Assessment of Pore Space Characteristics in Compacted Soils Using X-ray Micro tomography and Image Analysis

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ABSTRACT Compaction is a serious issue that occurs either as a result of human activity or naturally. The impact of compaction can be assessed by observing basic components within soil aggregate, as the properties of pores. The volume, shape and quantity in the form of pore characteristics, indicate soil stability and limit the flow of water and air through the soil. Essentially, in this study, used vital properties of inter and intra aggregate pores within soil aggregate fractions ranged from 2mm to 5mm. They have been used to observe and analyse the effect of manually extreme pressure on pore structures using X Ray Micro CT with a resolution of 10µm. The results from reconstructed 3D images by Simpleware Scan IP, for different moisture content of the top and bottom sections of soil samples, taken from grassy land, have shown that compaction led to a decline in porosity and void ratio, mainly at the top layer of soil for inter aggregate pores and voids. However, a significant decline occurred with a higher moisture content M2 of 18.27% compare to a natural moisture content M1 of 9.3%. A dramatic decline occurred with the biggest pores, which were replaced by further smaller pores. Oppositely, unexpected results have been evaluated for intra aggregate pores, when the porosity slightly increased due to compaction. Nevertheless, moisture content and depth did not affect the fate of soil. Eventually, this study confirms the major effect of using new methods and techniques for evaluating soil properties.

1 INTRODUCTION

Soil is an important component on this planet and plays a key role in the environment. Directly or indirectly it also affects the ecosystem, especially for agricultural production and human life (Batey, 2009). In general, the most substantial process of water storage and mobility, nutrients, aeration, and nitrogen and carbon cycles are driven by soil property (Menon et al., 2011).

Basically, soil could affect many processes physically, hydraulically and biochemically. Soil consists of aggregates that contain solid particles and pore spaces. Many studies have shown that the stability of soil is directly linked to soil structure, as well as the mechanical properties of the aggregate's components(Keller et al., 2013). This should be considered as a central issue with respect to stability in terms of any external or internal stress such as compaction, since soil outcomes and its productivity will be under threat when soil is compacted by different sources, either naturally or otherwise (Carminati et al., 2008). Previously, several studies have used different techniques and methods to estimate the impact of the physical changes of soil properties within

the whole soil structure. However, there is still insufficient knowledge that illustrates the direct effect on soil microstructure within an aggregate, such as pores and voids parameters against compaction (Keller et al., 2013; Menon et al., 2011).

This study is concerned with the impact of compaction on soil's mechanical characteristics. It uses X ray micro CT for scanning the different moisture content at the top layer of grassy land with sizes of 2mm to 5mm soil aggregate by the SoilTrEC EU-FP7 project. This is because the most effective stress occurs at the top layer, such as stress resulting from human activities, such as loading by vehicle wheels or animals for tillage, and natural stress by heavy precipitation on the soil surface (Chaplain et al., 2011).

Recently, the method of X-Ray Micro Computed Tomography has been developed and used for scanning micro portions, as it is considered one of the non-destructive technologies, with more accuracy output for demonstrating 2D and 3D images of soil aggregate (Ghezzehei, 2011;Taina et al., 2007).

In fact, this study used a resolution of 10µm for two main sections, such as the top and bottom of three replicates of soil samples, before and after compaction. Furthermore, the demonstration of results by using new techniques for evaluation of pore responses. Consequently, special software has been used for this aim, namely Simpleware Scan IP version 5, for rendering with different mask and visualizing as 3D images. This is to evaluate and analyse porosity and void ratio with respect to the parameters of pores, as well as volume, surface area, and the total number of pores.

Ultimately, heterogeneous responses appeared after compaction with regard to inter and intra aggregate pores. As well factors of moisture and depth of sample supported the mechanical logic that compaction leads to decline of pore's size and porosity. Nevertheless, the type of pores affected the trend of results, exclusively for intra aggregate pores, which may be a crucial evaluation in illustrating the importance of using new and accurate techniques for studying microstructure within soil aggregate.

