UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías.

Comparative analysis of experimental results and DIC analysis.

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Ingeniería Civil

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HOJA DE CALIFICACIÓN
DE TRABAJO DE FIN DE CARRERA

Comparative analysis of experimental results and DIC analysis.

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RESUMEN

La gran cantidad de carreteras no pavimentadas en el mundo constituyen una parte importante para la infraestructura vial nacional e internacional. A pesar de que estas no estén pavimentadas, su objetivo principal será el de adoptar y llevar a cabo las decisiones necesarias para mantener una vía, para que los límites admisibles de deterioro que se hayan fijado se cumplan lo máximo posible (Gutiérrez, 2017). El contacto directo entre las partículas de suelo y los neumáticos de los vehículos generan efectos de desgaste del suelo, que, con el tiempo, generan imperfecciones en la superficie que afectan a la seguridad de los vehículos que transitan. Uno de los efectos que más afectan al suelo es el *"washboard effect"* que genera deformaciones en el suelo con forma de ondas en el sentido longitudinal de la vía. Con el objetivo de analizar este tipo de fenómenos se ha realizado un modelo en centrífuga en donde una rueda se introduce poco a poco en un estrato de suelo, esta centrífuga de brazo giratorio generó una aceleración de 10 gravedades para, a través de leyes de escala, acelerar los procesos en el tiempo. En estos ensayos geotécnicos se busca variar ciertas condiciones del suelo y de la rueda para determinar cuáles son los factores que más contribuyen a la deformación del suelo, para ello se obtuvieron fotos de todos los procedimientos. A través de un análisis de correlación de imágenes digitales usando lagrangianos aumentados (AL-DIC) se busca determinar donde se concentran los desplazamientos en todas las secuencias de imágenes obtenidas y con ello concluir cuales son los factores que más afectan a la deformación del suelo.

ABSTRACT

The large number of unpaved roads in the world constitute an important part of national and international road infrastructure. Even though these are not paved, their main objective will be to adopt and carry out the necessary decisions to maintain a road, so that the permissible limits of deterioration that have been set are met as much as possible (Gutiérrez, 2017). Direct contact between soil particles and vehicle tires generates soil wear effects, which, over time, generate surface imperfections that affect the safety of the vehicles passing through. One of the effects that most affects the ground is the “washboard effect” that generates deformations in the ground in the form of waves in the longitudinal direction of the road. With the aim of analyzing this type of phenomena, a centrifuge model has been made where a wheel is introduced little by little into a stratum of soil. This rotating arm centrifuge generated an acceleration of 10 gravities to, through scale laws, accelerate processes over time. In these geotechnical tests, the aim is to vary certain conditions of the soil and the wheel to determine which factors contribute the most to the deformation of the soil; for this purpose, photos of all the procedures were obtained. Through an image evaluation analysis using increased Lagrangians (AL-DIC), we seek to determine where the displacements are concentrated in all the image sequences obtained and thereby conclude which are the factors that most affect soil deformation.

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1. INTRODUCTION.

In the last decade, due to the increasing traffic circulating amongst the secondary and tertiary roads of Latin America, the necessity of improving the soil conditions of these roads arose. The primary aim is to provide a beneficial, low-cost and long-lasting alternative for the road development in Latin American countries. That is the reason of why this study explores the application of augmented Lagrangian digital image correlation (AL-DIC) in geotechnical engineering, specifically focusing on the analysis of soils deformations under specific conditions. Using a centrifuge to simulate full-scale ground pressures equivalent to 10 times the force of gravity, the research captures detailed ground deformations and displacements when a wheel is driven into the ground. The images taken throughout this process form the data set for the AL-DIC analysis, with the aim of evaluating the accuracy of the method compared to traditional experimental results and obtain what are the main factors that generate deformations in the surface part of this type of unpaved roads. However, in real life these unpaved roads are affected by other factors such as vegetation, mixtures of various types of soils, slope changes on the roads, environmental conditions, among others (Digney, 2001).

The main objective is to determine the accuracy of AL-DIC in capturing intricate ground deformations under high stress conditions. Through meticulous analysis and comparison with traditional methods, this research seeks to provide insight into the reliability and potential advances that AL-DIC can bring to geotechnical engineering and ultimately improve our understanding of soil mechanics in real conditions and to apply the results in the road development.

2. INSTRUMENTATION.

Centrifuge

The cutting-edge centrifuge employed for geotechnical experiments at the University of Los Andes in Colombia is a sophisticated apparatus designed to replicate real-scale ground conditions. With the capability to exert pressures equivalent to 10 times the force of gravity, this high-performance centrifuge provides a controlled environment for in-depth geotechnical analysis. Housed within the geotechnical laboratory, it features a robust design that allows for versatile experimental setups, accommodating specialized components such as wheels to induce controlled soil deformation.

Functioning as a pivotal tool in soil mechanics studies, the centrifuge operates by rapidly rotating experimental setups at elevated speeds, creating centrifugal forces that simulate gravitational conditions. This dynamic process enables the emulation of real scenarios, providing invaluable insights into soil behavior under varying pressures. The centrifuge's adaptability and precision make it an essential asset in geotechnical research, particularly in this project where it played a key role in capturing images of incremental soil displacements and deformations induced by applied pressure and the introduction of a wheel. These images form the basis of a comprehensive dataset for subsequent Digital Image Correlation (DIC) analysis, facilitating a detailed exploration of soil mechanics under conditions closely resembling real-world geotechnical problems.

Load application

The axial load is applied by a mechanical actuator that pushes the wheel into the sand at a constant rate of displacement of 1.2 mm/min. Following proper laboratory procedures, the wheel must remain just above the soil layer without touching it for all results obtained to be valid.

Data acquisition system and measurements

The experimental data of displacement and load exerted by the wheel on the ground are obtained on average every 1.1 seconds. While the experimental images were obtained with a frequency of 25 seconds on average. These images were obtained by a color digital camera and passed through a rigid plastic (polyethylene) window.

3. MODEL PREPARATION

In the image sequences, three main conditions vary, which are: The density of the soil, which can vary between compact sand and loose sand. The material of the wheel that is inserted into the ground which can be a metal wheel or a rubber wheel, and the number of layers of geocells in the ground which can vary between zero, one and two layers of geocells.

Sand

Based on research done by L. Ibagón et al. in 2023. The soil that has been used for this analysis corresponds to a sandy river soil with some silt particles of medium to fine grain size. The particle size distribution was measured according to the standard ASTM D6913. The specific gravity was also measured according to ASTM D854, and the calculated result was equal to 2.66. In addition, the friction angle was measured following the ASTM D3080 standard. The result of this test was a friction angle of 31◦. For the angle of repose, the measured value was close to 37◦. The tests were carried out with simplified soil conditions corresponding to dry sand placed at different densities.

