Photogrammetry low-cost for geotechnical centrifuge modelling test

Alessio Cardaci, Daniela Giretti, Pietro Azzola

Department of Engineering and Applied Sciences, University of Bergamo, Bergamo, Italy
email: (alessio.cardaci; daniela.giretti; pietro.azzola)@unibg.it

Keywords: 3D Survey, Digital Photogrammetry, Civil Engineering, Geomechanical Characterization, ISMES.

Abstract

The buildings design is based on a thorough geotechnical study. Knowing the physical and mechanical properties of soils and rocks is a must for engineering calculations. The stability of the building and the lives of people are at risk if the relationship between the structure and the ground is not understood. Geotechnical centrifuges can be used to test physical models for geomeccanics characterization of the land. The first Italian centrifuge - still the only one active in Italy - is that of the former *Istituto Sperimentale Modelli e Strutture* (ISMES), now *Istituto Sperimentale Modelli Geotecnici* (ISMGEO). The elastoplastic properties of the soil can be estimated by observing the movement of critical points during the acceleration test. This is possible with traditional transducers, but also thanks to Close Range Multiview Photogrammetry, which allows you to return the digital model of the test before and after the test. By comparing the two models, target displacements can be evaluated, slope surfaces can be measured, and the steepest angle of descent can be determined. Additionally, the study of surface normals enables the identification of the degree of depression and the curved characteristics of the ground, such as anticlinal and synclinal. The contribution focuses on the experiences and outcomes obtained through digital photogrammetry during tests carried out for the SFARS project (Seismic FAilure and post-failure Response of Slopes) funded by the *Ministero dell'Istruzione, dell'Università e della Ricerca* (MIUR) for the Research Project of National Interest (PRIN 2022).

1. Introduction

Geotechnical modeling is crucial for the design and construction of any infrastructure or civil engineering work, and it is typically conducted using standard geotechnical tests at the volume element scale. In certain cases, due to the complexity of the phenomena and/or the high risk associated with potential failure mechanisms, it is possible to use geotechnical centrifuge physical modeling tests to reproduce a full-scale prototype in a reduced geometric scale. A geotechnical centrifuge is an apparatus which allows one to replicate the real stress state in a scaled-down physical model by imposing a given angular rotation speed on the model. The centrifuge tests can be very useful in the field of civil and building engineering. Unfortunately, they are rarely used as aids in the design of full-scale works, both because of the high cost of testing and the small number of laboratories that have such equipment; this often limits their use in the field of research (Bilotta & Taylor 2005). The first Italian centrifuge was made in 1988 by the *Istituto Sperimentale Modelli e Strutture* (ISMES), now known as the *Istituto Sperimentale Modelli Geotecnici* (ISMGEO). In 2010 the centrifuge - still the only one operating in Italy - was upgraded with the installation of a one degree of freedom shaking table in order to apply dynamic excitations to models and simulate the effects of earthquakes on geotechnical works (fig. 1). Appropriately equipped with miniaturized sensors, a physical model tested in centrifuge allows the measurement of a structure's mechanical response to any state of stress and applied loads. The use of displacement transducers, in particular, enables monitoring of the model's strain state. However, due to the limited size of a physical model in a centrifuge, only a limited number of sensors can be used, placed in strategic positions (Jiménez García & Melentijevic 2015; Ingegneri 2021). Direct investigation with sensors embedded in the model is sometimes assisted by indirect investigation with photographic sensors; in particular videogrammetric techniques are used. Where possible, test containers with transparent walls are employed to capture sequences of images of the glass-exposed section of the model. The measurement of deformations is done using an image processing technique called PIV (Particle Image Velocimetry), which identifies a set of markers and follows their movement from one frame to the next. The variation of the position of the markers between the two images, allows calculation of the vector of displacement. The photograph captures are made by a small number of stations (one or two) and carried out inside the centrifuge during the 'flight' (therefore with a high speed of rotation and high pressures), a complex and economically expensive operation. The accuracy of measurement is affected by image quality and resolution, camera calibration, lens distortion and refraction through the window. Furthermore PIV processing only allows 2D analysis on a vertical plane, generally the side section in contact with the transparent window monitor, which is also the least proper, because it is the most susceptible to the anomalies of the boundary effects (Ruiz Morales 2014; Alvarado Bueno et al. 2017). The Close-Range Multi-View photogrammetric techniques allow the study of the 3D geometry of the physical model in a precise and very high precision way. Deformation of the model is reconstructed in its material-metric state comparing the model surface before and after being tested in a centrifuge thanks to the acquisition of multiple photographic captures made from different positions. It is important that the photographic shots are taken quickly and in controlled light conditions. The speed of acquisition, which suggests the use of smart and low-cost systems for RGB data, and the specific environmental conditions must not compromise the accuracy and precision of the measurement. To execute everything quickly and without errors, it is crucial to have a serious project and proper automation of processes. The traditional photogrammetric workflow allows to obtain two digital models (before and after the test), sharing a common reference system by the selection of a set of point coordinates on the surface of the sample containers, as a discontinuous representation of points and mesh surfaces. The comparison of the two models allows not only to evaluate the displacements of the markers, but also to measure the slope of the surfaces. In addition, the evaluation of the normals to the surfaces allows us to know the yielding of the model and to identify the characteristics of the ground, such as anticlinal and synclinal.

1.1 Physical modeling in geotechnics

Physical modeling in geotechnics consists in replicating real scale geotechnical scenarios (like soil-structure interaction, slope stability, foundation performance, etc) by means of scaled-down models, to measure and evaluate the mechanical behavior of the elements, during operative and/or limit loading conditions. The accuracy and the reliability of a physical model relies on the proper scaling laws, which relates the geometric, kinematic and dynamic similarity between the small-scale model and the real-scale prototype in terms of forces, stresses, strains, etc.
It allows the evaluation of the results from the model to the full-scale condition. One of the most advanced and widely used method in physical modeling is centrifuge modeling, which relies on three key strategies:

1. a full scale element is replicated by a model geometrically scaled down by a factor n;
2. the prototype is accelerated by means of a centrifuge N times the earth gravity g, so that the centrifugal acceleration increases the gravitational forces on the model;
3. if the same soil is used in the model as in the prototype, the enhanced gravitational field reproduces in the model the same stresses as in the prototype in homologous locations.

