INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE.

The paper was published in the proceedings of the 11th International Conference on Physical Modelling in Geotechnics (ICPMG2026) and was edited by Ioannis Anastasopoulos. The conference was held from June 8th to June 12th 2026 in Zurich, Switzerland.

© 2026 the Authors

Tactile Pressure Sensors for Geotechnical Compression Testing

J. Schleicher, M.J. Rebhan, F. Tschuchnigg
Graz University of Technology, Graz, Austria, julian.schleicher@tugraz.at, rebhan@tugraz.at, franz.tschuchnigg@tugraz.at

S. Alber, I. Anastasopoulos
Eidgenössische Technische Hochschule, Zurich, Switzerland, simone.alber@igt.baug.ethz.ch, ioannis.anastasopoulos@igt.baug.ethz.ch

A. Arnold
Lucerne University of Applied Sciences and Arts, School of Engineering and Architecture, Lucerne, Switzerland, andre.arnold@hslu.ch

ABSTRACT: When standardized oedometer tests do not fulfil the geometrical prerequisites for certain soil samples, larger compression tests may be performed. However, this calls for consideration of wall friction effects on the effective stress distribution within the sample. Well-established measuring devices, such as Tactile Pressure Sensors (TPS), could be useful to investigate such boundary effects. Especially thanks to their thin structure and high resolution, such sensors have been extensively used to investigate stress quantification and distribution, mostly in centrifuge testing, since their introduction to geotechnical testing in the late 1990s. This paper provides insights into the application of TPS in 1D compression testing to experimentally determine the effect of wall friction. After describing the experimental setup, sensor preparation and calibration, the key findings are presented. The application of TPS to evaluate the quantitative impact of wall friction has provided valuable insights into the test results. In addition, it was possible to demonstrate the effect of the calibration method on the obtained results and identify the optimal approach.

1 INTRODUCTION

Laboratory testing plays a major role in geotechnical engineering, considering its output in terms of material properties and parameters. The latter form the basis for several engineering tasks, such as the design of retaining structures, ground improvement, planning of dam construction and many more. Especially due to an increasing use of advanced calculation techniques (such as finite element modelling), employing advanced constitutive models, the demand on high-quality parameter sets is rising accordingly (Marzouk et al., 2024).

In this regard, one important and well-established test is the oedometer test, which requires a certain geometry of the soil sample (height-to-diameter ratio, see Lovisa and Sivakugan, 2015) to obtain correct and reliable results. As this is not always possible, for example due to restrictions in terms of grain size, larger testing facilities are needed. But these call for careful consideration of certain boundary effects (e.g., wall friction in oedometric conditions), introducing a necessary correction of the test results. When such non-standardized facilities are used to determine soil parameters, these corrections may be determined by analytical methods, numerical simulations, or direct measurement using proper instrumentation; approaches combining these methods are also possible. If direct measurements are considered to derive the effect of wall friction, a quantitative determination of the load (stresses) at the bottom of the sample, compared to the applied load on top, may be satisfactory to evaluate the required corrections.

Tactile Pressure Sensors (TPS) could be an appropriate system for this purpose. Such sensors, often based on the piezoresistive principle (Kootahi and Leung, 2022), have been used in geotechnical engineering – especially in centrifuge model testing (e.g., Springman et al., 2002), since the late 1990s (Paikowsky and Hajduk, 1997). Thanks to their thin structure, TPS exhibit minimal interference with the soil. Consequently, the influence on the system stiffness is negligible, resulting in high-quality data acquisition (Guo and Zhou, 2025). Furthermore, the high resolution of the sensor allows not only for a quantitative assessment but also for a qualitative investigation of the stress distribution within the soil body or at the soil-structure interface.

The TPS technology has not yet become common in conventional geotechnical laboratory testing, like 1D compression tests, although the use of TPS already provided valuable information regarding soil behaviour and testing procedures (e.g., Ha et al., 2008; Madabhushi and Haigh, 2019). Hence, this paper examines the application of well-known TPS for geotechnical compression testing. Conducted at ETH Zurich, the performed tests focused on determining the influence of wall friction on the effective stress distribution within the soil sample. Therefore, confinement frames of different heights and different levels of internal surface roughness were used. After introducing the experimental setup and the calibration technique, key results are presented.

2 EXPERIMENTAL SETUP

A customized experimental setup was developed to analyse the effect of wall friction in a 1D compression test, matching the geometry of the employed TPS. The latter was a 5101 pressure mapping sensor (max. pressure of 345 kPa) from Tekscan Inc. (see Figure 1), which has 1936 sensels evenly distributed over a measuring area of 111.8 x 111.8 mm².