For the analysis of this sand through DIC, two different soil states were used. On the one hand we have tests that were carried out with loose soil, and tests were also carried out where the soil was compacted. The density results for both cases are shown below.

Table 1. Characteristics of dense sand.

DENSE SAND		
VOLUME	3578.38	cm3
DENSITY	1.79	g/cm3
	1788.52	kg/m3
UNIT WEIGHT	**17.55**	**kN/m3**

Table 2. Characteristics of loose sand.

LOOSE SAND		
VOLUME	4072.77	cm3
DENSITY	1.50	g/cm3
	1497.75	kg/m3
UNIT WEIGHT	**14.69**	**kN/m3**

Assembly

All the images obtained from the different tests have a size of 1920 pixels wide and 1080 pixels high. The focal point of all the images points to the upper part of the sand stratum, which is also the area where the greatest amount of deformations and soil displacements occur due to the proximity that exists with the wheel.

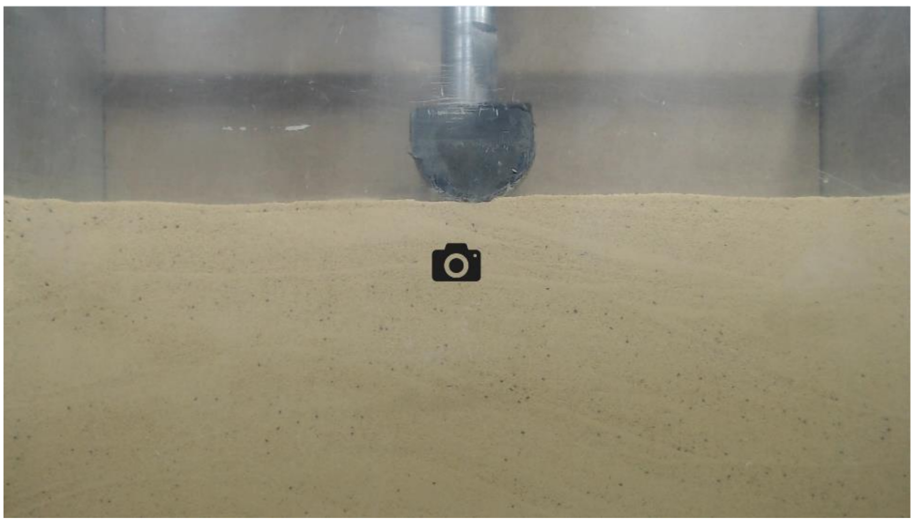

Figure 1. Representation of the focal point in the images used for the DIC analysis.

The number of photos obtained from each trial varies depending on the trial, as does the frequency with which the photos were obtained. General data for all trials are mentioned below.

Table 3. General characteristics of all photo sequences used for DIC analysis.

DATA OBTAINED		
PHOTO FRECUENCY		25 seconds
MINUMUM NUMBER OF PHOTOS		30 photos
PHOTO SIZE	WIDTH	1920px
	HEIGHT	1080px

Wheel

Another factor that varies in the tests is the material of the wheel. Where it has been chosen to use a metal wheel to represent a rigid material, and a rubber wheel to represent a more deformable and soft material. Both wheels have a diameter of 35 mm.

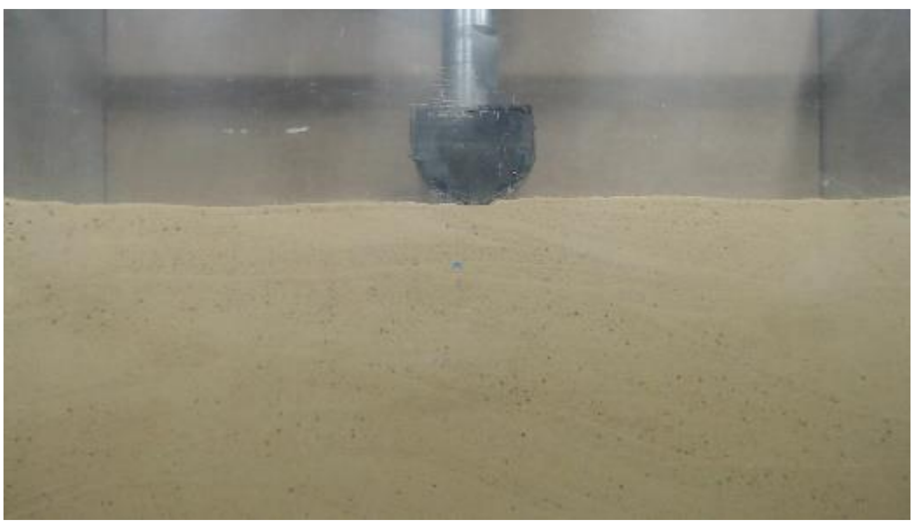

Figure 2. Test in the centrifuge with the metal wheel.

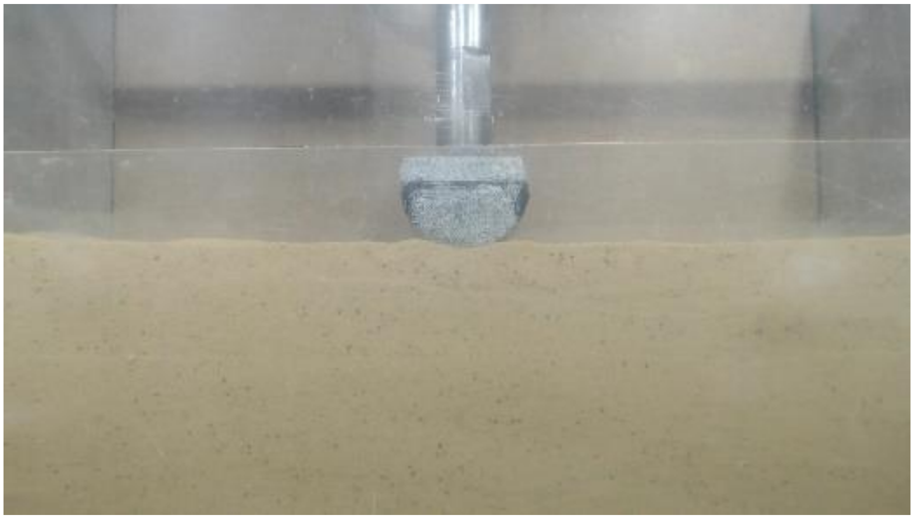

Figure 3. Test in the centrifuge with the rubber wheel.