The model can thus be tested under the widest loading conditions up to the failure (static, seismic, hydraulic loading scenarios) allowing to observe, in a controlled laboratory setting, phenomena not replicable at the full scale. The issue of the soil non-linear mechanical behaviour, which is a function of the type of soil, effective confining stress and stress history, is bypassed in centrifuge modelling as the increased gravitational field induced by the rotation and the use of the same soil enables to replicate of self-weight-stresses and strain between the model and the full-scale prototype. Thus, the measured results can be transposed to the real scale using the proper scaling laws. Centrifuge model testing enhances the understanding of fundamental deformation and failure mechanisms and allows to gather valuable data for tackling complex geotechnical issues as well as critical benchmarks for validating numerical models.

1.2 The Italian geotechnical centrifuge

The geotechnical centrifuge at the ISMGEO (formerly ISMES – Italy) is a beam centrifuge with a symmetrical rotating arm measuring 6 meters in diameter, 2 meters in height, and 1 meter in width, providing a nominal radius of 2 meters. The arm supports two swinging platforms at each side, for accommodating the model container for static and dynamic tests. During testing, the platforms lock horizontally to the arm to prevent the transmission of working loads to the basket suspensions. An outer fairing encloses the arm, rotating in tandem to minimize air resistance and disturbances during operation (fig. 2). The centrifuge is capable of reaching accelerations up to 600g with a maximum payload of 400 kg. One side of the arm is equipped with a single-degree-of-freedom shaking table, directly connected to the rigid arm, so that the arm provides the seismic mass to the table. The shaker works under an artificial acceleration field up to 100 g and provides excitations at frequencies up to 500 Hz and seismic accelerations up to 50 g. It allows to apply properly scaled real time histories as input. The arm design guarantees minimal distortion of the centrifugal field in the model, as the primary model dimension is aligned with the rotation axis, low deflection on the support plane of the swinging basket, easy instrument placement near the rotation axis, facilitated by the absence of a central shaft. With the shaker's axis of motion parallel to the centrifuge's rotation axis, Coriolis acceleration effects are minimised.

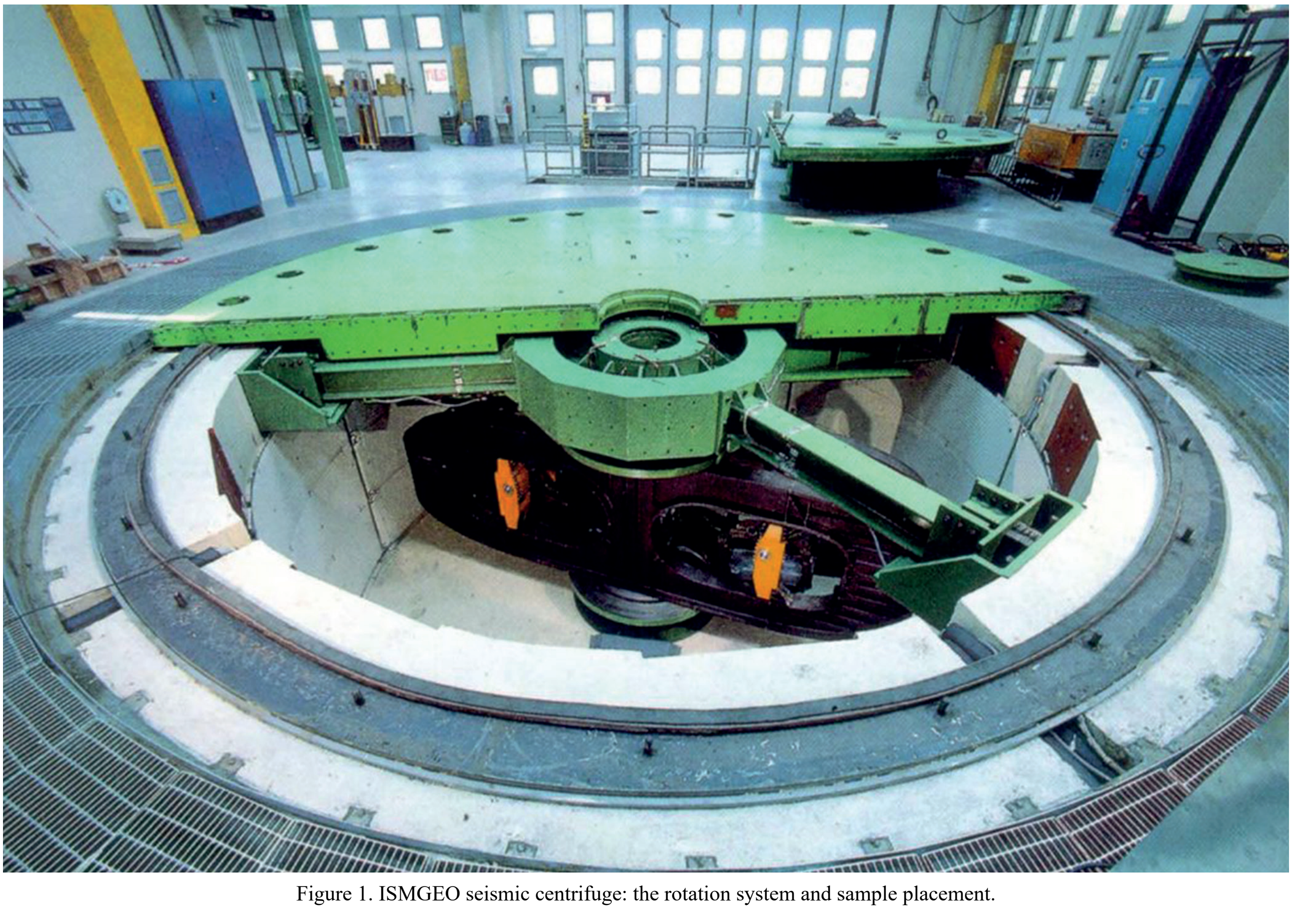

Figure 1. ISMGEO seismic centrifuge: the rotation system and sample placement.

https://doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-69-2024 | © Author(s) 2024. CC BY 4.0 License.