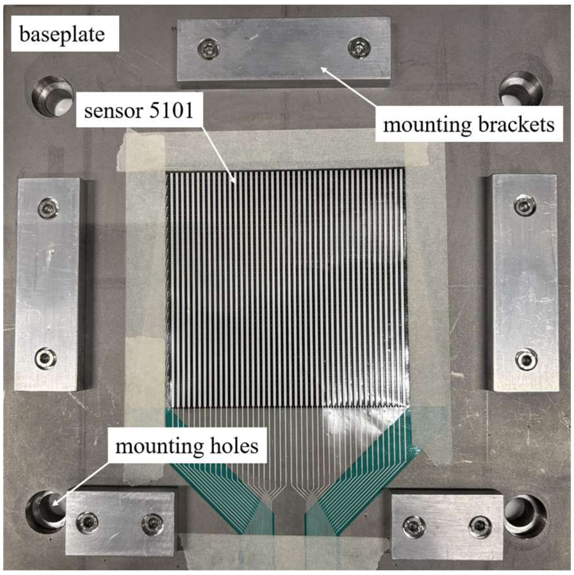

Figure 1. Sensor 5101 on stainless-steel baseplate.

Consequently, the compression box was designed with a footprint of 112.5 x 112.5 mm² to allow for a margin of error in positioning of the sensor, while ensuring that the entire footprint of the box is covered by the TPS. The sensor itself was mounted on a 20 mm thick stainless-steel baseplate with a machined and polished top, to ensure a smooth surface.

The TPS was fixed to the plate using masking tape to avoid any movement of the sensor during testing. Additionally, five mounting brackets were attached to the baseplate to hold the confinement frame, forming the compression box. To investigate the effect of wall friction during 1D compression testing, three different frames were prepared, which were 3D printed using Polylactic Acid (PLA) filament with an appropriate infill ratio of 30 % (rectilinear pattern) and wall thickness of ~2 mm. Two frame heights were adopted (10 mm and 100 mm), both with a wall roughness according to the 3D printing procedure. In addition, a third frame (100 mm) was prepared, using a Polytetrafluoroethylene (PTFE) foil as inner wall cover to reduce friction. The baseplate was fixed via four bolts to a test bench with a press (see Figure 2).

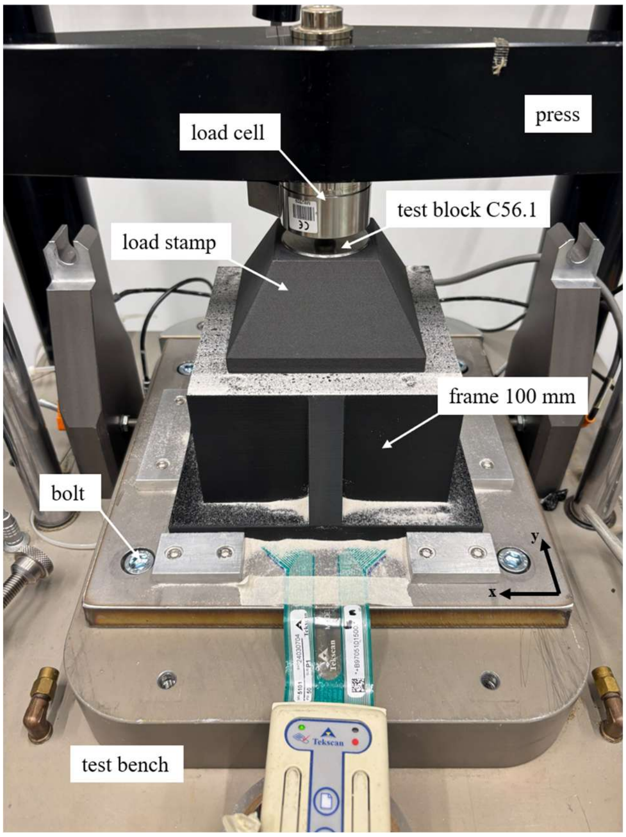

Figure 2. Test bench – full assembly of the setup.

In conjunction with the base of the test bench, the thickness of steel beneath the sensor increased to 120 mm, which can be considered adequately rigid for the applied loads. Consequently, it is assumed that no deformation occurs at the base of the setup. Furthermore, a load stamp in the shape of a truncated pyramid was used to transfer the point load from the press to the soil sample within the confinement frame. The load stamp had a height of 56 mm with a load distribution angle of 60 degrees, and a footprint of 111.5 x 111.5 mm². The stamp's footprint was chosen to be slightly smaller than that of the box to prevent jamming in the frame. The load stamp was made from Polyethylene Terephthalate, carbon-fibre reinforced filament (PET-CF) with an infill of 70 % (grid pattern) to ensure a stiff structure. According to the filament manufacturer (Bambulab GmbH), the used material offers a stiffness of 5320 MPa, which was assumed to be appropriate for the setup, particularly since the comparison between different confinement frames is unaffected by the stamp itself. Furthermore, a Rockwell test block, type C56.1 (high-quality hardened and tempered steel), with a thickness of 7 mm and a diameter of 51 mm was embedded into the top of the load stamp to avoid indentation and ensure uniform load distribution. The test bench allowed for precise adjustment of the position of the setup on the y-axis (see Figure 2) to ensure central positioning of the sample below the load application point. The used load cell, a HBM C2 (max. load 10 kN) was attached to the press. The load application was executed by vertically moving the press downwards in a force-controlled manner, which is achieved by the customised control system of the press.