Geocells

As mentioned previously, the number of geocells can vary between zero, one and two layers of geocells that provide mechanical cohesion to the soil and be able to observe how beneficial these are to mitigate the effects of deformation in the soil.

4. DATA PROCESSING

The program that is being used for the correlation analysis of digital images is AL-DIC, which, as mentioned before, is a program that uses an augmented Lagrangian to determine the deformations and displacements in the images (Yang, 2015). This program was developed by PhD. Jin Yang. The creation date of this program was in April 2015, and its last update in November 2021, which is the version used for this analysis. All images were scaled to millimeters.

Mathematical parameters.

The region of interest (ROI) that was selected for analysis in all images is the region occupied by the ground under the wheel, which represents an approximate region of 1900px wide by 700px high.

The subset size for all images was defined as 70 pixels, this parameter refers to the size of the square region that is chosen to perform the correlation between the reference and deformed images. The subset step for all images was defined as 15 pixels, this parameter refers to the distance between the centers of adjacent subsets in the image.

It has been decided to solve Sub-problem 2 (global step) through the finite difference method, since this gives more precise results compared to the other resolution method offered by the program. This is the phase of the algorithm that seeks to optimize the deformation estimation at a global level, guaranteeing consistency and smoothness in all images.

Because the frequency with which the photos were taken is high and therefore the deformations between photos are also high, it has been decided that in each new image the program again makes an initial assumption with each image in the sequence. This is recommended when the displacements in the images between images are greater than 7 pixels. Additionally, the incremental method was used. Which allows the reference image to be updated every certain number of images. In our case, since the quality of our images is not that good, the reference image was updated every 1 image to minimize errors.

To make the assumption of the first displacements, the "Multigrid search based on an image pyramid" method was used, which is the most precise of all the methods given by the program, at least in this case. The advantage of this approach lies in its ability to address problems related to large deformations and local variations in the image, while maintaining computational efficiency by working with reduced resolutions in the initial stages. The image pyramid acts as a strategic tool to guide the search for correlation across different scales, adapting to the complexity of the deformation in the image. It also allows us to work with images of a resolution not as high as in our case, minimizing errors in the results of displacements and deformations of soil particles.

Once the images are processed to this point, we move on to determine the characteristics of the material being analyzed, in this case the sand (loose or dense). For loose sand, a modulus of elasticity of 7 MPa was used, while for dense sand, a modulus of elasticity of 15 MPa was used. For both cases, a Poisson ratio of 0.30 was used.

5. RESULTS

So that the results are comparable to each other, it has been decided to do an analysis of the experimental results of the centrifuge and the DIC results when there is the same penetration of the wheel in both cases. The penetration will be measured with respect to the diameter of the wheel (35 mm) in all cases. All analyzes are done when the penetration with respect to the wheel diameter is 0.1 and 0.35. In each analysis the experimental results will be shown first and then the DIC results.

Rubber and Metal wheel without geocells in compact soil.

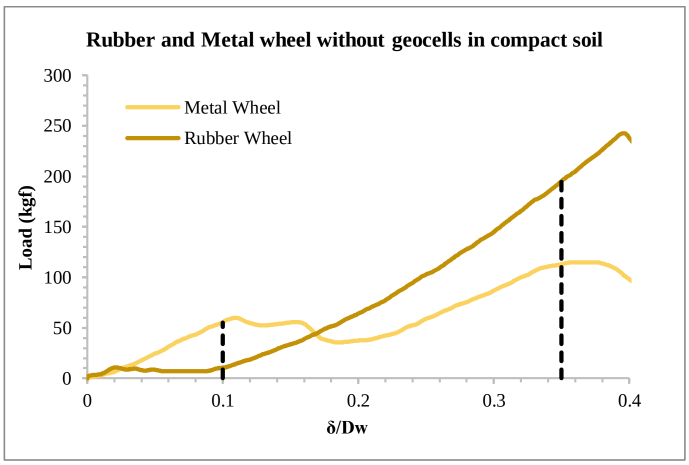

Figure 4. Results of the wheel penetration centrifuge, normalized with respect to the wheel diameter Dw=35mm when comparing the rubber wheel against the metal wheel applied in the compact soil without geocells.

The experimental results suggest that when there is a penetration of 0.1 with respect to the diameter of the wheel, the soil supports more load when the metal wheel is applied, compared to the rubber wheel. This may be due to the lower friction that exists between the metal wheel and the soil particles compared to the rubber wheel. The particles have the opportunity to rearrange themselves after supporting a certain load since there is not enough friction to load continuously. However, when there is a penetration of 0.35 with respect to the diameter of the wheel, the ground supports more load when the rubber wheel acts.

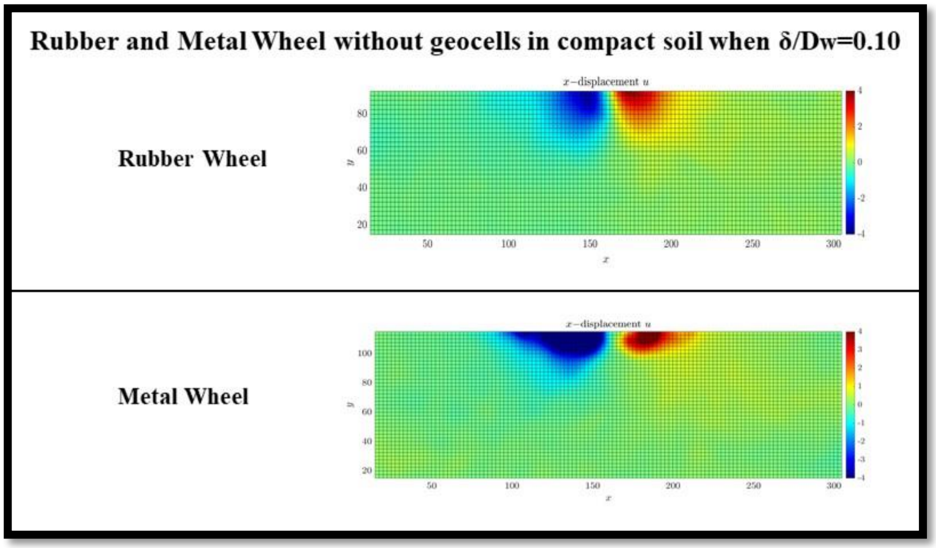

Figure 5. Comparison of DIC results between the rubber and metal wheel under the same conditions and at the same penetration (δ/Dw=0.10).