2 THE NECESSITY OF USING X RAY MICRO TOMOGRAPHY

In order to realize the aims and to demonstrate the compaction's influences on pore's structure, use an accurate and new method as a non-destructive technique for scanning micro slice of soil so as to achieve following aims;

- Illustrate pores and voids in term of size, shape and quantities within a selected soil sample aggregate for both cases of incompact and compacted soil.
- Understand how effective moisture and the moisture content is it on the pore spaces microstructure.
- Using 3D images instead of plain or 2D images as has been used in the past. Correspondingly all the results will be represented using particular software as well as Simpleware scan IP, so as to build a model of three dimensional bodies with different masks with the aim of calculate all statistical and geometrical values digitally for each parameter within the soil samples.
- Recognize the impact of stress on the surface layer of soil meanwhile the top layer of soil is the most vulnerable part under threat from many different sorts of external impact as well as compaction.

2.1 Assessed Moisture Content

The principle for collecting data in the field and analysing its main properties which has been done by finding the natural moisture content of the sample as it exists when collected from the top layer in the field by SoilTrEC EU-FP7.

The traditional method was used as well as that of an oven for drying the soil. As a result, the mean value of the three soil samples show that the initial moisture content M1as it was collected from the field was 9.34% based on the weights. Furthermore, in order to prepare samples with an additional moisture content so as to represent the case of unsaturated soil, since the most effective factor is the moisture content. Water was therefore added by spraying as it happen with rain and the mean of additional moisture content M2 after 24 hour was 18.27%.

2.2 Compaction Process

The process of compaction was done based on a calculation of bulk density and void ratio for each replicate within the natural moisture content M1 and additional moisture content M2 at the time of the scanning process.

In general, the soil samples were compacted through the use of a piston within a plastic tube as syringe 10ml which was used for the scanning process. The loading process followed static loading stress as a maximum pressure manually. The main reason for this was that the majority of compaction followed the same scenario in terms of what might be done by the tyre of a truck as part of the tillage process, or human and animal actions, and even the pressure of precipitation.

Eventually, the mean value of bulk density for the natural moisture M1 was 0.842gm/cm^3 before compaction and has been increased to 1.123gm/cm^3 after compaction, this result was changed regard to additional moisture M2 which was 0.92gm/cm^3 and 1.62gm/cm^3 for incompact and compacted soil samples respectively.

2.3 Scanning Soil Samples

Lately, X Ray computation tomography and micro tomography have been considered to be the most effective and accurate technology which has been widely used in many different fields of science for visualizing and analysing 2D and 3D images of any material, ever since it is a non-destructive and non-invasive technique in terms of the sample (Taina et al., 2007). Though, the technology was largely used in the medical field. More recently, it has been used for soil and plant analysis, especially for illustrating pore and soil particle structure. The main process is based on passing of X ray beams through the sample with different angles and make a lot of slices as a shadow on the detector.

Essentially, the X ray micro CT scanner which was used for scanning soil samples was a model of the Sky scan BRU 1172 in DU14 at Royal Hallam Shire Hospital. This scanner consists of two main parts; the scanner device and the X ray software for controlling the scanner. Medium camera was used as 2000x1048 pixels with

0.5mm Aluminium filter to allow alterations of the image's resolution and considered the assumption energy with time as well.

Eventually, the images were in the range of 10μm on average, since the tube's diameter as just below 15mm proportion to 2000pixels and the different height of the soil sample within the tube on 1048 cells. Moreover, the conical shape of the attenuation of the X ray on the soil sample will be three times of the main selected pixel as a geometrical distribution shape of the X ray when the fixed sample is at the centre of the conical beam.

The energy source which controlled the scanning process was the maximum as 100 electron KV for creating X ray to be path through the sample. Similarly the acceptable rate for the minimum range was 20% to 40% of absorption according to the thickness of sample. As a final step of scanning, all scanned images as a TIF files have been reconstructed by NRecocn software to be orientate all slices and created a raw of 3D images as BMB file format.

2.4 Process of Three Dimensional Imaging

The construction of 3D images for scanned samples can be done by X ray CT and Micro CT. Conversely, analysing and finding the most important physical parameters can be done using a range of different kinds of software in order to visualize images clearly.

For this study, one of the most accurate and reliable types of software which is used frequently was Simpleware Scan IP version 5. This was because it is capable to deal with the most types of images certainly and has many preferences regard to visualizing, measuring main parameters and segmenting any interesting part of the volumetric 3D data within a sample.

