Design of centrifuge modelling of geotextile-encased column foundation systems subjected to reloading

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ABSTRACT: This paper outlines the methodology for investigating the performance of soil foundation systems utilizing Geotextile Encased Columns (GECs) subjected to reloading. The study involves multiple centrifuge tests at Deltares geotechnical facilities, employing physical models optimized for efficient testing within a constrained time frame and minimal disturbance to the clay model. Sensors track the development of load distribution and settlement of both the columns and surrounding soil. Additionally, the response of pore water pressures to surcharge load changes are monitored.
The research examines changes in the stiffness of columns and surrounding soil during loading, unloading and reloading phases, and their possible impact on the load-bearing behaviour of GEC-based foundation systems. The insights gained are relevant for infrastructure projects subjected to load changes, such as partial embankment removal for additional foundation works. This study anticipates providing valuable insights into the reloading response of GEC foundation systems.

1 INTRODUCTION

The objective of this project is to improve our understanding of Geotextile Encased Columns (GECs) through examination of the effects of loading, unloading and reloading cycles. Our study entails the execution of three model tests within the Deltares geotechnical centrifuge, with subsequent analysis of the obtained data. The project is subject to a three-week restriction on the direct utilization of experimental facilities. The study aims to provide insights into whether the behaviour and effectiveness of foundation systems with GECs differ during reloading compared to the initial loading phase. This potential difference may lead to alterations in system stiffness and overall bearing capacity.

Building upon the findings of di Prisco et al. (2006), who observed an increase in vertical stiffness during reloading cycles in small-scale 1g laboratory tests, our project aims to investigate how the ratio of GEC stiffness to the surrounding soft stratum changes during the unloading and reloading phases. This investigation is expected to shed light on the impact of these changes on the load-bearing behaviour of the GEC foundation systems.

Previous studies (Raithel, 1999; Ardakani et al., 2018; Yoo and Abbas, 2019) on Ordinary Stone Columns (OSCs) or GECs mainly focused on high-frequency cyclic loading scenarios, representative of typical traffic conditions or earthquakes (Cengiz and Güler, 2021).

In contrast, our study examined another loading regime: namely a single cycle of loading, unloading, and reloading. This approach allows for sufficient time for consolidation between each loading cycle. This alternative loading regime resembles the construction sequence: preloading, subsequent removal, and reloading by the completion of the final embankment. At the time of writing, the tests have been designed and carried out and the results are being analysed.

2 CENTRIFUGE MODELLING

2.1 Centrifuge apparatus

This study employed the Actidyn C72-3 beam centrifuge of Deltares in Delft, the Netherlands, which has been in operation since 2021. The centrifuge features a 5-meter platform radius and a capacity of 260 g-tonnes. With a maximum g-level of 150 g, this equipment facilitates the emulation of significant gravitational forces. The centrifuge operates at a maximum speed of 309 km/h and a rotational speed of nearly 3/sec.

2.2 Scaling considerations

Several researchers (Viswanadham and König, 2004; Caicedo et al., 2015; Reshma et al., 2020; Bhattacherjee and Viswanadham, 2019) have derived and presented scaling factors to model geosynthetic-reinforced structures in centrifuge studies. Table 1 summarizes the primary scale factors involved in the centrifuge modelling of GEC foundation systems.

Table 1. Scale factors in centrifuge modelling

Parameter	Units	Scale factor for Ng model / prototype
Classical dimensions		
Length	m	1/N
Load	kN	$1/N^2$
Stress	kPa	1
Weight	kg	$1/N^3$
Time (consolidation)	s	$1/N^2$
Strain	%	1
Density	kg/m^3	1
Geosynthetic parameters		
Tensile load	kN/m	1/N
Secant stiffness modulus	kN/m	1/N
Tensile strength	kN/m	1/N
Strain	%	1

Note: Ng is the centrifuge acceleration level (N times the gravity acceleration g)

2.3 Geometry of the model

The models were built in circular strong steel cylinders with a 600 mm internal diameter. Two configurations with different area replacement ratios of the GEC foundation system were placed in the cylinders. One setup had a 10% replacement ratio, resulting in 19 columns, while the other had a 20% replacement ratio, resulting in 37 columns. The GECs had a diameter of 4 cm and an initial length of 240 mm embedded in clay. They were filled with sand and had an additional 10 mm embedment in the top sand and 20 mm in the base sand layer, resulting in a total initial length of 270 mm.