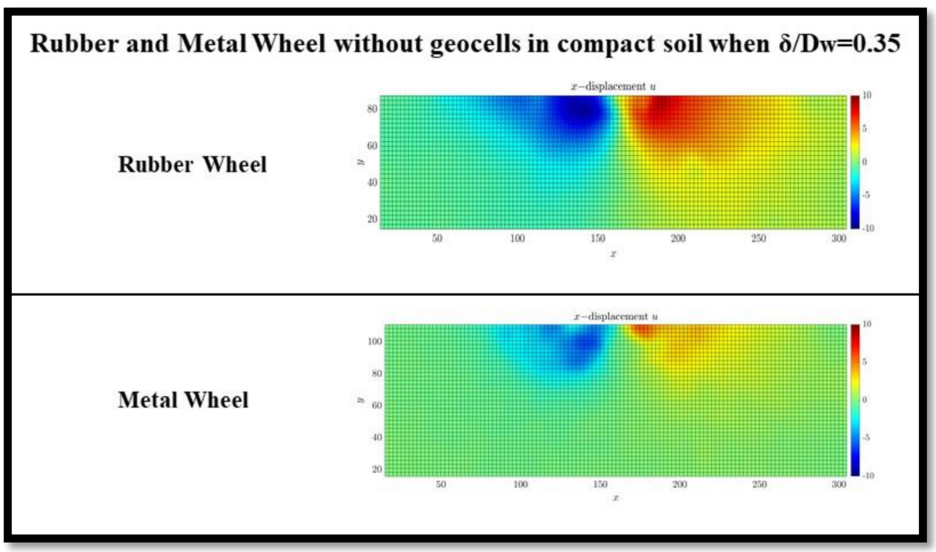

Figure 6. Comparison of DIC results between the rubber and metal wheel under the same conditions and at the same penetration (δ/Dw=0.35).

The results show that when there is a penetration of δ/Dw= 0.1, the rubber wheel affects a larger area of ground than the metal wheel. However, the area of soil affected when the metal wheel is applied tends to expand towards the sides, while when the rubber wheel is applied, the area of soil affected tends to expand towards the bottom of the soil stratum. When the penetration is δ/Dw= 0.35, the rubber wheel affects a greater area of soil compared to the area of soil affected by the metal wheel, which tends to stay on top of the soil stratum. We can also see that, under the same scale, the rubber wheel generates a greater amount of displacement on the ground than the metal wheel.

Rubber and Metal wheel without geocells in loose soil.

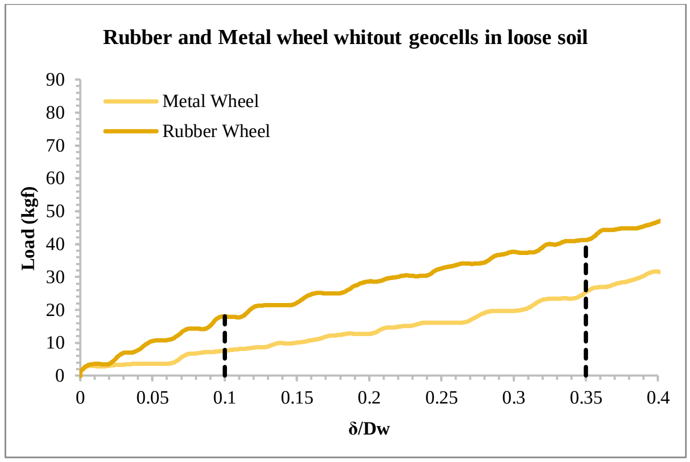

Figure 7. Results of the wheel penetration centrifuge, normalized with respect to the wheel diameter Dw=35mm when comparing the rubber wheel against the metal wheel applied in the loose soil without geocells.

In this case, the experimental results in the centrifuge show the same trend in both penetrations. Where the rubber wheel supports a greater load than the metal wheel when there are no reinforcing geocells and when it is loose soil.

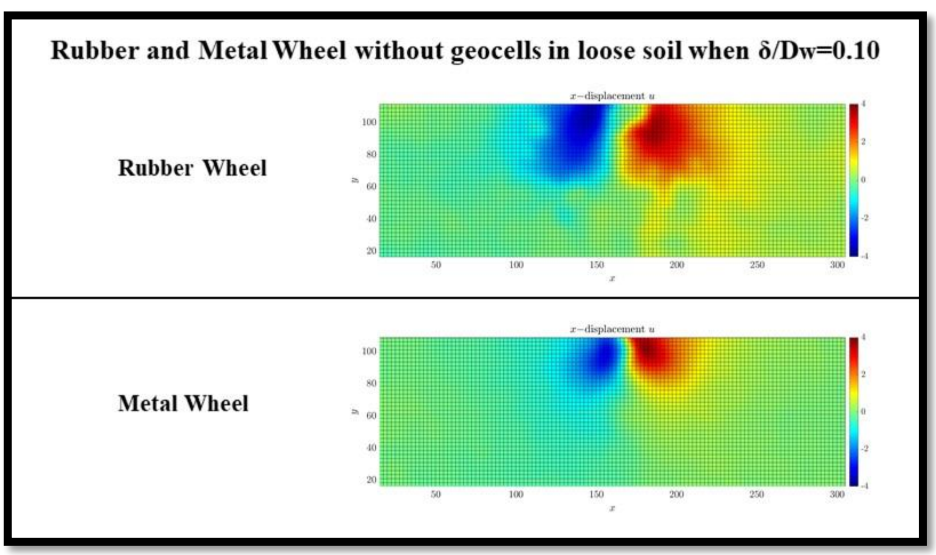

Figure 8. Comparison of DIC results between the rubber and metal wheel under the same conditions and at the same penetration (δ/Dw=0.10).

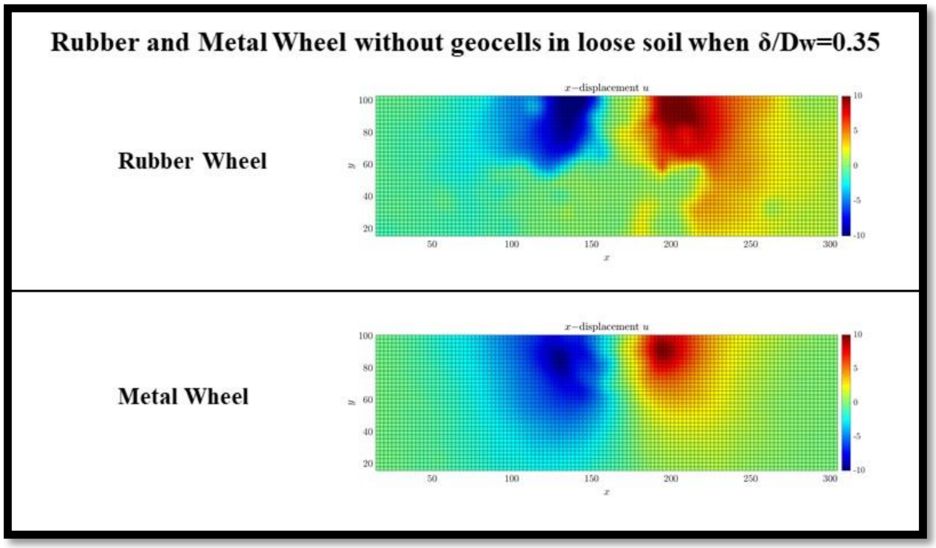

Figure 9. Comparison of DIC results between the rubber and metal wheel under the same conditions and at the same penetration (δ/Dw=0.35).