In general, many tools and options are provided to manage the process of visualizing and analysing the massive files related to slices that have been scanned by X ray micro CT, such as measuring tools for finding distances of 3D and 2D images, centre of mass, histogram, volume, surface area, mean value, standard deviation, region centre and the number of the element's parameters based on counted voxels.

Moreover, there are many sustainable options for editing images such as crop, pad, rescale, flip, paint, filling segment, shear and many kinds of filters for controlling masks and the appearance of images. Ultimately, it would be possible to use different masks with rendering the slices, as different parts which are useful for subtracting the solid part from the total volume of the 3D shape in this study, so as to evaluate pore spaces.

Essentially, the resolution spacing for each axis X, Y, and Z was fixed on the range of scanned and adequate values which were used in the test, as well as 10μm.

The process of creating masks with different options was followed by the segmentation and selection of the threshold range to illustrate the acceptable value of image brightness, and the background pixel noise with its grey scale was released. In this case the lower value of the image threshold was fixed on 30 and a higher value on 255, which corresponded to the Hounsfield Unit HU level of the X ray with a lower value of digit pixels.

The step of defining interested masks was done by a duplication of the original mask to represent all parts of soil elements, as well as solid and pores. Additionally, segmentation and threshold followed other actions within the material mask by applying Flood fill route so as to connect pixels in particular for solid elements. And then applied a median filter in order to reduce noise with radius or space of neighbourhood 2 pixel for all directions.

Consequently, it appeared smoother for elements by using the median method in terms of statistical output values to be considered as an average among all pixels for the filling body. The mask of intra aggregate pores filled by cavity filter and morphological so as to close and fill all pores below 4pixel within solid mask and be released from solid particles by considering the 3D spaces of pixel values instead of the numerical distribution.

However, for inter aggregate pores created new solid cylinder model from +CAD software to display voids and external pores in term of soil aggregate.

3 RESULTS OF 3D IMAGE ANALYSIS

3.1 Inter Aggregate Pores

Mostly, the 3D images indicated the effects of compaction on soil parameters, as well as pores and voids which illustrated different responses according to the type of pores and for two different states of moisture content and depth.

In fact, a significant decline occurred in terms of the size and number of pores, particularly within the top layer for all states, but the higher moisture M2 was effected dramatically .Clearly, the bigger voids and pores have disappeared due to compaction and replaced by numerous number of smaller pores instead as shown in Figure 1.

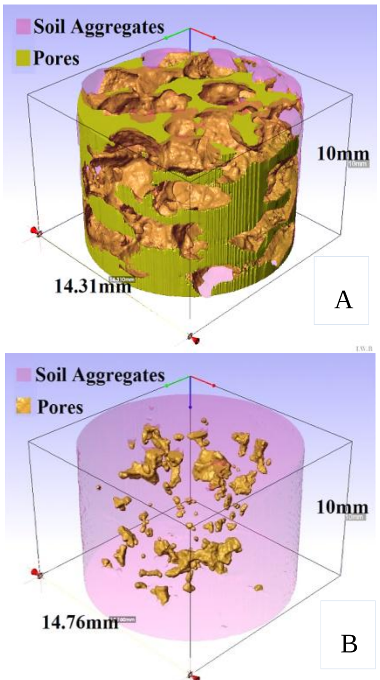

Figure 1. 3D image of the M2 at the top layer for inter aggregate pores before compaction A. and after compaction B.

3.1.1 Response of Pore Characteristics

The mean of porosity, void ratio and surface area's ratio for the three soil samples' replicates with regard to inter aggregate pores and structural voids between loosely organized aggregates, have been dramatically decreased after compaction especially at the top layer for the both cases of M1 and M2 compare to bottom part. The huge change was happened within the M2 in all cases subsequently the water made an additional negative pressure on pore's structure, and the connection points between two neighbour aggregate increased as well. As a result of compaction, mean porosity from 0.35 declined to 0.12 at the top layer, and from 0.42 to 0.20 at the bottom for the M1. Alternatively, for the M2 it has plunged from 0.39 to 0.03 regard to the top section, and from 0.40 to 0.04 at the bottom part.

Furthermore, mean void ratio at the top part decreased from 0.50 to 0.12, and from 0.60 to 0.20 at the bottom part for the M1 caused by compaction. Yet the trend for the M2 was decrease from 0.60 to 0.20 at the top layer and from 0.56 to 0.03 at the bottom layer.