Basal reinforcement was embedded in the top sand layer and installed directly on the GEC heads, covering the entire surface of the model. Load was applied through an actuator using an inflatable PVC cushion pressurized with water. The tests were conducted under a 20 g gravitational force (N=20) applied at the top of the clay model. Figure 1 shows the first setup with a 10% area replacement ratio. Figure 2 shows the second with a 20% area replacement ratio.

2.4 Materials

2.4.1 Foundation and fill soil

The foundation soil consisted of two soil layers: a 50 mm base sand layer and a 240 mm soft clay layer. The soft clay layer consists of Kaolin clay (KD 2000), which is often used in geotechnical studies (Al-Tabbaa and Wood, 1987; Sharma and Bolton, 2001). The clay demonstrated liquid and plastic indexes of 38.5% and 0.66, respectively. It was determined that the clay possesses an effective friction angle of 16.2°, while exhibiting no cohesion. The saturated unit weight of the clay was 16.4 kN/m³ and the initial void ratio was 1.7.

The top sand layer, column fill, and base sand layer were made of the same poorly graded fine silica sand (GEBA). The D_{50} of this sand is 0.137 mm with c_c and c_u values equal 1.12 and 1.35, respectively.

2.4.2 Textiles

The basal reinforcement was a circular piece of biaxial PP geotextile Basetrac Woven PP 30, glued along its edges to rings made of W8SVR thermoplastic material, each 2 mm thick, with an outer diameter of 580 mm and an inner diameter of 530 mm. These rings had a high radial stiffness, ensuring the horizontal fixation of the woven material, while maintaining vertical flexibility.

The column encasements were seamless textile sleeves. Their water permeability was modified by selectively removing some longitudinal (MD) yarns.

The selection of textiles adhered to the scaling criteria outlined in Table 1. The tensile load-strain behaviour of the textiles was evaluated through a wide-width tensile test at a specific strain rate according to DIN EN ISO 10319. The corresponding properties of the centrifuge model and the prototype geotextile are detailed in Table 2.

Table 2. Properties of the textiles for the model test and the corresponding prototype

Property	Units	Value for model test	Value for corresponding prototype at N=20
Material type		**Basal reinforcement**	
Polymer		PP (polypropylene)	
Tensile load at:	kN/m		
2% strain		5.5	110.0
3% strain		8.3	166.0
6% strain		16.4	328.4
Secant stiffness modulus at: 6% strain	kN/m	308.0	6160.0
Nominal tensile strength, T_0	kN/m	30.0	600.0
Nominal tensile strain, ε_0	%	16.0	16.0
Material type		**Column encasement**	
Polymer		Na (Nylon)	
Tensile load at:	kN/m		
2% strain		2.0	40.0
3% strain		3.2	64.0
5% strain		5.6	112.0
Secant stiffness modulus at: 5% strain	kN/m	89.0	1780.0
Nominal tensile strength	kN/m	60.0	1200.0
Nominal tensile strain	%	43.0	43.0