The DIC results show that when there is a penetration of δ/Dw= 0.1. The rubber wheel affects a larger area of ground than the metal wheel. In this case, both results show that the two wheels generate a behavior where the affected soil area tends to expand towards the lower part of the soil stratum. When the penetration is δ/Dw= 0.35 the behavior is similar, however, the metal wheel affects a greater area of soil than the rubber wheel in this case and its affected surface is more uniform.

Rubber wheel without geocells in compact and loose soil.

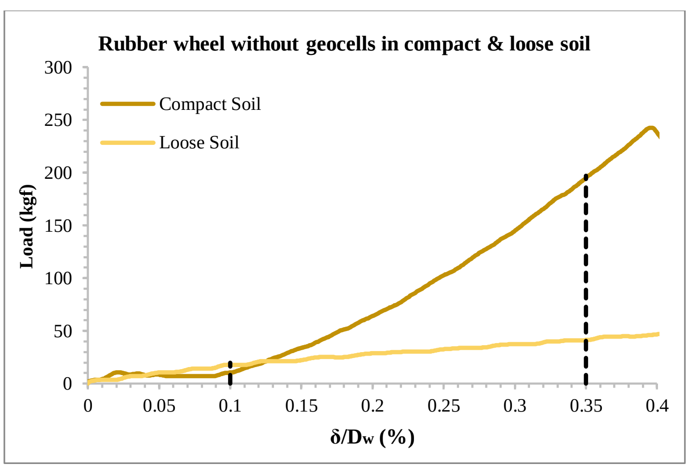

Figure 10. Results of the wheel penetration centrifuge, normalized with respect to the wheel diameter Dw=35mm when comparing the compact soil against the loose soil without geocells when the rubber wheel is applied.

In this case, the experimental results suggest that when there is a penetration of δ/Dw= 0.1, both the compact soil and the loose soil support a similar load applied by the rubber wheel. When there is a penetration of δ/Dw= 0.35, the compact soil supports a much greater load than the loose soil.

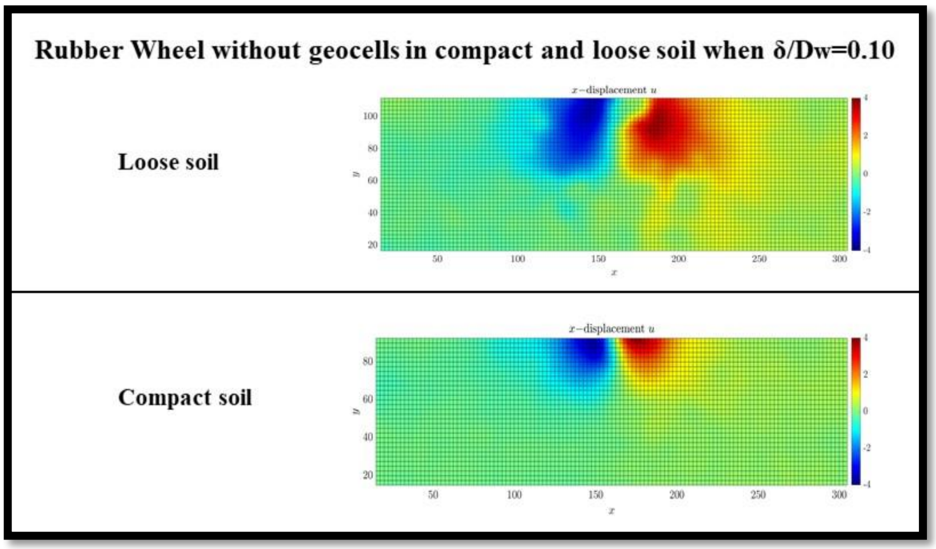

Figure 11. Comparison of DIC results between the loose and compact soil under the same conditions and at the same penetration (δ/Dw=0.10).

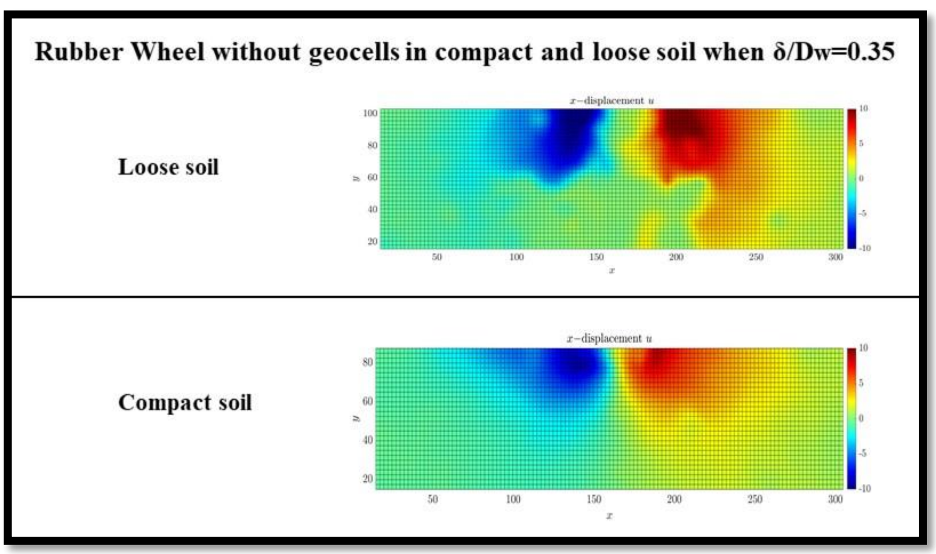

Figure 12. Comparison of DIC results between the loose and compact soil under the same conditions and at the same penetration (δ/Dw=0.35).

The DIC results in this case show that when there is a penetration of δ/Dw= 0.1. Loose soil is affected more than compact soil, which has displacements only in the most superficial part of the soil. Furthermore, both results show that the displacements expand towards the depth of the stratum. When we have a penetration of δ/Dw= 0.35. Loose soil affects a deeper part of the soil, while compact soil has more uniform displacements of soil particles that expand to the sides.