In addition, the trend for surface area ratio to solid part and bulk volume was the same trend as well as porosity and void ratio after compaction.

Statistically, the probability values of the distribution data in terms of the T-test compared to a 5% and 1% probability distribution between compacted and incompact soil have shown significant differences (*) for the M1 at top and bottom layers, since this was less than 5%.

As well a huge significant difference (**) when P value was lower than 1% has been found within the M2 and the bottom part of the M1 as shown in Table1. Therefore it rejected null hypotheses which assumed there was no difference between two states of incompact and compacted soil.

Table 1. P value by T- Test for inter aggregate pores before and after compaction

Soil Moistures	Layer	Porosity	Void Ratio	S. Area / Total
M1	Top	0.0150*	0.0291*	0.0017**
	Bottom	0.002**	0.0015**	0.0040**
M2	Top	0.000**	0.001**	0.0020**
	Bottom	0.000**	0.0007**	0.0005**

For the reason that the shapes of pores are non-geometric, then pore's classification based on the number of counted voxel, for volume was counted by Simpleware scan IP. Essentially, the total volume of the inter aggregate pores have been classified into seven classes ranging from greater than 100mm^3 to smaller than 0.001mm^3. But the minimum range classes for the mean volume of below 0.01 mm^3 have not appeared as an effective range to compare with the bigger volume.

As a result of compaction, all of the classes for the mean pore sizes have been changed but different fate for each size as well as the bigger pores have been crashed to the smaller size. For the M1 state and at the top, the maximum volume of pore was517.34 mm^3 broken down to a smaller pore size of 158.67 mm^3, yet the fate was significantly changed for the top layer of the M2, the biggest pore 546.3 mm^3 compensated by multi smaller pores. However, for the both states of moisture content M1 and M2 at the bottom layer, the effects of compaction were not as significant as on the top layer.

Regard to surface area, six classes have been used as the range for covering all the sample results, as well as those ranging from greater than 1000mm^2 to those below 0.1 mm^2, though there was no considerable response for the range below 0.1 mm^2.

Ultimately, due to compaction the mean value of 3503.3 mm^2 which then decreased to 1603.3mm^2 for the top layer of the M1, but the result significantly responded with regard to the M2 which mean value of 2763.3mm^2 was 100% disappeared to be replaced by smaller classes. Although, in the case of bottom layer for the both states of moisture content M1 and M2, the effects of compaction were not as substantial as for the top layer.

Mostly, the counting of inter aggregate pores for each case has been done using 3D images. The mean of total number of pores has increased more than three times compared with the original state due to compaction for the both states of moisture content M1 and M2 at the top section and the same is true for the bottom layer. This confirm that the total number of pores before compaction consisted bigger size of pore with smaller number, but after compaction the great size of pores were broken down to many smaller pores because of repacking and rearranging from loose distribution to more denser state of soil. Likewise this led to widening area of attachment between aggregate to close open pores mainly in the case of M2.

3.2 Intra Aggregate Pores

Certainly, the importance of the results may be accumulated by illustrating all kinds of pores. Then the most interesting physical properties have been analysed for intra aggregate pores which are considered to be the smallest size of pores within soil aggregate such as micro pores. In contrast to inter aggregate pores, the 3D images show that the smaller pores' properties within soil aggregate have increased due to compaction, especially in terms of quantity and kinds of smaller intra aggregate pores which can clearly be recognised with the naked eye as shown in Figures 2.

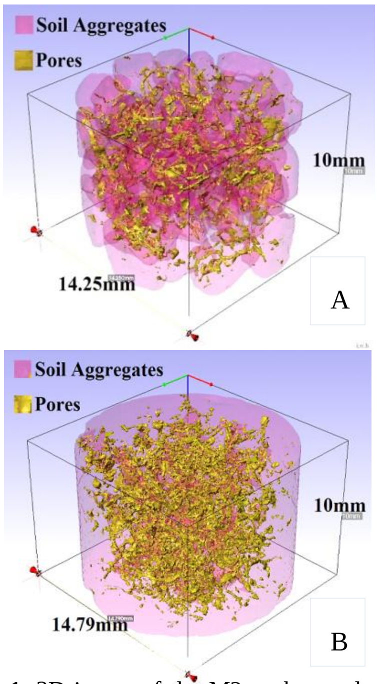

Figure 1. 3D image of the M2 at the top layer for intra aggregate pores before compaction A. and after compaction B.