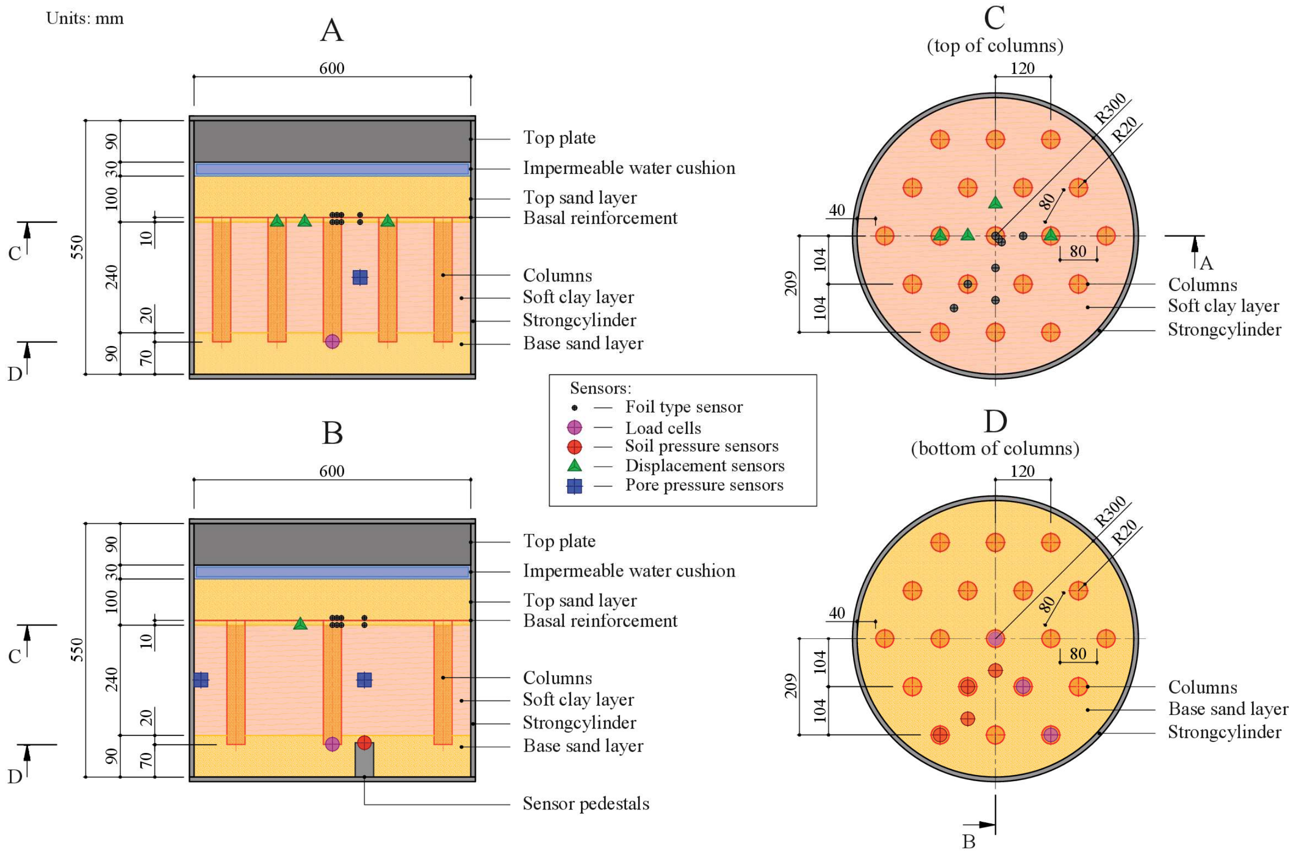

Figure 1. Cross-sectional and plan views of the centrifuge model setup 1 (area replacement ratio 10%)

