of detail that is obtained with the model, as it can be observed in the following figures.

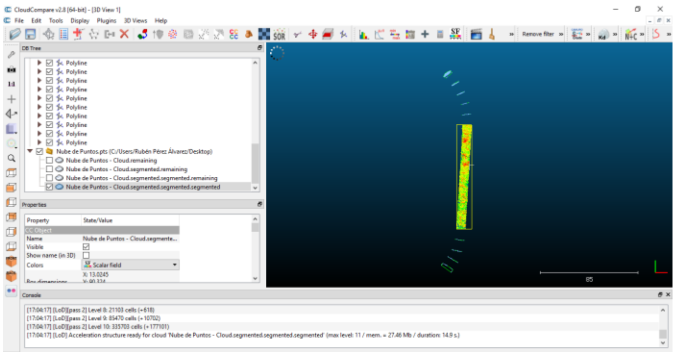

Figure 5.- Plan view of the segment of interest and discarded sections.

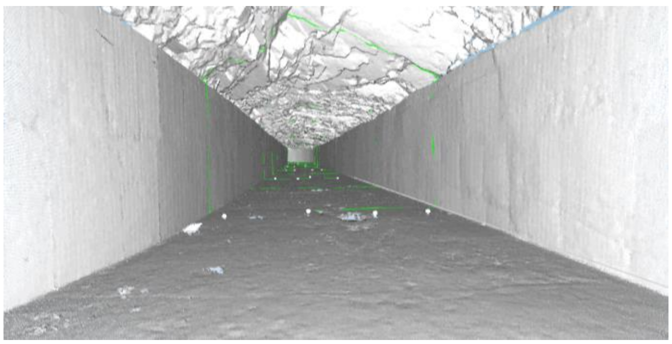

Figure 6.- Inner perspective of the segment of the tunnel that has been subject to contrast.

Had the segment of interest been defined, the point-cloud was exported to MeshLab, so as to generate a watertight mesh and to develop the subsequent volume calculation. It must be noted that the application of the "Screened Poisson Surface Reconstruction" smoothed the mesh to its final shape, with 15,615 vertices and 31,230 faces, which allows the use of a computer with modest features (Acer Aspire V15, with Intel Core i7-6500U Processor, 2.5 GHz and Turbo Boost of up to 3.1 GHz, 16 Gb RAM DDR3 L Memory and NVIDIA GeForce 940 M Graphic Card, with 4 Gb of dedicated VRAM). The following image shows the result of the watertight surface.

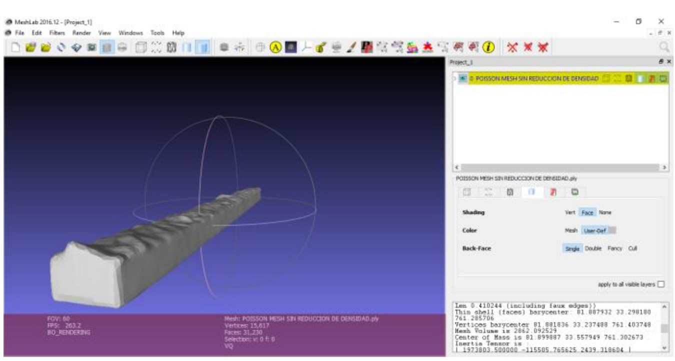

Figure 7.- Watertight surface and determination of volume.

The same software allows calculating the volume that is enclosed by the generated watertight surface, which corresponds to the hypothetic actual volume of excavation of the tunnel, with a resulting value of 2862,09 m^3.

The final result of this research is obtained by comparing the results of the actual volume of excavation that is provided by both methods. In this regard, it can be seen that the resulting volumes have a difference of 70,11 m3, which implies an approximate variation of 2.5% of the total volume of excavation for this segment.

V. Discussion.

Nowadays, the discussion about the instrumental and the technique to be developed in order to obtain a quasi-continuous and accurate model of an excavated tunnel is clearly overcome. In this regard, the classical surveying stations have been left behind with the irruption of laser scanners in the field of Geomatics. This research is focused on the calculation process of a volume from a model that has been exclusively obtained from laser scanner observations. This is the reason why the possible differences in the volume calculation cannot be attributed to the instruments or the model, as there is a single model, which has been obtained with the same device.

Other similar works of research have tried to establish the methodological differences that allow calculating the volume of excavation of a tunnel, but the relevant fact of this research is that the difference between the volumes that are obtained by the use of cross-sections and by managing the 3D model as a solid have been quantified for the first time.

At the moment of the acquisition of data with laser scanner, the tunnel in which this research has been developed was characterized by having a partially coated section, of about 75% of its perimeter. Hence, the obtained results can be multiplied by four to allow extrapolating this research for the calculation of a full section. This would imply a variation in the volume of excavation of a 10% of the total volume, which is a very high value, due to the elevated costs of this unit of measurement.

Other important aspect to consider when interpreting the results arises from the reality under which this research has been developed. The cross-sections have been generated from the 3D model that has been obtained with laser scanner observations, and not from classic methods that usually require the use of a surveying station. This implies that the variation of 10% in the estimation of the volume of excavation of the tunnel only takes into account the deviation that is due to the methodology of calculation from the 3D model itself, and not the instruments, given the fact that the stating point is always the 3D model. .