2.1 Test programme and material

The loading pattern was chosen according to standard oedometer testing schemes (EN ISO 17892-5, 2017), which involve loading, unloading and reloading of the soil sample. During all testing the sensitivity of the TPS was set to 21 (default settings). The load steps in kPa and kN (effective area = load stamp footprint = 111.5 x 111.5 mm²) are summarized in Table 1.

Table 1. Load steps for compression tests.

Load Phase	kPa	kN
loading	10	0.12
	20	0.25
	40	0.50
	80	0.99
	160	1.99
	320	3.98
unloading	80	0.99
	20	0.25
reloading	40	0.50
	80	0.99
	160	1.99
	320	3.98

For reasons of simplicity, dry Perth sand was used as testing material. Further information related to Perth sand can be found in e.g., Buchheister (2009); Alber (2025). Following the absence of water, no consolidation phase had to be considered, consequently uncertainties in sensor readings due to excess pore water pressure could be avoided. Furthermore, it was possible to keep the load steps short, without significant static load drift effects of the TPS, setting the load step duration to around two minutes each.

Additionally, as the performance of the TPS depends greatly on the grain size distribution (Kootahi and Leung, 2022), given its uniformity $C_u = 1.53$ and small grain sizes $d_{60} = 0.21$ mm and $d_{max} = 0.40$, the utilised Perth sand fits the sensors' application range well. Numerous experiments using similar materials in combination with Tekscan pressure mapping sensors have already been carried out, yielding satisfactory results (e.g., Deng and Haigh, 2021).

2.2 Air pluviation

To allow for comparison between different experimental setups (e.g., different frame heights), comparable soil samples are essential; they were achieved by using a special air pluviation apparatus (Figure 3).

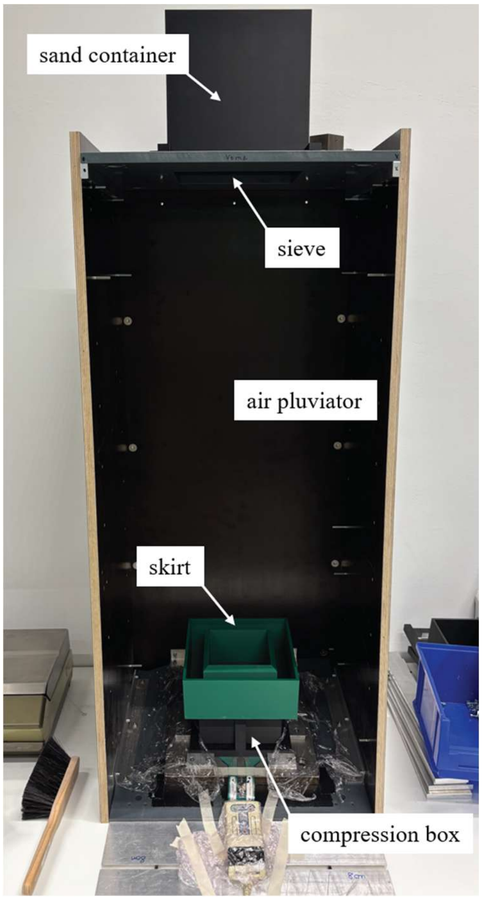

Figure 3. Air pluviator used for the experiments.

The latter has a footprint of 200 x 200 mm², completely covering the compression box. The installed sieve has holes of 2.5 mm diameter, with an edge-to-edge spacing of 2.0 mm. The same sieve with identical fall height was used for all sample preparations. To prepare soil samples for the frame height of 100 mm, the container of the pluviator was filled to a height of 100 mm, whereas for the 10 mm frame, the container of the pluviator was filled to a height of 10 mm. During pluviation, a sharp-edged skirt was installed on top of the confinement frame to avoid any shadowing at the sample edges that might occur due to sand accumulation on top of the frame. After pluviation, any excess material was carefully removed avoiding interference with the sample. Finally, the compression box was placed on the test bench.