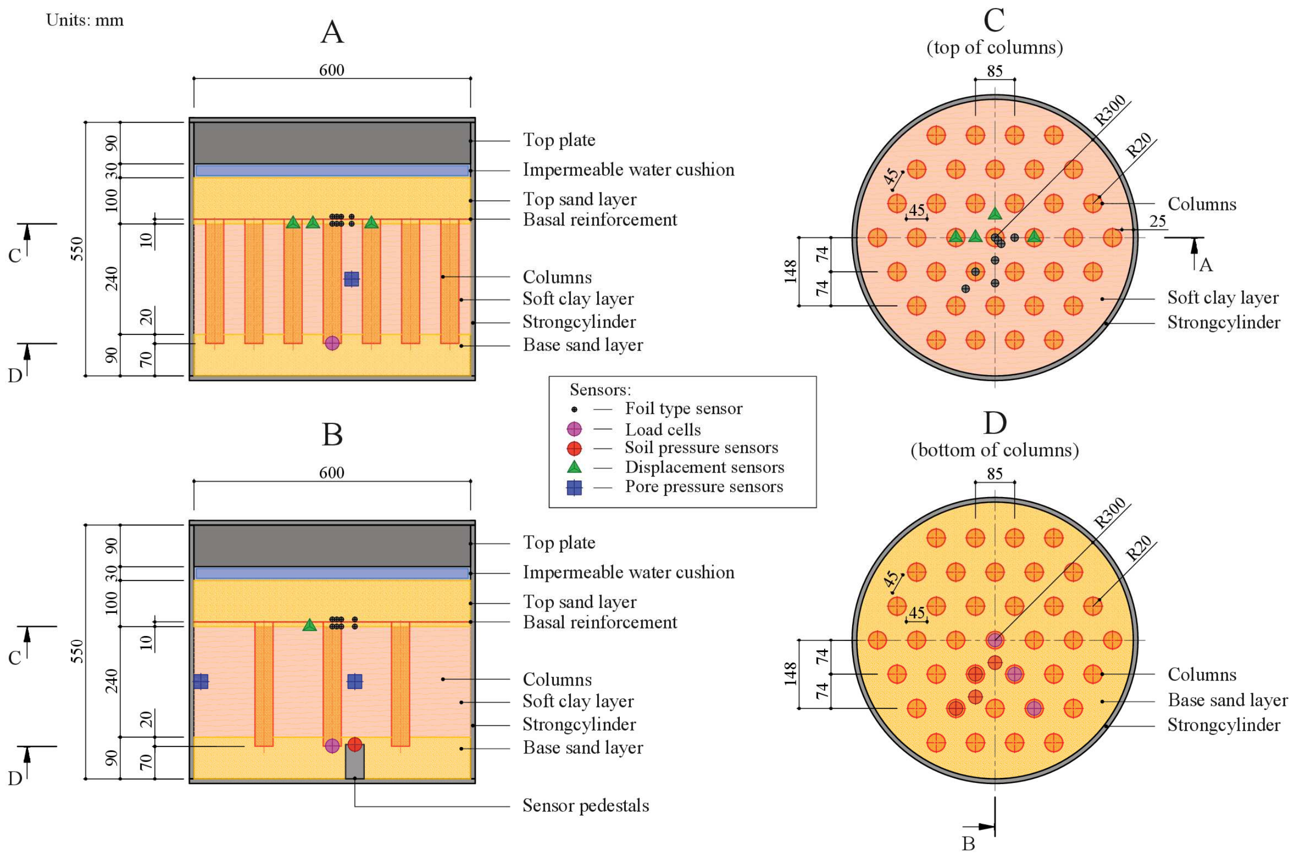

Figure 2. Cross-sectional and plan views of the centrifuge model setup 2 (area replacement ratio 20%)

2.5 Actuator

An impermeable polymeric cushion was installed directly on top of the top sand layer and was used to load the foundation system during the flight. A water reservoir was connected to the cushion, which in turn was pressurized by a proportional pressure regulator on air.

An additional pore pressure sensor is included in the pressurization system, to control the realized pressure. The maximum vertical pressure applied to the foundation via the actuator is 100 kPa.

2.6 Model preparation and construction

The foundation clay was prepared by mixing Kaolin clay powder with water in a 1:1.2 ratio to produce a clay slurry. The slurry was poured into the strong cylinder over a saturated base sand layer that contained soil pressure sensors. Before the soil material was placed in the strong cylinder, the side walls were covered with Teflon dry spray to reduce contact friction and adhesion. The foundation soil was then loaded with 40 kPa to achieve the desired degree of consolidation. The consolidated foundation soil was then trimmed to match the required thickness.

After the consolidation of the foundation soil, the models are built at 1 g. Construction of the model involves the following steps:

- Installation of columns including the ones with load cells
- Placement of instrumentation on the surface of the soft clay layer
- Filling the levelling layer
- Placement of instrumentation on GECs
- Placement of basal reinforcement
- Placement of instrumentation on basal reinforcement
- Filling the top sand layer
- Model saturation (from bottom to top)
- Installation of the surcharge load cushion
- Closing the model with the top plate

The columns were installed using the replacement method, to minimize the disturbance of the foundation soil, even though the displacement method is used in most of the projects carried out. The columns were placed one-by-one. First, a steel casing with an outer diameter 40 mm, an open bottom, with a special widening was inserted into the soft clay layer. A special double-frame device ensured the correct positioning and verticality of the columns. After reaching the base sand layer and inserting the casing, the clay was extracted using an auger. Then the casing was extracted which left an empty void in the clay. The textile encasement was placed over a tube with an outer diameter of 38 mm. This tube with the textile encasement was inserted into the void. The column was subsequently filled with sand. The sand was compacted layer by layer using a tempering device while the tube with a diameter of 38 mm was extracted, which is a diviation from the real installation procedure. When completed, the column heads extended 10 mm above the clay layer. Sensors were installed over the clay surface.

A 10 mm levelling sand layer was placed, and the sensors were installed on the GECs. The basal reinforcement was placed, and the rest of the sensors is installed.

The top sand layer is placed and compacted to the desired height, layer by layer. The actuator is installed, and the top lead is placed to close the model.

When the model is complete, it is transported to the centrifuge, the bottom drainage is connected to the standpipe water tank and the sensors are connected to the data acquisition system. Figure 3 shows the final model setup after its placement into the centrifuge basket.