1.3 The SFARS project

The SFARS (Seismic FAilure and post-failure Response of Slopes) project has been funded by the *Ministero dell'Istruzione, dell'Università e della Ricerca* (MIUR) for the Research Project of National Interest (PRIN 2022). The research is aimed at studying the complex phenomena involved in earthquake-induced landslides, focusing mainly on the failure and post-failure stages that have the major consequences in terms of possible economic losses and casualties. Indeed, earthquakes have long been recognised as a major cause of landslides involving development of massive soil movement and large deformations in the post-failure phase both in natural slopes and earth structures, such as dams and embankments. The research will benefit of both numerical analyses and centrifuge tests, the latter carried out on small-scale models of slopes subjected to seismic excitations of increasing intensity up to causing a slope failure. The scope of the physical modelling is to analyse in detail the observed seismic and post-seismic behaviour of the slopes for a better understanding of the occurring deformation processes and collect a set of experimental data to validate the analysis methods and assess their predictive capability.

1.4 The test in geotechnical centrifuge

The model here discussed consisted in a submerged slope, made of compacted sand and resting on a subsoil made of loose sand, dynamically tested to observe the effect on the slope stability of earthquake induced liquefaction of the foundation layer. The model was geometrically scaled down by a factor of N = 50 and the centrifugal acceleration of 50g was applied at the model base. The slope was 140 mm high (7 m at the prototype scale), the crown and the base were 95 mm and 300 mm wide (4.75 m and 15 m), with a downstream slope of 34°. The foundation layer was 151 mm high (7.55 m at the prototype scale). The model was reconstituted in plane strain conditions in an equivalent shear beam (ESB) box, 337 mm high, 250 mm wide, 750 mm long (fig. 2). The model was instrumented with miniaturized tensiometers, pore pressure transducers, accelerometers. Linear displacement transducers and roto-translative sensors allowed to monitor vertical and horizontal displacements of some relevant points along the slope and the free field. The sensors were located along the longitudinal midsection of the model. The transducer P2 in the picture did not work during the test. The time history of the dynamic input applied at the model base by the shaking table is shown in the graph (fig. 4). It's worth noting that in centrifuge modelling the similarity relationships require the seismic accelerations to be amplified by the factor N (N being the geometrical scaling factor), the dynamic time to be reduced by the factor N. As an effect of the applied seismic motion, the foundation sandy layer approached the liquefaction condition, i.e. it underwent a significant pore water pressure build-up with consequent reduction of the effective stress field, triggering a slope instability. A picture shows the model after the test at 1g, once the model was unloaded from the centrifuge (fig. 5a); in particular compares the initial shape of the model with the deformed shape at the end of the earthquake, as inferred from the displacement transducers. the final picture shows also the shape measured at 1g at the end of the test along 4 longitudinal sections, two on the right side (D) and two on the left side (S) of the container (fig. 5b).

2. Towards a procedural protocol for measuring

The aim of this research is to develop a measurement protocol that will enable the conduct of deformation analyses on physical soil models before and after the centrifuge test. An operational workflow that allows for quick and effective results, using smart and low-cost instruments. This is possible through a set of rules and a sequence of simple and unbreakable operations, which should be repeated for each test in a rigid and scrupulous way. A set of operational requirements and predetermined processing parameters that must be carried out without modification in order to ensure repeatable measurements that can be carried out by different personnel. The protocol, still in definition, provides for the differentiation of the process into three main stages: digitization and photo capture, data processing, analysis, and interpretation of results (Toschi et al. 2014; Cardaci et al. 2024).

2.1 Digitizing and taking photos

The specimen must be placed on a rigid support near the centrifuge to capture images both before and after testing. This is to allow the campaign to be carried out shortly before the start

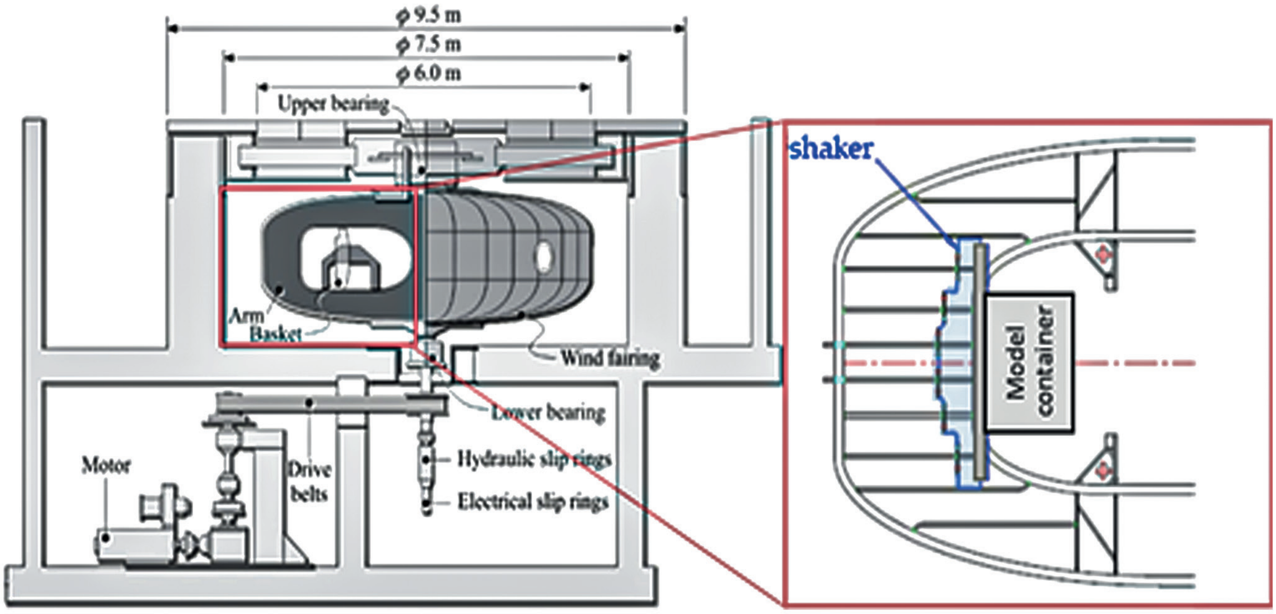

Figure 2. ISMGEO seismic centrifuge: element diagram.