3.2.1 Response of Pore Characteristics

Quite the opposite to the previous cases for inter aggregate pores and voids, the mean porosity has been slightly increased from 0.06 to 0.063 for the top section of the soil sample with the natural moisture content M1, and from 0.049 to 0.067 for bottom layer by compaction.

On the other hand, the trend for the M2 of mean porosity has very slightly declined also by compaction from 0.030 to 0.028 at the top layer, yet the trend shows that the porosity at the bottom layer increased slightly from 0.033 to 0.035 as a result of compaction.

Obviously, the same trend with regard to higher changes of the mean surface area has occurred as happened with porosity after compaction.

Owing to compaction, the mean ratio of the pore's surface area to the total surface area for the natural moisture content M1 increased by nearly 23% for the top layer and more than 33% within the bottom layer.

Equally, the trend for the higher moisture content M2 has increased by more than 23% and 33% for the top and bottom sections respectively after compaction. Nevertheless, the results confirm that moisture content might not be effective for responding against compacting stress. Meanwhile, the grassy land soil aggregate seem strong enough to prevent effective stress and separate inner pore from surrounding pores.

The probability values compare to 5% and 1% of the probability distribution between incompact and compacted soil show that there was no significant difference regard to mean porosity. Unless surface area ratio which accepted null hypotheses subsequently the p value lower than 0.05 as a Significant differences (*), as shown in Table 2.

Table 2. P value by T- Test for intra aggregate pores before and after compaction

Soil Moistures	Layer	Porosity	Surface Area/ All
M1	Top	0.766	0.028*
	Bottom	0.054	0.013*
M2	Top	0.907	0.018*
	Bottom	0.842	0.005**

4 CONCLUSIONS

In summary, soil is one of the most significant elements on this planet which is directly and indirectly connected with all sectors of life. Thus the concern about soil properties and its future may be required, especially due to the frequent impacts that can lead to drastic changes. Compaction is one of the most serious issues that have an impact on soil aggregate's elements in term of physical or biochemical properties.

This study has been carried out in order to illustrate the influence of compaction on pore structure in terms of size and shape in that these aspects directly affect all other characteristics of soil, expressly porosity and void ratio in the case of grassy land soil. This is principally true of the top layer as a main part which is directly affected by external stress. Also it is necessary to examine factors such as moisture content within the soil aggregate in order to evaluate the responses of soil in different states as happens in the reality. The significance of this study's outcomes is that used a new technique and method for demonstrating 3D images of micro portions with high precision in terms of counting the variables voxel involved. To achieve this aim, X Ray Micro CT was used as a scanner with a resolution of 10μm. The scanned images obtained were then reconstructed with the use of new software entitled Simpleware Scan IP to allow the assessment all of volume and surface area parameters with regard to pore structure, before and after compaction.

The results have shown that the impact of external stress as well as compaction causes different responses on the different parts of inters and intra aggregate pores. The top layer of soil directly responds to compaction in the form of a decline in porosity and void ratio as a result of a reduction in pore volume. This consequence can be dramatically verified with higher moisture content with regard to inter aggregate pores and voids. In other words, the relationship between moisture content and compaction effects is a directly related.

Contrariwise, intra aggregate pores responded to the compaction contrary compare to inter aggregate pores. The mean porosity slightly improved after compaction, but this outcome was not encountered in respect to a change in moisture content. In actual fact, this phenomenon was not expected, which approves the importance of using three dimensional imaging processing using X ray micro CT.

Nevertheless, this method has been used in a different way previously in terms of studying dissimilar issues regarding soil. So this study is unique in that, it is specifically concerned with the mechanical behaviour of pores with respect to compaction stress. Besides, it is strongly recommended that there is a need of further work using this method and technique to explain the fate of different value of pressure systematically with different land use of soil aggregate and altered fraction as well.

Moreover, it would be preferable to develop a model which can be used to evaluate water flow through aggregate within a soil sample in order to predict hydraulic parameters.

Even the value of compaction stress may be used to show the possible variety of loading states instead of maximum stress which proceeded manually.

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