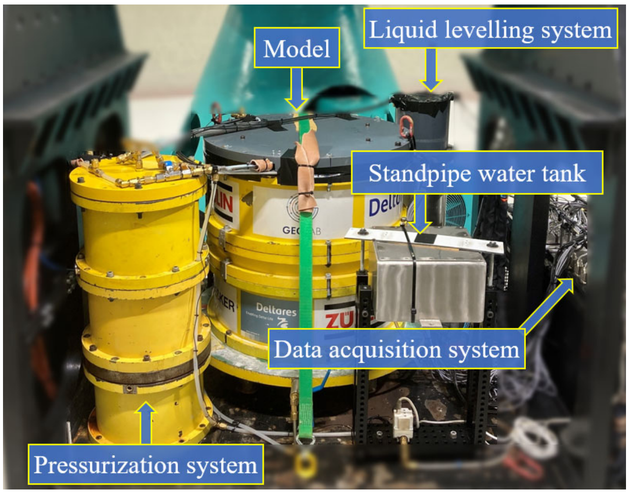

Figure 3. Final setup of the centrifuge model

2.7 Instrumentation

Various sensors were strategically placed to monitor the behaviour of the foundation system during the load cycles in flight. The main parameters to be monitored were the distribution of vertical forces and stresses at the top and bottom of the foundation system, the settlements of the GECs and the soft clay layer, and the development of pore water pressure in the foundation soil.

- Pore pressure sensors with a pressure measuring range -100 kPa to 60 MPa were installed in the clay using the technique described in König et al. (1994). Two sensors were placed at two different points between the central columns in the middle of the soft clay layer, other sensors were placed at the sidewall of the strong cylinder.
- A liquid levelling system was applied to monitor the settlement at various locations, including the clay in the centre of the model and at the top of the columns. The liquid levelling consisted of pore pressure sensors in hoses that were connected to a water tank with a known water level.
- Foil-type sensors with different diameters (8 mm and 15 mm) and capacities (100 N and 450 N) were installed on top of the foundation system and basal reinforcement. They were used to record the vertical forces acting on the GECs and clay. Most foil-type sensors were installed directly on the GEC heads and clay surface, and some were installed on top of the basal reinforcement.
- Load cells with a capacity of 3000 N and soil pressure sensors with a capacity of 500 kPa and 1 MPa were placed at the bottom of the model to measure the development of vertical forces and stresses at the bottom of the foundation system. The load cells were placed in the columns at the bottom. The soil pressure sensors were placed in the base sand layer either under the columns (1 MPa sensors) or under the soft clay layer (500 kPa sensors). Special pedestals of various heights were made to provide the base for the soil pressure sensors.

Figure 4 shows a 3D scan of the surface of the soft clay layer after the placement of sensors on its surface (setup 1).

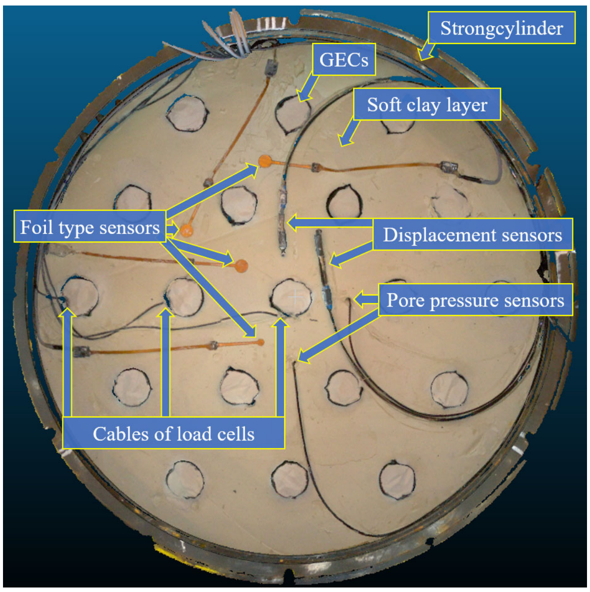

Figure 4. Surface of the soft clay layer after the placement of sensors

Figure 5 shows a 3D scan of the surface of the sand levelling layer after the placement of sensors on GECs (setup 1).