The sample preparation resulted in a void's ratio of 0.76 (without PTFE) and 0.77 (with PTFE) for the 100 mm sample height, and 0.66 for the 10 mm sample height. The difference in achieved relative density may be attributed to the relatively small soil volume in the case of the 10 mm frame height. Despite the repeatability and consistency of the pluviation procedure, the filling of the shorter frame may be strongly affected by the opening process of the sieve, which is necessary to initiate sand raining. However, it was assumed that deviation of the void's ratio between the two frame sizes can be neglected.

2.3 Calibration of the TPS

Concerning calibration of the TPS, two different procedures were compared. Firstly, a standard two-load calibration was performed using Tekscan's equilibration device and I-Scan software (hereafter referred as *automatic* calibration). This method has already been presented several times (e.g., Palmer et al., 2009). Secondly, a more versatile calibration approach was investigated, where a multitude of load steps were performed in a customized air-pressure chamber to capture the response of the sensor at different pressures, resulting in multiple calibration points. For this calibration method (hereafter referred as *manual* calibration), load steps of 10 kPa were chosen to guarantee a dense resolution of the sensors' load response. TPS performance may also improve by applying alternative calibration methods, as for example a ten-point cubic calibration according to Brimacombe et al. (2009). However, these are not discussed herein.

The maximum applied load was selected according to the TPS behaviour: as soon as a single sensel within the sensor matrix reached saturation, the calibration was aborted, as this particular sensel would not be able to account for any further load changes. Consequently, proceeding with the calibration procedure would result in a distortion of the overall sensor response. Linear interpolation was performed between individual calibration points to approximate the entire load-response curve of each sensel.

The calibration procedures were performed using two different devices operating based on air pressure application. Both machines use confined air bladders to apply the load to the TPS, which ensures a physically comprehensible procedure and allows for a direct and evenly distributed load application. Calibration was performed both with and without soil, either using an actual sand layer or sandpaper, where a thin layer of Perth Sand was glued to a sheet of paper, applied between the TPS and the air bladder. This was done to investigate the extent to which soil-specific TPS calibration for compression testing is beneficial. The consideration of soil in the calibration should improve TPS performance to a certain extent (Żarkiewicz and Qatrameez, 2021) but would also increase the effort required for sensor preparation.

3 TEST RESULTS AND ANALYSIS

Using the two calibration procedures (*manual* and *automatic*), several scenarios were investigated to reveal the effect of the calibration technique on the performance of the TPS. All calibration datasets were applied to a representative raw dataset to compare the different calibration scenarios. The raw data was retrieved from a compression test using the 10 mm high confinement frame in the experimental setup. The data was selected based on the assumption that, given the low frame height, wall friction would be negligible and consequently no arching effects (principal stress rotations) would occur in the soil. Therefore, it can be expected that the applied load on top of the soil sample should also be measured by the TPS on the bottom.

Figure 4 shows the comparison of the different calibration scenarios. The graph displays the measured load in kN over the applied loading curve according to Table 1. Calibrated load values are compared to the readings of the load cell, which are marked by grey crosses. Regarding the TPS measurements, we distinguish between manual and automatic calibration (designated as *man* and *auto*, respectively). For both calibration procedures, the sensor was calibrated using air pressure only (*air*) and using Perth sand between the air bladder and the TPS (*sand / sandpaper*).

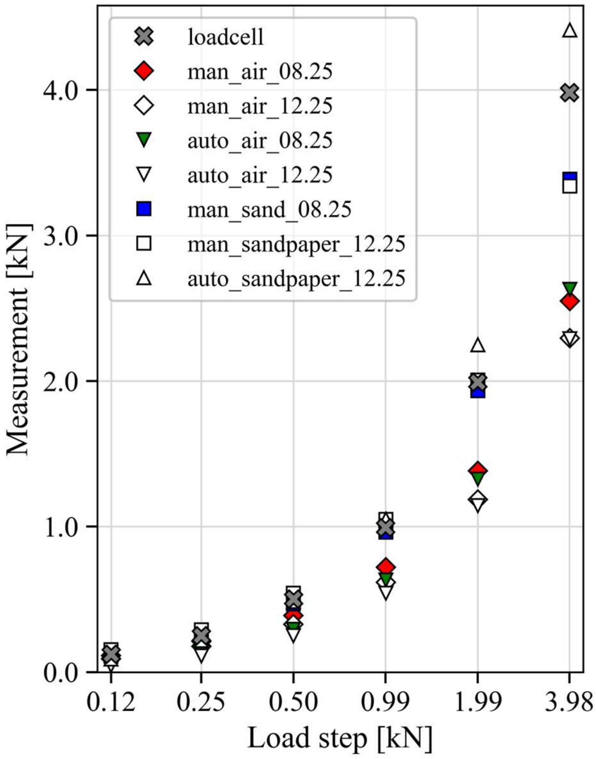

Figure 4. Comparison of different calibration techniques.