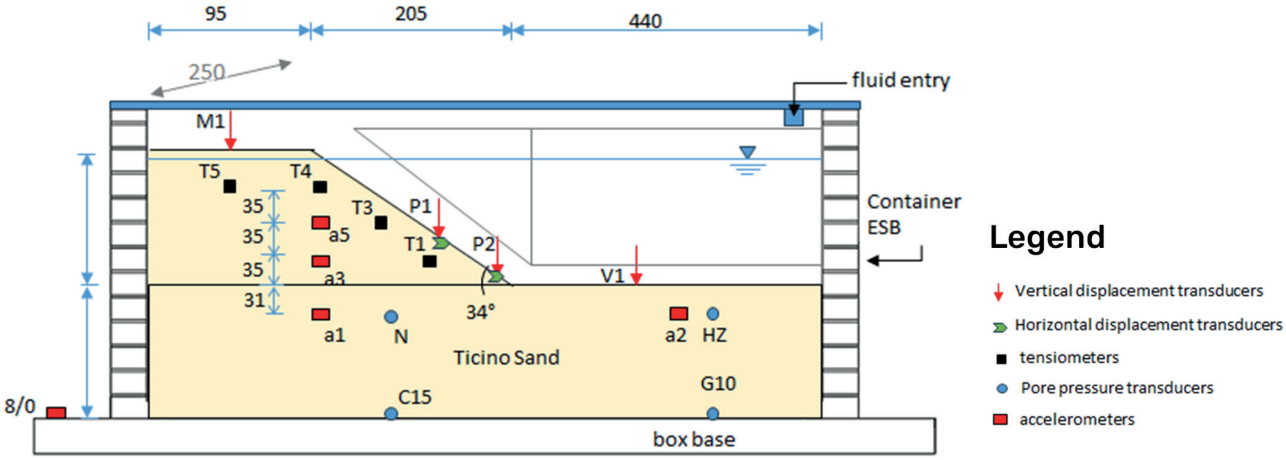

Figure 3. Scheme of the small scale model.

and immediately after the end of the tests, as well as to limit any deformations of the sample following movement with the overhead crane. It is important to ensure the same lighting conditions by choosing a closed environment without large windows and illuminated from the ceiling with a system of artificial lamps capable of ensuring diffused and intense light at any time of day. It is not required for the photographs to be taken with the same camera (although it is recommended), but they must meet the same criteria. In particular, the camera must be a Full Frame with a resolution greater than 18 MP; the shots must be taken with an aperture of f22 and an ISO value of 100 in order to have the maximum depth of field and reduce the effects of motion blur. The exposure times are chosen by measuring the light from the internal exposure meter of the camera according to a matrix reading with preponderance in the center; in order to avoid overexposed areas in correspondence with the metal elements, it is good practice to underexpose the frames by 2/3 eV. To minimize the effects of micro-blur, shots should be taken with a tripod and rotating head, and vibrations can be avoided by remotely controlling the shutter. To obtain images, the camera should be pointed towards the center of the container and rotated around it; the shots must be taken by rotating the camera with respect to the vertical axis; the first ones should be frontal and gradually change in inclination until the last ones are taken from a zenithal position above the container (fig. 6). It is important to verify and establish the distances based on the hyperfocal distance; in general, a range of 0.5 to 5 meters can be assumed to obtain a GSD value between 0.1 and 1 mm. Finally, it is very important to set up the campaign to achieve a high value of overlap between the frames between the individual images, not less than 75% and never more than 90%.

2.2 Data processing

The 3D reconstruction of the specimen should be done using the same algorithms and parameters for every test. It is crucial to attain a cloud that has the same number of points, accuracy, and precision. Furthermore, the size of the ESB container does not change and the volumes of the specimens do not change. The number of shots taken and the location of stations are both standardized and constant. It is therefore essential to obtain homogeneous data within strict tolerances, so that it can be compared for different specimens performed by different operators. The SFM process cannot be automated, but it must be performed critically and in a reasoned way. The first phase involves verifying the quality of the images, which must satisfy qualitative indices. It is not possible to eliminate or replace photographs at a later time (in order to comply with the protocol described in the previous paragraph), therefore, to validate the test, it is good practice to perform at least two photographic campaigns, even if they yield redundant data. The chamber alignment procedure is performed with a very high value of the ratio between the Key

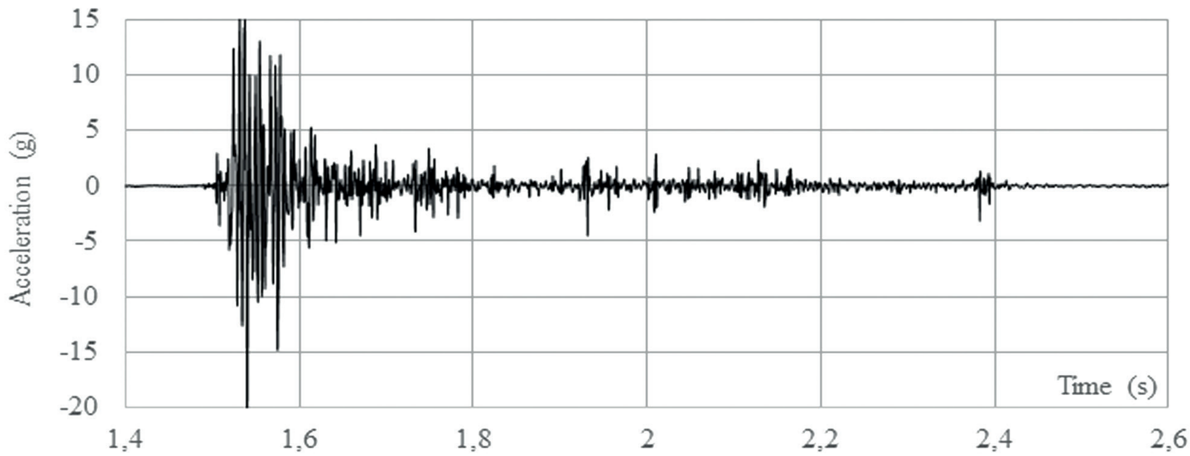

Figure 4. Applied input motion (model scale).