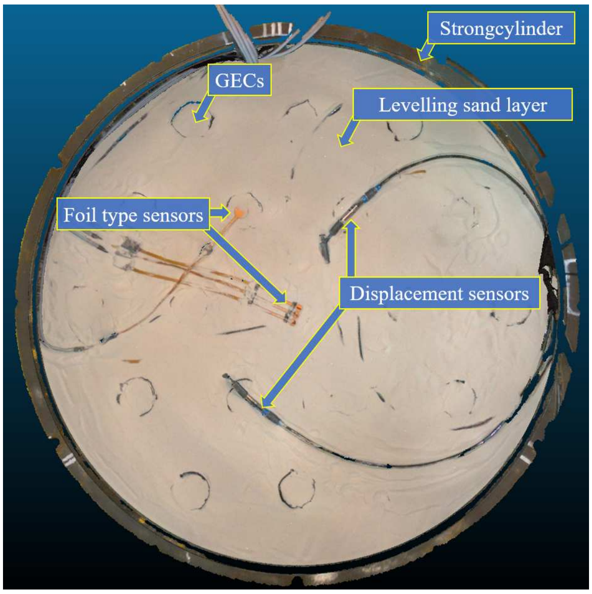

Figure 5. Surface of the sand levelling layer after the placement of sensors

2.8 Test procedures

After completing the model construction, the instrumentation was connected to the data acquisition system. During the flight, the following loading phases were conducted.

- The initial loading phase begins by rotating the model to reach the 20 g level without operating the actuator. This generated the initial stress state, due to the soil weight, including the load of a 2 m high embankment (prototype scale). Once the desired *g* level was reached, the centrifuge continued spinning until the end of consolidation.
- After completing the initial consolidation phase, the loading phase began by pressurizing the actuator to apply a vertical pressure of 100 kPa, simulating an additional 5 m of prototype embankment height. The centrifuge continued to rotate with this 100 kPa active load until the consolidation was completed.
- Then, the unloading phase followed, by depressurizing the actuator, and the vertical stress applied to the foundation system by the actuator dropped to near zero. This was again followed by a consolidation phase.
- A reloading phase began by reactivating the pressure applied by the actuator. The vertical stress had to reach 100 kPa again, followed by the last consolidation phase.

After the centrifuge was spun down and stopped, the model was disassembled for detailed examination and documentation. The surface of the model at each stage of construction and dismantling, as well as model elements such as columns, were selectively 3D scanned. This technique allows a very accurate estimation of the model dimensions, including the possibility to compare the dimensions before and after the test. However, it should be noted that there will be a difference to the dimensions at the increased g level. Figure 6 shows the coloured scale differences in height (distances) between two scans of the model surface at the level of the top of the soft clay layer, where the reference surface is that scanned after the columns were installed (zero signed distance, pre-test, setup 1) and the compared surface is that scanned after the model was dismantled (post-test, setup 1).

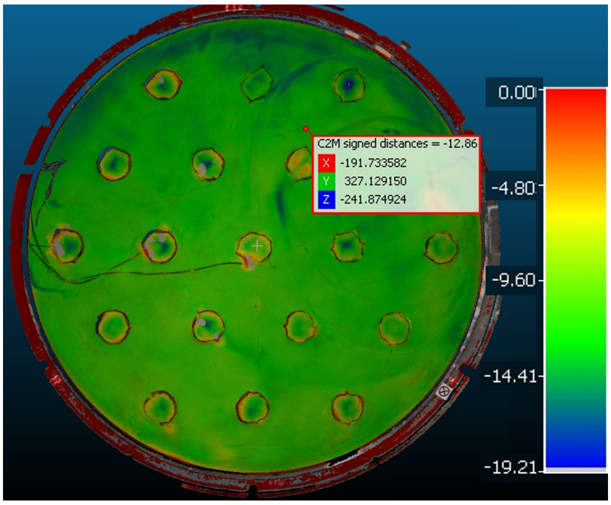

Figure 6. Coloured scale differences in height between two scans of the model surface (distances in mm)

3 CONCLUSIONS

This paper outlines a study on Geotextile Encased Columns (GECs) in soil foundation systems, aimed at investigating the impact of various loading cycles. As of now, the tests have been designed and conducted at Deltares GeoCentrifuge, and the results are currently being analysed. The findings will be presented in a separate publication. The focus of the research is on understanding the changes in stiffness of foundation systems with GECs during loading, unloading, and reloading.

While the paper primarily focuses on the methodology and experimental setup, it details the experimental lay-out carefully and therefore lays a strong foundation for future discussions on the outcomes and implications of the centrifuge tests. As the project progresses, the results are expected to contribute significantly to advancing the understanding of GEC-based foundation systems, offering valuable insights for practitioners and researchers in the field of geotechnical engineering.

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