The calibrations were performed on two occasions: the first calibration took place directly before the compression tests were carried out in August 2025 (*08.25*), and the second calibration was performed four months later in December 2025 (*12.25*). The latter was primarily carried out to validate the initial datasets collected in August. However, it was also possible to compare the influence of the sand layer thickness on top of the TPS during calibration, since the first calibration was performed with a 3 mm thick sand layer on the TPS and the second one used sandpaper. In Figure 4, the first calibration data is represented by filled markers, while the second is indicated by hollow markers. The findings can be summarized as follows:

- The best fit over the entire load range was achieved by manual calibration including Perth sand, marked by squares. Nevertheless, the highest load step (3.98 kN) was underestimated. This was caused by exceeding the sensel's pressure limit (saturation) of 345 kPa. For clarification, Figure 5 (top) shows a heatmap of all sensels for the representative dataset (10 mm frame) and their corresponding kPa-value at 3.98 kN (maximum load). Yellow-coloured sensels already reach saturation.
- Automatic calibration using Perth sand did not provide as good results as the manual one, leading to an overestimation of the applied load, especially in the higher load range (1.99 and 3.98 kN).
- With respect to a comparison of the manual calibration scenarios with both the 3 mm sand layer (*08.25*) and the sandpaper (*12.25*), it is apparent that there is no significant deviation. However, several more tests would be necessary to confirm these findings.
- Calibration with air pressure, without sand, resulted in an underestimation of the applied load over the entire load range. This may be caused by the load application type: air pressure results in an even, full surface load, whereas the application of sand results in a multitude of point loads, caused by the soil grains. No significant difference between manual and automatic calibration was observed.
- Concerning air pressure calibration, a clear difference between the first and second calibration can be identified. The later (*12.25*) shows lower readings than the first one (*08.25*). This emphasizes that TPS should ideally be calibrated directly prior to testing, as the sensitivity of the system appears to have changed slightly during storage (TPS was not used in the meantime).

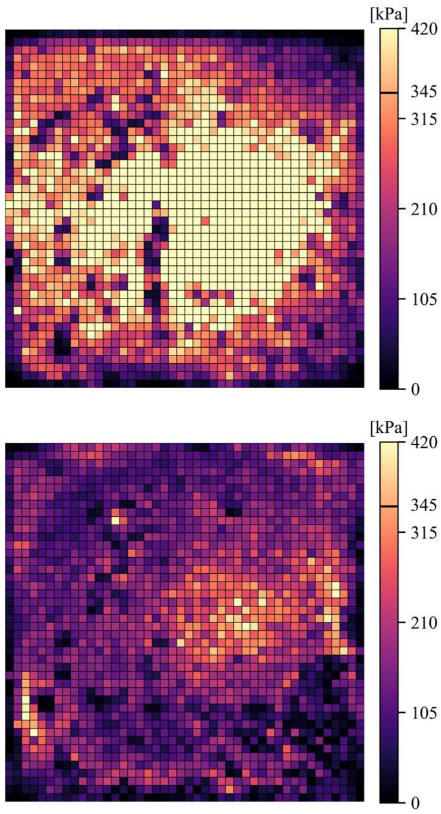

Figure 5. Sensor heatmap for 10 mm frame (top) and 100 mm frame (bottom), load step: 3.98 kN (loading).