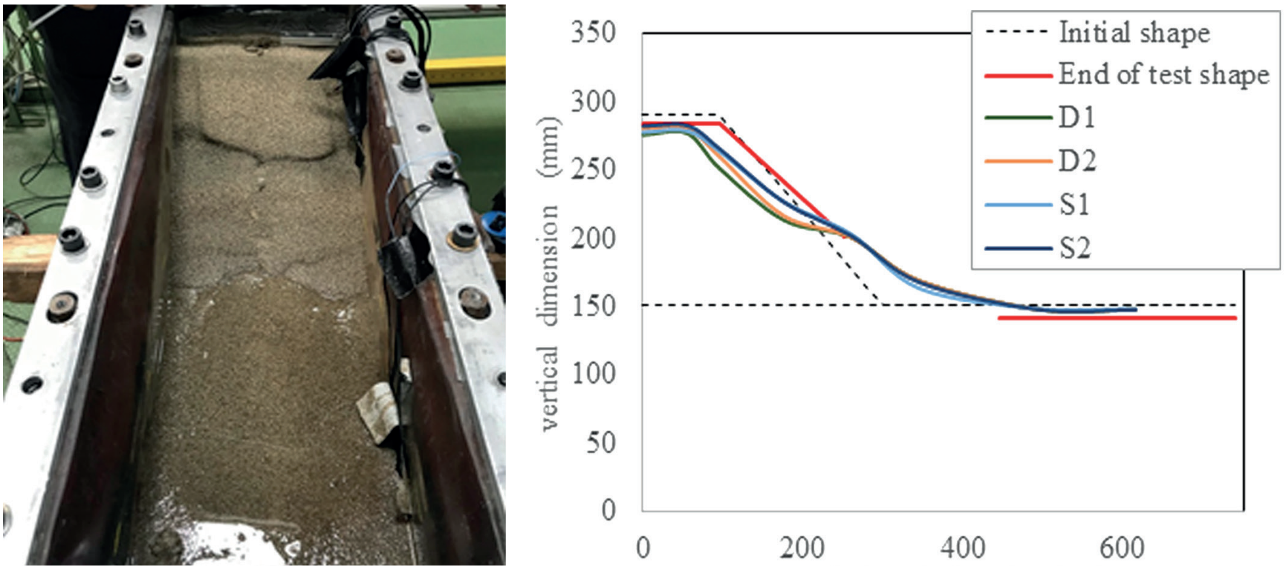

Figure 5. Picture of the model at the end of the test and initial and deformed shape of the model (model scale).

Point Limit and the Tie Point Limit: previous tests have highlighted how the optimal value – for the tests performed with the geotechnical centrifuge of Bergamo and with the ESB container previously described – is included in a range between 10K/100K and 50K/500K. This allows for the creation of a sparse cloud of over 550K points with an RMS Reprojection Error below 0.65 pixels and a Max Reprojection Error of approximately 35 pixels. The subsequent correction of the camera calibration parameters - with bundle adjustment algorithms using known coordinate markers identified on the specimen with an accuracy of 1mm - and a subsequent Gradual Selection filtering (through the setting of the Maximum Reprojection Error, Reconstruction Uncertainty and Projection Accuracy parameters) allows to have a new sparse cloud of about 100k points with an RMS Reprojection Error lower than 0.35 pixels with a Max Reprojection Error of about 3/5 pixels. The construction phase of the dense cloud, starting from these values, even if from a computational point of view very expensive in terms of time and hardware performance, allows to obtain a dense cloud of about 65M having a Control Point Error of about 0.5 pixels. The mesh model, reconstructed by limiting the minimum size of each surface to 2.5 times the average value of the GSD, is made up of about 3.5 million faces and 1.7 million vertices (fig. 7a). The visual comparison between the orthographic projections between the two 3D models, both before and after the centrifuge test, is already able to highlight the deformations caused by the breakage of the specimen. Although this is the first quantitative investigation, it reveals that we have a general framework that is useful for comprehending the physical-mechanical processes the specimen undergoes.

2.3 Analyzing and interpreting the results

The use of algorithms that can compare the geometries of the two models enables a timely and qualitative interpretation of the results. The first processing carried out was aimed at interrogating the clouds to understand the variations related to the displacements, both on the horizontal plane and in altitude, as well as to have an indication of the slopes and gradients through the study of the normal vectors to the individual points (figs. 7, 8 e 9). The information was returned in both graphic form (through false-color orthographic images) and numerical form. The orthographic image related to the displacements allows us to understand which