Metal wheel without geocells in compact and loose soil.

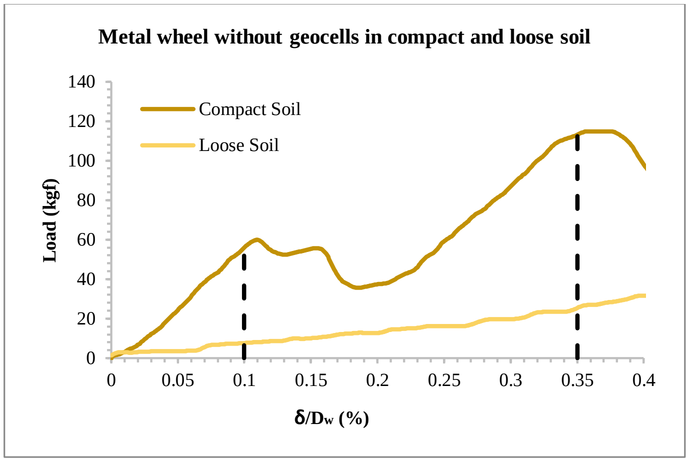

Figure 13. Results of the wheel penetration centrifuge, normalized with respect to the wheel diameter Dw=35mm when comparing the compact soil against the loose soil without geocells when the metal wheel is applied.

The experimental results when the metal wheel is applied in soils (compact and loose) without geocells show two peaks at δ/Dw= 0.1 and δ/Dw= 0.35 penetration with respect to the diameter of the wheel respectively. In these two peaks the compact soil supports a much greater load than in the loose soil.

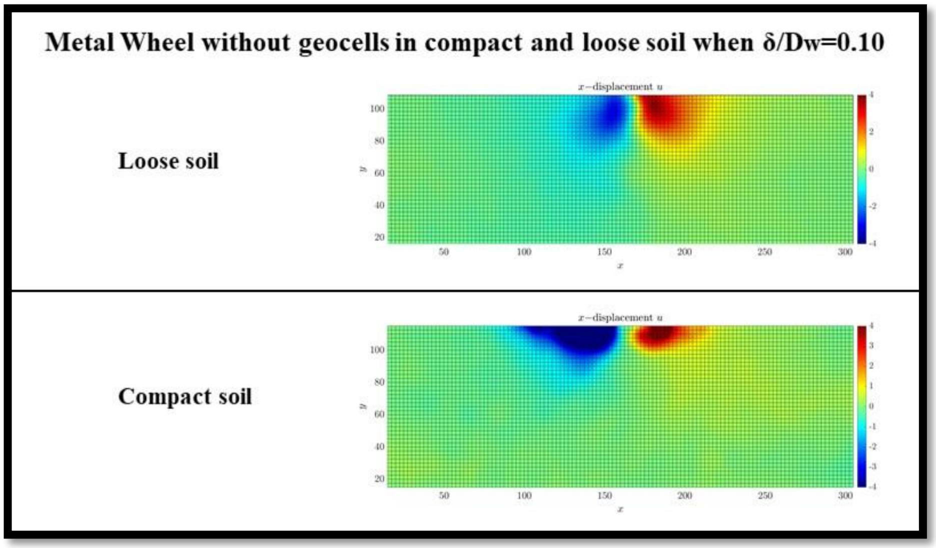

Figure 14. Comparison of DIC results between the loose and compact soil under the same conditions and at the same penetration (δ/Dw=0.10).

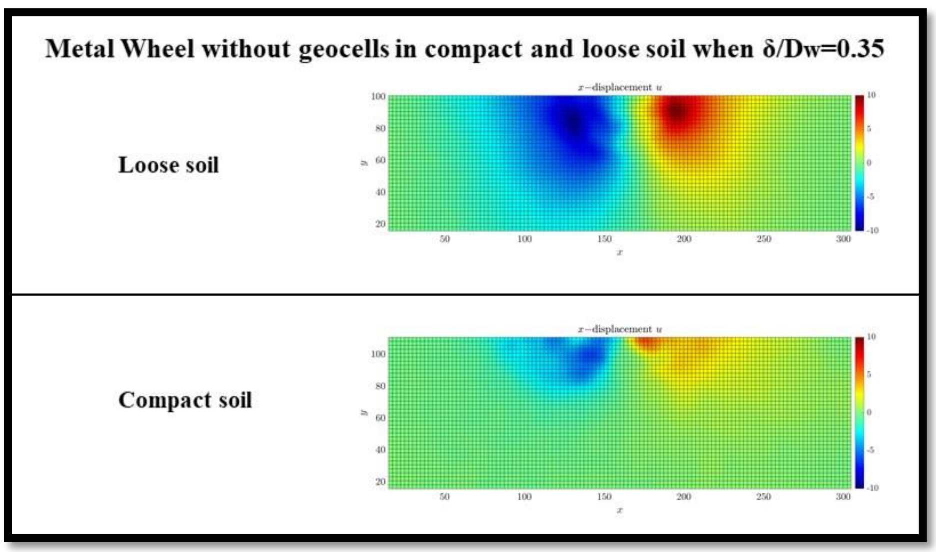

Figure 15. Comparison of DIC results between the loose and compact soil under the same conditions and at the same penetration (δ/Dw=0.35).

The DIC results for this case show a similar trend. When there is a penetration of δ/Dw= 0.1, the compact soil concentrates a greater amount of displacements in the superficial part of the soil. In loose soil the displacements are less intense but expand towards the depth of the stratum. This same trend occurs when there is a penetration of δ/Dw= 0.35. Here the compact soil has less intense displacements that do not expand towards the depth of the stratum. While in loose soil the displacements are greater and a much larger amount of soil is involved.

Metal wheel with 0, 1 and 2 geocells in compact soil.

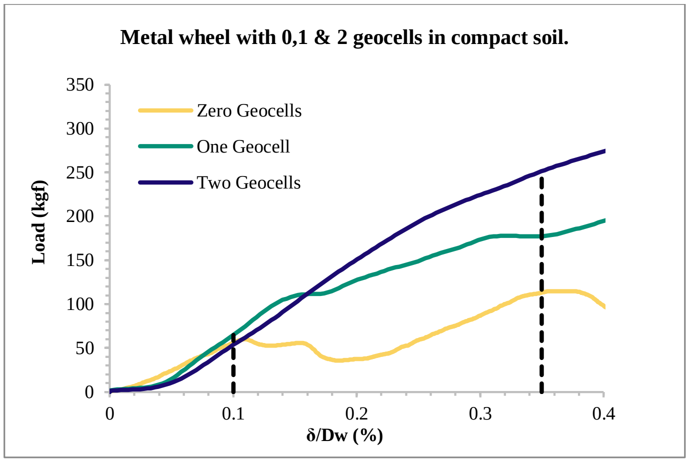

Figure 16. Results of the wheel penetration centrifuge, normalized with respect to the wheel diameter Dw=35mm when comparing the number of geocells in a compact soil using a metal wheel.