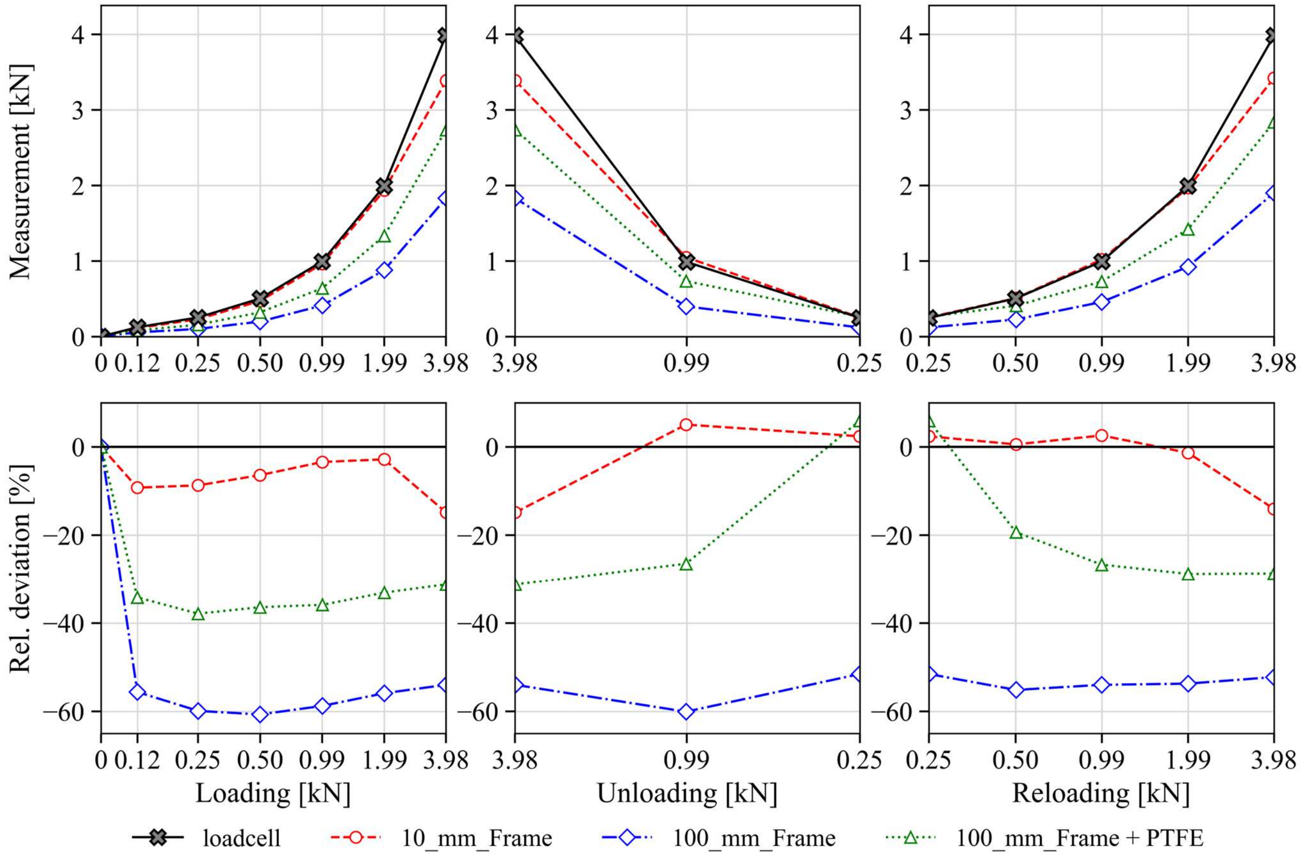

Figure 6. Evaluation of wall-friction influence for loading, unloading and reloading phase.

Considering the results from the calibration study, calibration *man_sand_08.25* (manual calibration with multiple load steps and with a sand layer of 3 mm on top of the sensor) was further used, as it seemed to obtain the best results.

To evaluate the influence of wall-friction within the experimental setup, the three different confinement frames described previously were used, and the loading procedure according to Table 1 was applied. Consequently, the readings were categorised as loading, unloading and reloading, as shown in Figure 6 (from left to right). The chart shows the TPS measurements for all three frame types, comparing them to the reference values recorded by the load cell, which are represented by a solid line with crosses.

The top three plots display a comparison of the measured loads in kN over the applied loading steps for the loading, unloading and reloading phase. Whereas the bottom plots compare the TPS measurements with the readings of the loadcell in terms of relative error (related to load cell readings), expressed in %. As previously mentioned, pluviation of both frame types resulted in void ratios of 0.66 and 0.76; 0.77 for the 10 mm and 100 mm frames, respectively. The findings presented in Figure 6 do not indicate any severe influence of this discrepancy on the plausibility of the measurements.

In general, a clear trend can be observed, as the effect of the wall roughness and height clearly influences the load distribution within the sample. The 10 mm frame (red dashed line, circular markers) provides the best fit to the reference, excluding the highest load step, which cannot be accurately captured due to sensor saturation. Hence, when the highest load step is disregarded, a maximum relative error of ~10 % is achieved for the 10 mm frame setup. The effect of sensor saturation was barely detectable for larger frames. This was due to the greater influence of wall friction, decreasing the amount of stress acting at the bottom of the sample, thereby preventing most of the sensels from oversaturation (see Figure 5, bottom).

Furthermore, hysteresis effects can be observed, as the accuracy of the measurements seems to increase due to the load history, resulting in an error below 5 % for the reloading pattern (10 mm frame). The least accurate readings are provided by measurements taken using the standard 100 mm frame (blue dash dotted line, diamond markers), with a relative error of up to 60 %, remaining quite consistent throughout all load phases. During reloading phase, the maximum error decreases to approximately 55 % (0.50 kN) and a hysteresis of up to 8 % (0.25 kN) can be identified. Installation of a PTFE foil at the internal walls of the 100 mm frame (green dotted line, triangular marker) reduced the influence of wall-friction significantly, decreasing the relative error for the loading pattern to a maximum of 40 %. Furthermore, this setup was most susceptible to hysteresis effects, with the relative error decreasing by a maximum of ~20 % at a load of 0.50 kN. It is assumed that this is due to higher compaction of the sample during the loading process, caused by the internal walls being less rough than those of frames without PTFE. Consequently, the sample behaves stiffer during the reloading process, resulting in an improved load transfer from top to bottom.