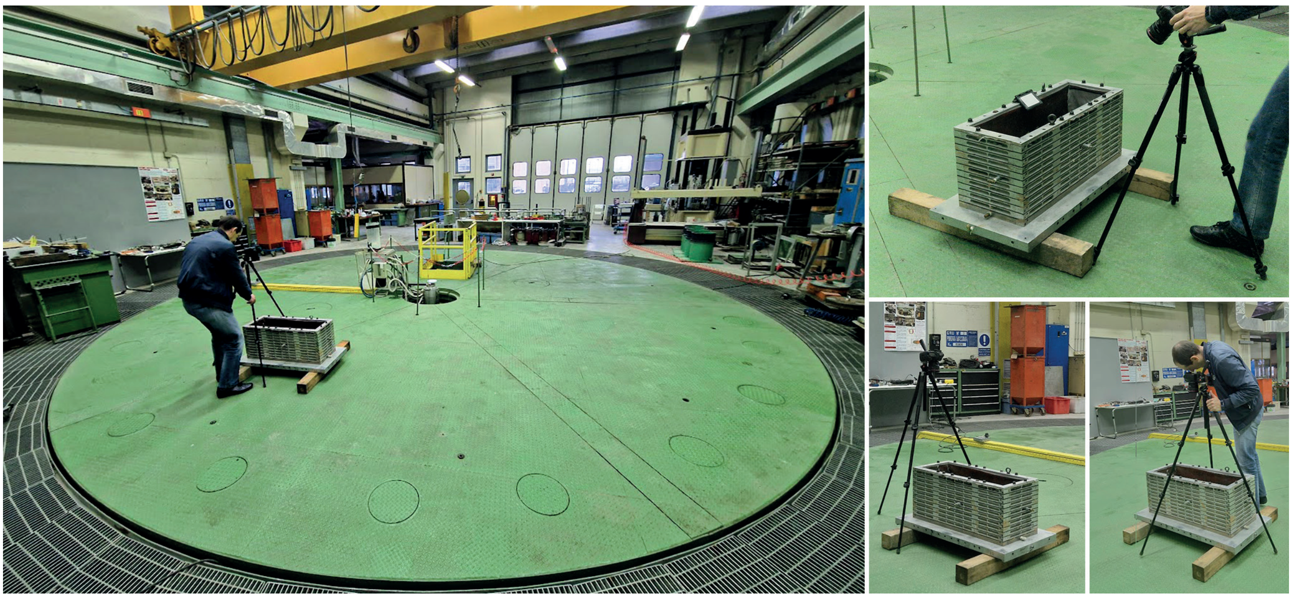

Figure 6. The photogrammetry data acquisition of the sample and the ESB support.

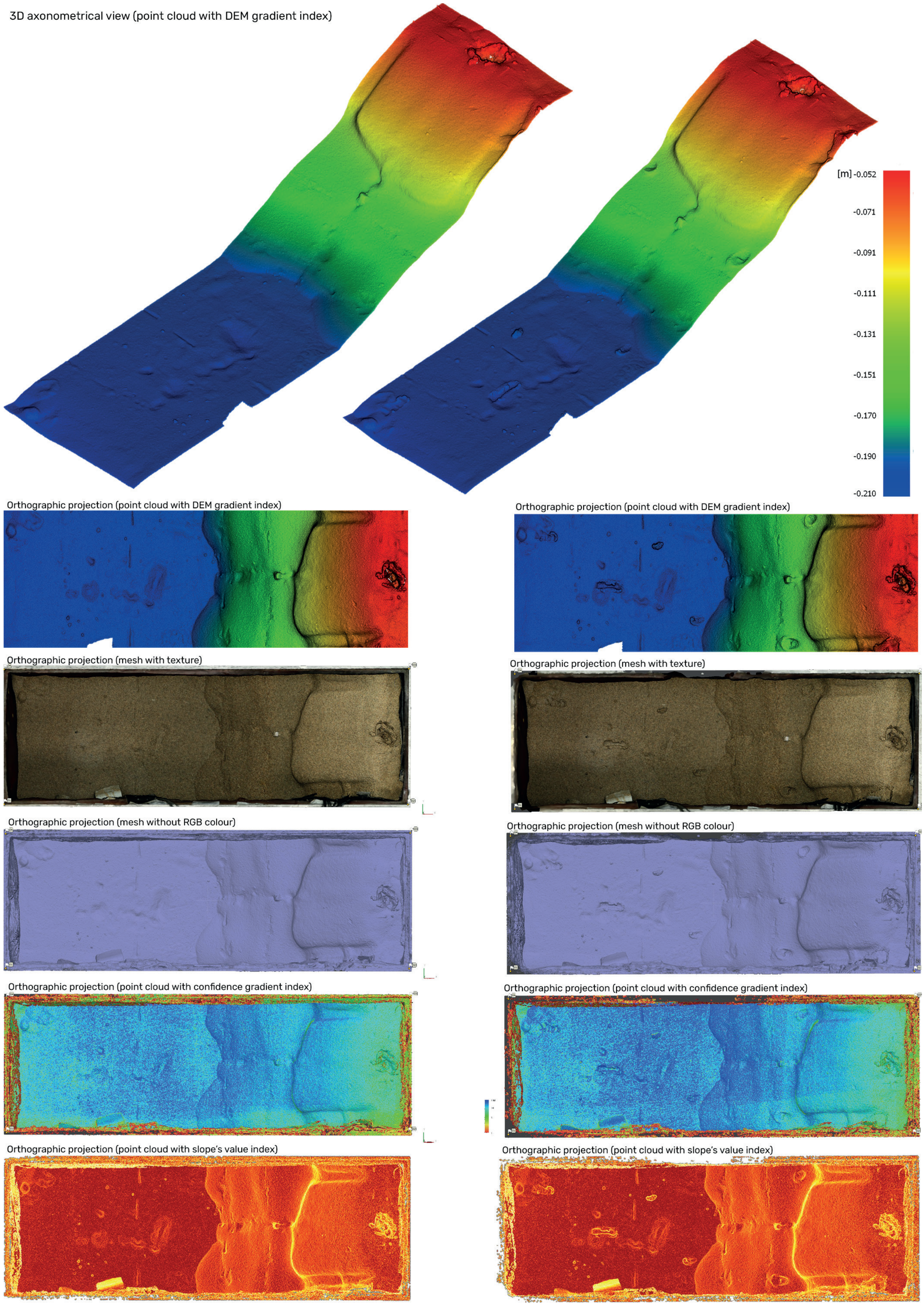

Figure 7. The sample before the test (a) and after the test (b): 3D view and ortographic projection.