When we compare the number of geocells in the ground, the experimental results show that at a penetration of δ/Dw= 0.1, the load supported by the 3 analysis cases is very similar. While when the penetration is δ/Dw= 0.35, it can clearly be observed that the compact soil with 2 geocells supports a greater load, followed by the compact soil with one layer of geocells and finally the compact soil without geocells.

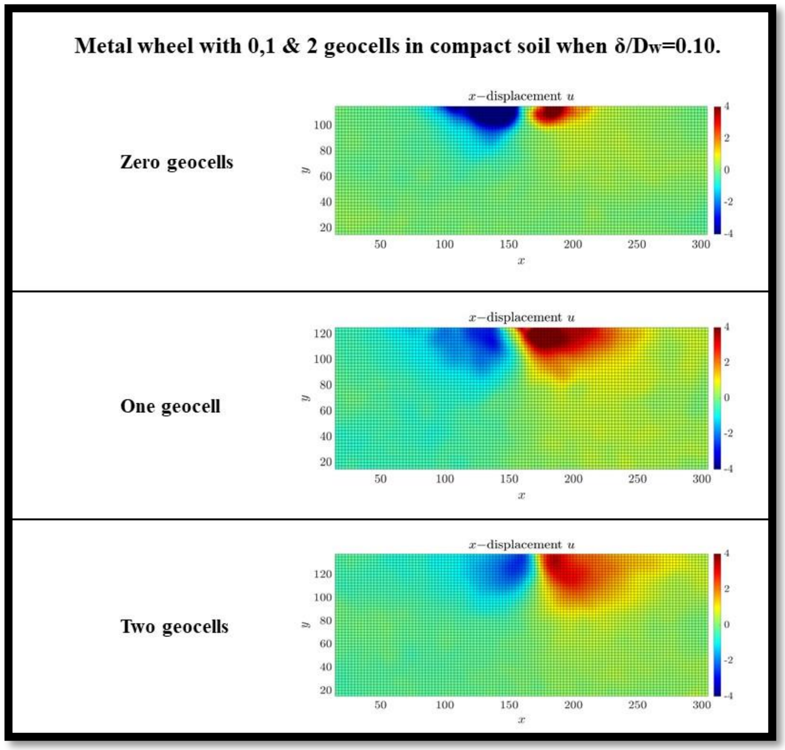

Figure 17. Comparison of DIC results between the number of geocells in a compact soil when a metal wheel is applied at the same penetration (δ/Dw=0.10).

In the compact soil at a penetration of δ/Dw= 0.1, we can see how increasing geocells reduces the intensity of displacements as more geocells are increased. When the soil is compact without geocells, the displacements are concentrated in the superficial part of the soil with a tendency to expand to the sides. When geocells are increased, these displacements expand a little in all directions, following the same previous trend but with a lower intensity. When you have two geocells, the displacements expand very little compared to the soil with one geocell, but it is much less intense; This means that soil particles move less when geocells in the soil are increased.

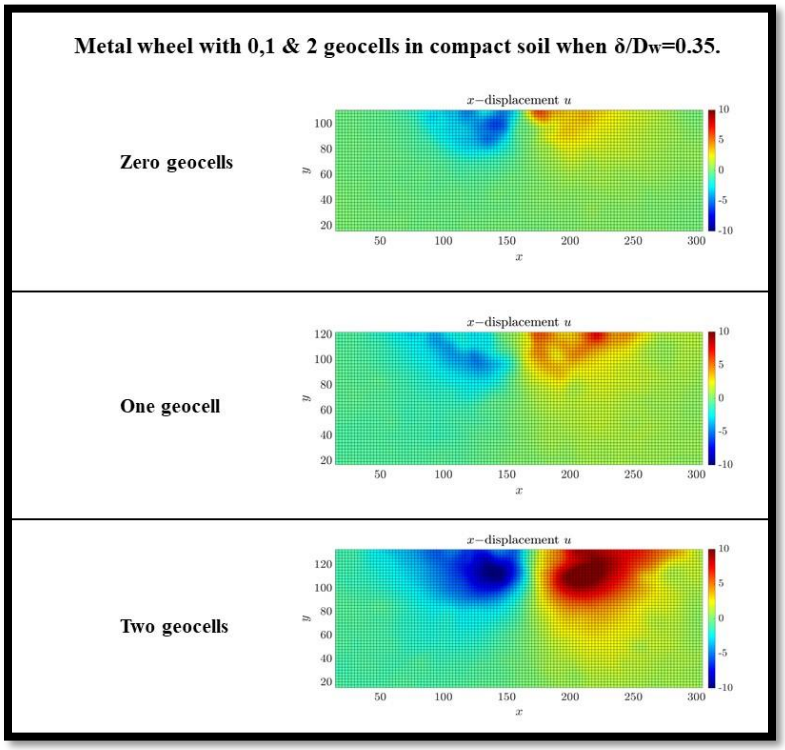

Figure 18. Comparison of DIC results between the number of geocells in a compact soil when a metal wheel is applied at the same penetration (δ/Dw=0.35).

When the penetration increases to δ/Dw= 0.35. We can observe that the involved soil area increases very little as geocells are increased. When there are no geocells in the compact soil, the displacements are very intense and tend to concentrate in the upper part of the soil stratum seeking to expand towards the sides. When a geocell is increased in the soil, it continues to have less intense displacements but more marked than in the soil without geocells. When we have the soil stratum with two layers of geocells we can see that the displacements have grown in intensity and a greater area of soil is involved that suffers these displacements. This is because as geocells increase, the cohesion of the soil increases and this allows it to resist a greater load, which is why the displacements are greater when there are two geocells in the soil.