To further investigate this assumption, additional measurements were performed (100 mm frame + PTFE). Following the first test, consisting of loading, unloading and reloading phase, the applied load was set to zero and subsequently a second loading phase was conducted. Figure 7 shows a comparison of the relative error, related to the load cell readings, for the first loading (green solid line), the first reloading (brown dashed line) and the second loading phase (orange dotted line). The corresponding load steps in kN are shown on the x-axis.

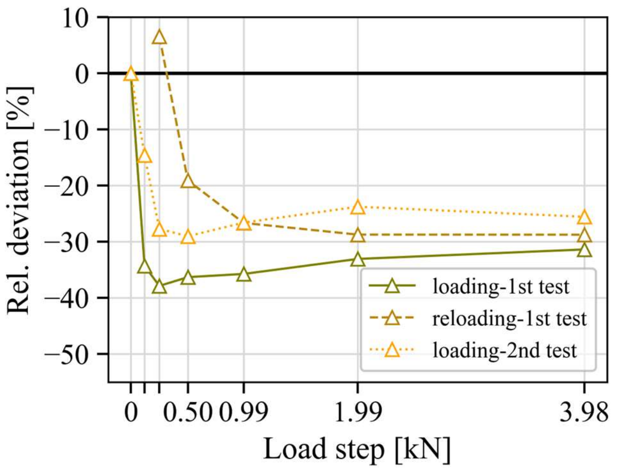

Figure 7. Evaluation of hysteresis effects, 100 mm + PTFE

As already mentioned, a significant hysteresis effect was observed when comparing the first loading and unloading phase. Furthermore, it is evident that the first and second loading phase do show similar curves, with the second loading phase shifted upwards by a maximum of ~10 %. When compared to the first unloading, the second loading phase underestimates loads of up to 0.50 kN, matches the reading at 0.99 kN well, and results in smaller errors for higher load steps of 1.99 and 3.98 kN, respectively. It seems that elastic deformation resulting from completely unloading the sample after the first test, allows for more friction mobilised at lower loads during the second loading phase, compared to the first unloading phase. Once this friction has been overcome, the second loading phase achieves lower relative errors compared to the first loading phase, resulting from the sample's load history.

4 CONCLUSIONS

The use of Tactile Pressure Sensors (TPS) in 1D geotechnical compression testing proved to be useful for the interpretation of the executed tests. Analysis of different calibration procedures emphasized the importance of a thorough calibration for the given task. Whereby, material specific calibration of the TPS showed to achieve the most accurate preparation of the system. However, the calibration type (*manual* or *automatic*) itself seemed to influence the quality of the dataset as well: for instance, the automatic calibration including sandpaper resulted in an unexpected overshooting of the obtained results at higher loads compared to the reference. In contrast, the manual calibration in the identical experimental setup matched well with the reference measurements.

It was evident that the height of the frame and the roughness of its internal walls influenced the load transfer significantly. The application of the lowest frame with a height of 10 mm did result in the best fit to the reference with a maximum deviation of 10 %. Whereas a 100 mm frame caused a maximum error of 60 %. Further, installation of a PTFE foil inside the 100 mm frame reduced the error to a maximum of 40 % indicating a decisive influence of the wall roughness.

Hysteresis effects were observed for all tests, showing the largest influence for the 100 mm frame with PTFE. A maximum error reduction of ~20 % was measured comparing its loading and unloading pattern. Whereas the 100 mm frame without PTFE showed a maximum reduction due to hysteresis below 10 %. It is assumed that this is caused by a higher compaction of the soil during the loading phase, if PTFE is applied, which results in a stiffer soil, that allows for a better load transfer in the reloading phase. This assumption was partially confirmed by comparing two loading phases (test 1 & 2), with different load history. However, the hysteresis arising in the tests might not only be attributed to the soil, but also to the sensor, as the TPS itself may also introduce load history dependency. As a result, the presented hypothesis needs to be further investigated.

It can be concluded that the application of Tactile Pressure Sensors provides valuable insights into the soil's behaviour during compression. The results obtained emphasize the potential advantages of incorporating additional measuring devices into geotechnical laboratory testing procedures. However, it should be noted that the presented experiments did not utilise the full potential of TPS application in compression testing. For example, using more sensors, mounted not only at the bottom, but for instance at the vertical boundaries as well, may provide a more complete investigation of the tests. This would allow to not only investigate the vertical stress distribution, but also the horizontal stress distribution, which could be used to e.g., identify arching effects within the soil body or to determine the type of consolidation process during testing. Further, the observed friction effects do directly affect the vertical stress distribution within the soil sample. Consequently, the determination of the soil's stiffness for larger samples, may result in an overestimation of the stiffness, as the effective stress decreases with the sample height. This must be considered if larger samples are investigated.