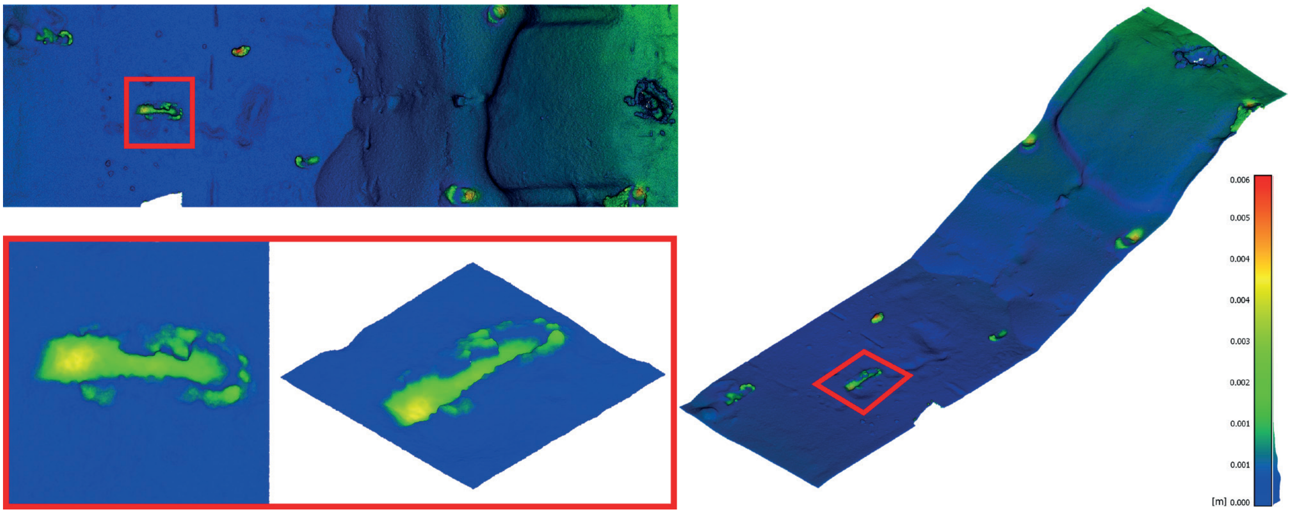

Figure 8. The distance between the two point clouds represents the displacement of the sample at the end of the test.

parts of the specimen were more affected than others by the effect of the high accelerations (Skarlatos & Yiatros 2016; Teo 2020). The numerical restitution within a single database requires sampling of the models starting from a grid whose minimum interval is equal to 1mm, which is due to the measurement accuracy of the system. This interval can be increased depending on the precision required for the creation of the profiles; although this results in lower precision in the definition of the interpolated curves, it significantly reduces calculation times. In particular, it is necessary to investigate three significant longitudinal sections, the two outermost (but not close to the border) and the central one (fig. 10).

3. Conclusions

3D models are large databases of metric material information on the specimens, both before and after the centrifuge test. They are vast reserves of raw data that contain much more information than is strictly necessary for the geotechnical study. This multitude of indications makes them extremely flexible and adaptable to different needs, even very specific ones. The analysis process can use data selected and chosen for a given query, operation, or moment. A 3D database extends to the entire surface of the specimen, queries are not restricted to 2D data related to a single section and only during the dynamic test of the PIV analysis, which allows it to be used in different ways and by many different users over time.

Acknowledgements

The authors express their gratitude to Professors Enrico Conte, Ernesto Cascone and Vincenzo Fioravante for sharing the results and images from the SFARS project. The authors acknowledge the activity of ISMGEO laboratory for their support during the surveying activities and are grateful to them.

References

Alvarado Bueno, M., Ruiz, Á. & Pinyol Puigmartí, N. M. 2017: Nuevo método para la interpretación de imágenes digitales de inestabilidad mediante la técnica PIV. "IX Simposio Nacional sobre Taludes y Laderas Inestables". Barcellona, Publicado por España International Centre for Numerical Methods in Engineering (CIMNE), 307-313.

Bilotta, E. & Taylor, N. 2005: Modellazione geotecnica in centrifuga. Benevento, Hevelius.

Cardaci, A., Versaci, A., & Azzola, P. 2024: 3D photogrammetric models from HDR images: the case study of the *Fontanone Visconteo* in *Bergamo*, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, xlviii-2/w4-2024, 95–102. doi.org/10.5194/isprs-archives-xlviii-2-w4-2024-95-2024.

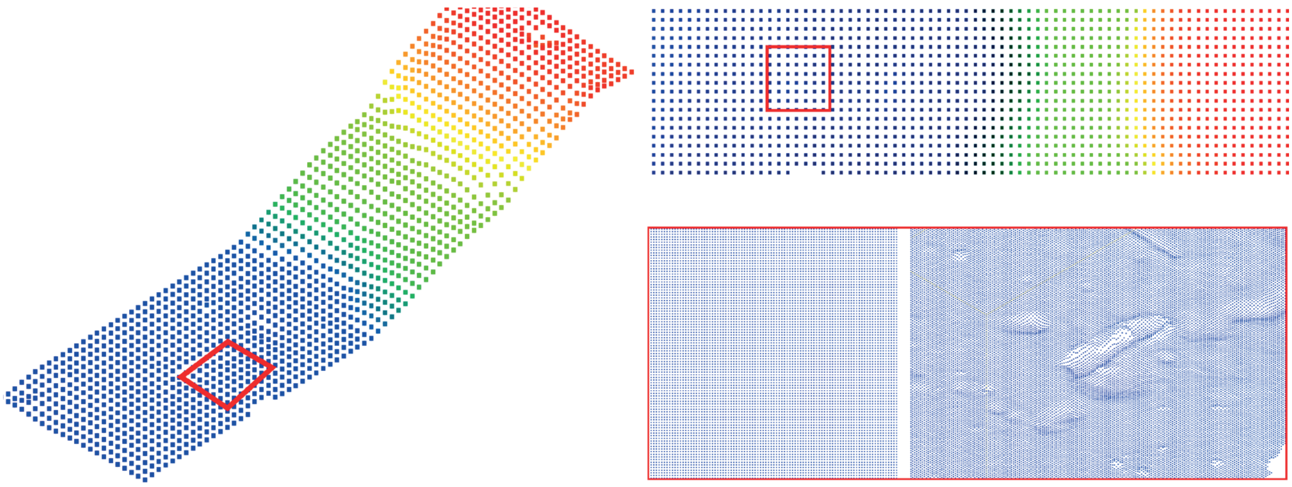

Figure 9. The grid subsampling of the point cloud with 10 mm and 1 mm of space.