The process that is used to manage the laser scanner data is mainly conditioned by the hardware and software that is available for the user. In this regard, it is worth noting that there is a wide range of computer tools which allow developing the treatment of data nowadays. As it is obvious, the know-how that has been applied by the authors for the development of the calculation of this research could vary with respect to other computer tools, but the obtained results should be very similar or equal.

VI. Conclusions.

The first conclusion must be focused on highlighting the importance of the volume calculation of the excavation of a tunnel that has been developed with explosives. This is due to the high costs of this unit of measurement and, therefore, to the economic mismatch that can be generated with little variations in volume which, as it is obvious, must be avoided.

The second conclusion is related to the main aim of this research, which does not pursue the contrast of the devices that can be applied to generate models of tunnels, but the method of volume evaluation that can be used once the model has been generated. In this regard, this research seeks to establish the difference between the volume that has been obtained by the classical method of cross-sections, and a less traditional alternative that treats the tunnel as a 3D solid. The results of this difference, of about 10% of the volume, support the technique that considers the tunnel as a 3D solid as the most suitable one for the estimation of volume.

Nowadays, there are is a wide range of computer tools that allow implementing 3D solid models, and the subsequent volume calculation. This variety implies that the workflow or know-how largely depends on the available tools. In this research, the methodology has been developed with a well-defined set of software programs, but it could differ according to the available tools.

The results support that the management of data is laborious, but the difference in volume and the related economic cost, make the proposed methodology for the treatment of the records as a 3D solid model very interesting.

Acknowledgment.

This work has been possible due to the data provided by the Enteprise “Saltos del Nansa S.L.”, which constantly supports the research that is developed by this Area of Knowledge of University of Cantabria.

References.

[1] Chen, K.; Zhang, D.; Zhang, Y. 2013 “Point cloud data processing method of cavity 3D laser scanner” Guangxue Xuebao/Acta Optica Sinica, 33 (8). Pp. 0812003.

[2] Dias, D.; Kastner, R. 2013. “Movements caused by the excavation of tunnels using face pressurized shields - Analysis of monitoring and numerical modeling results” Engineering Geology, 152 (1), pp. 17-25.

[3] Kazhdan, M.; Hoppes, H. 2013. ACM Transactions on Graphics (TOG), 32 (3), June 2013, Article No. 29

[4] Liang, X.; Zhang, H.; Song, Z.; Zhou, X.; Hao, H. 2013. “Application of 3D laser scanner to measure the volume of an oil storage cave”. Journal of Scientific Instrument, 34-6. Pp. 237-241.

[5] Liang, Q.; Xu, W.; Ma, Q.; Yang, D.; Zhang, W.; Fu, Y. 2016. “A new type of rapid and simple coal and other bulk commodities inventory system based on two-dimensional laser scanner”. Proceedings of SPIE - The International Society for Optical Engineering, 10155, art. no. 1015527.

[6] Luo, Z.-Q.; Zhang, W.-F.; Lu, H.; Xu, S.-M. 2014. “Calculus algorithm of triangular mesh model profiles for cavity volume”. Beijing Keji Daxue Xuebao/Journal of University of Science and Technology Beijing, 36 (9), pp. 1143-1148.

[7] Lü, X.; Liu, X.; Duan, Y.; Liang, J. 2016. “Laser measurement method and in-situ experiment of underground energy storage caverns volume”. Zhongguo Jiguang/Chinese Journal of Lasers, 43 (10), art. no. 1004002.

[8] Mukhtar, S. 2018. “Underground 3D scanning in Bhutan”. GIM International, 32 (3), pp. 22-25.

[9] Nguyen, T.T.; Liu, X.G.; Huang, Y.; Wang, H.P.; Kieu, Q.L.; Dang, T.S. 2013. “Ore volume measurement based on 3D laser scanning technique: A case study”. Advanced Materials Research, Vol 610-613. Pp. 3708-3714.

[10] Parente, C.; Pepe, M. 2018. “Uncertainty in landslides volume estimation using DEMs generated by Airborne Laser Scanner and Photogrammetry data”. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42 (3W4), pp. 397-404.

[11] Szafarczyk, A.; Gawałkiewicz, R. 2018. “Defining the Cubature Changes of Historic St. Kinga Chamber in Bochnia Salt Mine, Using Laser Scanning Technology”. E3S Web of Conferences, 35, art. no. 04006.

[12] Rysdahl, B.; Mooney, M.; Grasmick, J. 2015. “Calculation of volume loss using machine data from two slurry TBMS during the excavation of the Queens bored tunnels”. Proceedings - Rapid Excavation and Tunneling Conference, 2015-January, pp. 554-563.

[13] Xu, D.; Feng, X.-T.; Li, S.-J.; Wu, S.-Y.; Qiu, S.-L.; Zhou, Y.-Y.; Gao, Y.-H. 2017. “Research on key information extraction of rock mass deformation and failure characteristics in Jinping underground laboratory based on 3 D laser scanning technique”. Yantu Lixue/Rock and Soil Mechanics, 38, pp. 488-495.Sundakov, Y.A., “Trabajos geodésicos en la construcción de grandes obras industriales y altos edificios”, Editorial Mir, 1980.