ACKNOWLEDGEMENTS

The work presented herein forms part of the research project SG4SSI (Sensor Grid for Soil-Structure Interaction). The authors express their gratitude to the Austrian Research Promotion Agency (FFG) for the funding, and the workshop of IGT at ETH Zurich for providing all necessary infrastructure to perform the tests.

REFERENCES

Alber, S. (2025). *Novel self-burrowing probe for in-situ soil investigation: development and testing in a calibration chamber*. PhD thesis, Eidgenössische Technische Hochschule ETH, Zurich, https://doi.org/10.3929/ethz-c-000791266

Brimacombe, J.M., Wilson, D.R., Hodgson, A.J., Ho, K.C.T. and Anglin, C. (2009). Effect of Calibration Method on Tekscan Sensor Accuracy. *Journal of Biomechanical Engineering*, Vol. 131. https://doi.org/10.1115/1.3005165

Buchheister, J.A. (2009). *Verflüssigungspotenzial von reinem und siltigem Sand unter multiaxialer Belastung, Liquefaction potential of pure and silty sand under multiaxial loading* [in german]. PhD thesis, Eidgenössische Technische Hochschule ETH, Zurich, https://doi.org/10.3929/ethz-a-006020660

Deng, C. and Haigh, S.K. (2021). Earth pressures mobilised in dry sand with active rigid retaining wall movement. *Géotechnique Letters*, 11 (3): 202-208. https://doi.org/10.1680/jgele.20.00116

Guo, C. and Zhou, C. (2025). Novel Single-Point-Type Tactile Pressure Sensors for Earth and Soil-Structure Interface Contact Pressures Measurement. *Geotechnical Testing Journal*, 48 (5): 728-746. https://doi.org/10.1520/GTJ20240066

Ha, D., Abdoun, T.H., O'Rourke, M.J., Symans, M.D., O'Rourke, T.D., Palmer, M.C. and Stewart, H.E. (2008). Centrifuge modeling of earthquake effects on buried high-density polyethylene (HDPE) pipelines crossing fault zones. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 134, No. 10, pp. 1501-1515. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:10(1501)

International Organization for Standardization (2017). *Geotechnical investigation and testing - Laboratory testing of soil - Part 5: Incremental loading oedometer test* (EN ISO 17892-5:2017).

Kootahi, K. and Leung, A.K. (2022). Effect of Soil Particle Size on the Accuracy of Tactile Pressure Sensors. *Journal of Geotechnical and Geoenvironmental Engineering*, 148(10). https://doi.org/10.1061/(ASCE)GT.1943-5606.0002899

Lovisa, J. and Sivakugan, N. (2015). Tall Oedometer Testing: Method to Account for Wall Friction. *International Journal of Geomechanics*, 15(2). https://doi.org/10.1061/(ASCE)GM.1943-5622.0000359

Madabhushi, S.S.C and Haigh, S.K. (2019). Using tactile pressure sensors to measure dynamic earth pressures around dual-row walls. *International Journal of Physical Modelling in Geotechnics*, Vol. 19 No. 2 pp. 58–71. https://doi.org/10.1680/jphmg.17.00053

Marzouk, I., Brinkgreve, R., Lengkeek, A. and Tschuchnigg, F. (2024). APD: An automated parameter determination system based on in-situ tests. *Computers and Geotechnics*, 176, Article 106799. https://doi.org/10.1016/j.compgeo.2024.106799

Paikowsky, S.G. and Hajduk, E.L. (1997). Calibration and Use of Grid-Based Tactile Pressure Sensors in Granular Material. *Geotechnical Testing Journal*, Vol. 20, No. 2, pp. 218-241. https://doi.org/10.1520/GTJ10741J

Palmer, M.C., O'Rourke, T.D., Olson, N.A., Abdoun, T., Ha, D. and O'Rourke, M.J. (2009). Tactile Pressure Sensors for Soil-Structure Interaction Assessment. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(11): 1638-1645. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000143

Springman, S.M., Nater, P., Chikatamarla, R. and Laue, J. (2002). Use of flexible tactile pressure sensors in geotechnical centrifuges. *Physical Modelling in Geotechnics*, 1st Edition, Routledge, London, UK. https://doi.org/10.1201/9780203743362-20

Żarkiewicz, K., & Qatrameez, W. (2021). Assessment of Stress in the Soil Surrounding the Axially Loaded Model Pile by Thin, Flexible Sensors. *Sensors*, 21(21), 7214. https://doi.org/10.3390/s21217214