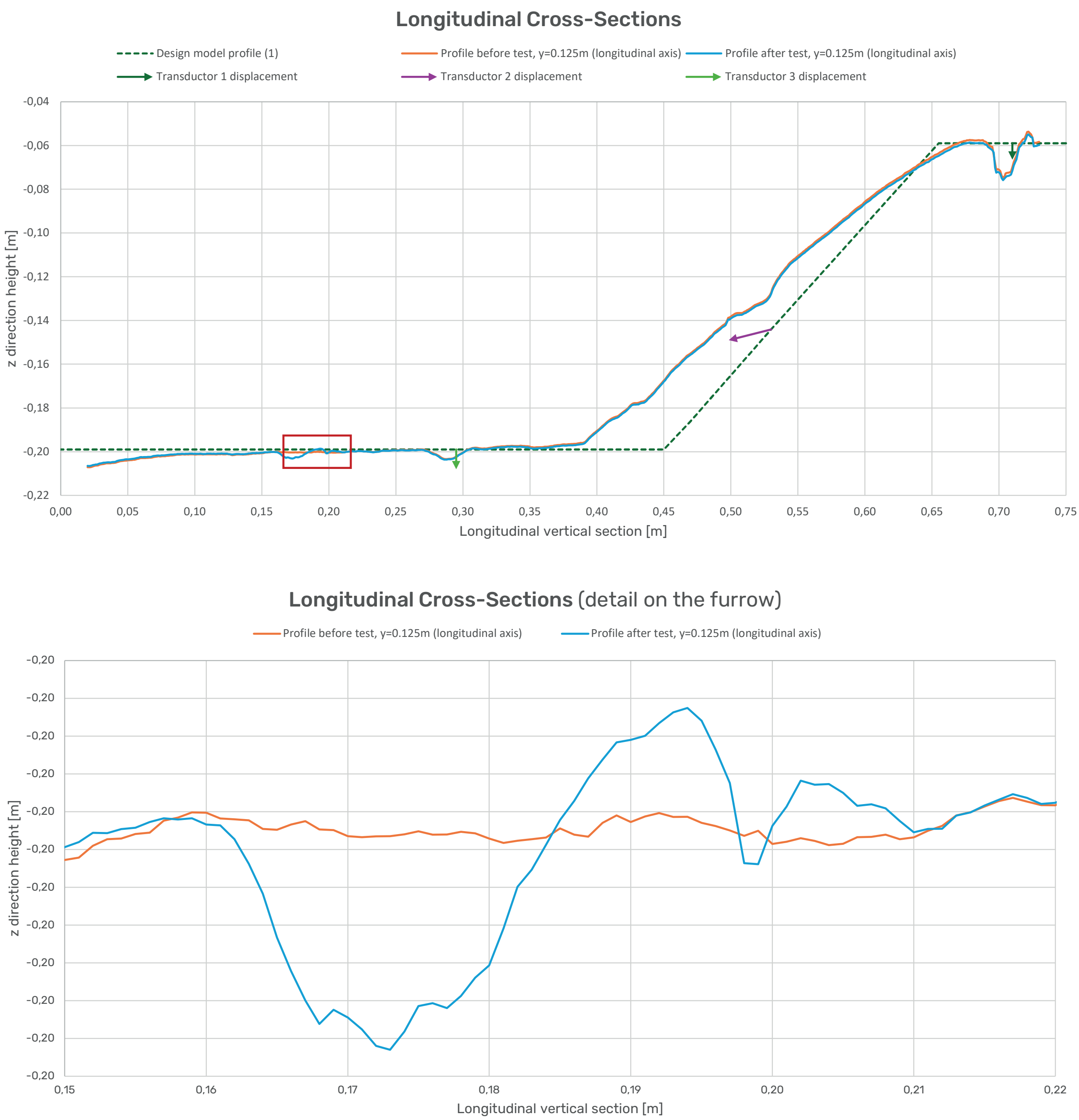

Figure 10. Cross sections of the model, defined by the subsampled point cloud.

Ingegneri, S. 2021: Calibrazione di un simulatore geotecnico sismico di grandi dimensioni. UNITesi - Deposit Doctoral Thesis of University of Reggio Calabria “Mediterrana”. Https://hdl.handle.net/20.500.14242/116913 (October 28, 2024).

Jiménez García, E. & Melentijevic, S. 2015: Centrífuga Geotécnica. *Revista Digital Del Cedex*, (178) 85. ingenieriacivil.cedex.es/index.php/ingenieria-civil/article/view/549 (October 28, 2024).

Ruiz Morales, A. E. 2014: Evaluación del PIV como método de medida en Geotecnia (Projecte Final de Màster Oficial). Bercellona, UPCommons. Global access to UPC knowledge. Http://hdl.handle.net/2099.1/25452 (October 28, 2024).

Skarlatos, D. & Yiatros, S. 2026: Deformation monitoring of materials under stress in laboratory experiments, *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, i5, 35–41. doi.org/10.5194/isprs-annals-iii-5-35-2016.

Teo, T. 2020: 3D deformation measurement of concrete wall using close-range photogrammetry, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, xliii-b2-2020, 1175–1179. doi.org/10.5194/isprs-archives-xliii-b2-2020-1175-2020.

Toschi, I., Capra, A., De Luca, L., Beraldin, J. & Cournoyer, L. 2014: On the evaluation of photogrammetric methods for dense 3D surface reconstruction in a metrological context, *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, ii-5, 371–378. doi.org/10.5194/isprsannals-ii-5-371-2014.