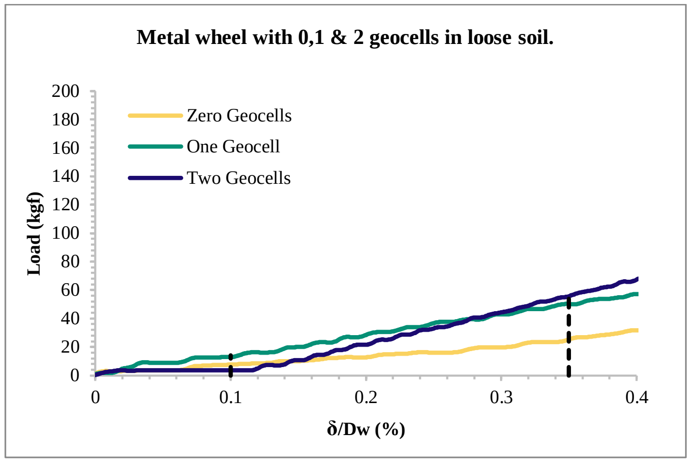

Figure 19. Results of the wheel penetration centrifuge, normalized with respect to the wheel diameter Dw=35mm when comparing the number of geocells in a loose soil using a metal wheel.

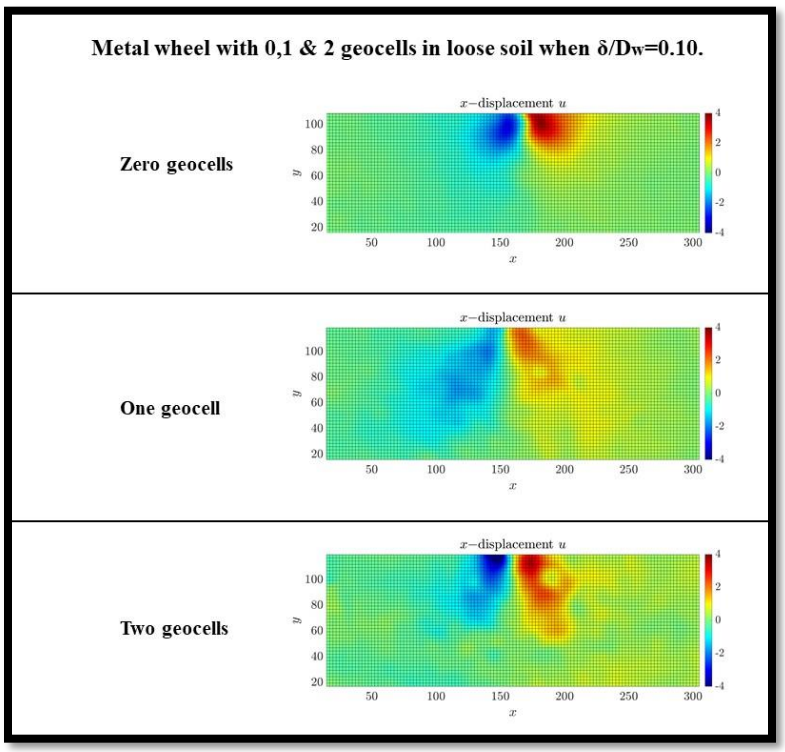

Figure 20. Comparison of DIC results between the number of geocells in a loose soil when a metal wheel is applied at the same penetration (δ/Dw=0.10).

When you have a penetration of δ/Dw= 0.1 into the loose soil. We can observe that in the soil without geocells the displacements are intense and superficial, without involving a large area of soil. When we increase a geocell in the soil, the intensity of the displacements decreases but it implies a greater area of soil that tends to expand towards the depth of the stratum. When two geocells are increased, the area of soil involved is similar to when there was only one geocell, but the displacements in this area become more intense.

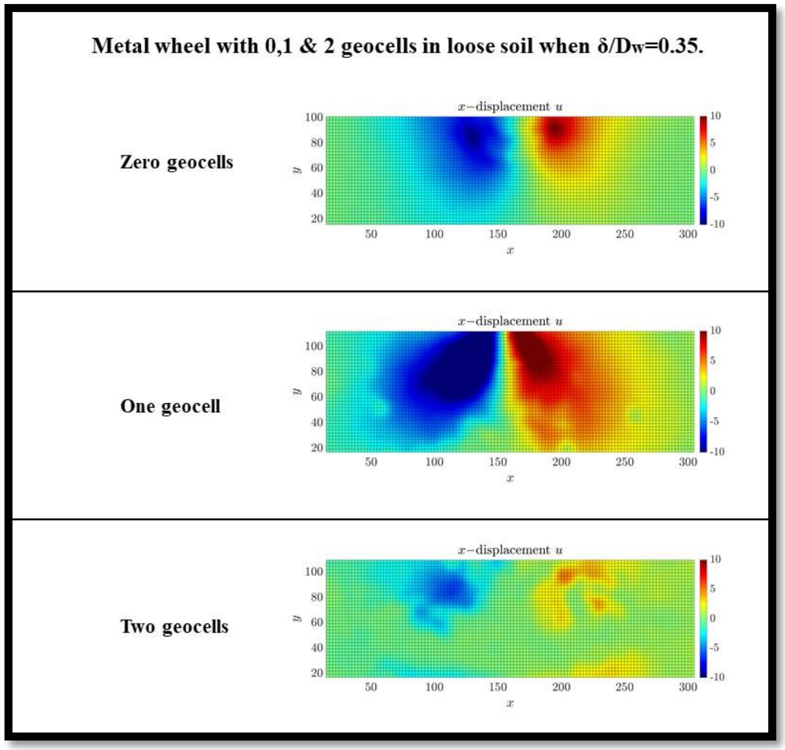

Figure 21. Comparison of DIC results between the number of geocells in a loose soil when a metal wheel is applied at the same penetration (δ/Dw=0.35).

When we have a penetration of δ/Dw= 0.35 in the loose soil, we can observe how the displacements occupy a large area of soil when there are no geocells, reaching quite deep parts of the soil. When a geocell is added, these displacements occupy a larger area and in a more intense manner, that is, the particles travel a greater distance. In both cases we can see how there is a tendency for displacements to expand towards the deepest part of the stratum. When we have two geocells on the ground we could not obtain coherent results since unfortunately the quality of the photos did not allow us to work as in the other photo sequences. However, observing the previous trend, we may have expected that the displacements would occupy a similar or greater ground area than when there was a single layer of geocells and that they would have increased in intensity.

6. CONCLUSIONS

In general, we observe that loose soils are more affected by the displacements generated by the wheel, whether metal or rubber. This means that increasing soil density not only decreases the movement of particles but also decreases the area of soil that is affected.

The use of geocells prevents displacements from expanding to the deepest part of the soil. However, with a greater number of geocells, the soil acquires greater cohesion and therefore has the capacity to withstand a greater load applied by the wheel, which causes the particles that are closer to the surface to move more.

When a rubber wheel is applied, it generates displacements in a larger area of soil, especially in loose soils. This causes the displacements to reach a deeper part of the soil stratum.

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