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.

Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

New sensor for measuring earth pressures in centrifuge model tests.

G. Portmann, A. Arnold
Institute of Civil Engineering, Lucerne University of Applied Sciences and Arts, Horw, Switzerland, gregor.portmann@hslu.ch, andre.arnold@hslu.ch

R. Herzog, I. Anastasopoulos
Institute for Geotechnical Engineering, ETH Zurich, Zurich, Switzerland, ralf.herzog@igt.baug.ethz.ch, ioannis.anastasopoulos@igt.baug.ethz.ch

J. Schleicher, M.J. Rebhan
Institute of Soil Mechanics, Foundation Engineering and Computational Geotechnics, TU Graz, Graz, Austria julian.schleicher@tugraz.at, rebhan@tugraz.at

ABSTRACT: This article presents a novel method to measure earth pressures in centrifuge model tests. Monitoring earth pressure changes during a test provides valuable information on soil-structure-interaction (*SSI*), which is essential to understand how structures perform, from serviceability (*SLS*) to ultimate limit state (*ULS*). Implementing a tailor-made tactile pressure sensor (*TPS*), earth pressures were recorded during two centrifuge model tests. The sensor is characterised by its small size (single sensor: 6 x 14 mm), flexible arrangement, and water resistance. Data has been recorded using a data logger directly attached to the *TPS*, which is advantageous for use in centrifuge model testing. An initial evaluation shows that the sensors can provide valuable information on earth pressure development. However, it was found that pressures below 50 kPa could not be determined reliably. Additionally, an offset in the absolute value and a time lag in data acquisition were observed in individual sensors. However, improvements of sensor performance are needed, particularly regarding responsiveness and the detection of low pressures. These important issues are given strong consideration in the ongoing development process described.

1 INTRODUCTION

Soil-structure interaction (*SSI*) describes the process of load transfer, deformation behaviour and the overall performance of structures in geotechnical and structural engineering. However, understanding and predicting *SSI* requires high-quality experimental data and suitable methods for accurately measuring distributed earth pressures at the soil-structure interface remain limited. As part of the SG4SSI project, Rebhan et al. (2024) describe a novel piezoresistive tactile pressure sensor (*TPS*) for geotechnical applications adapted to address this issue.

The *TPS* is characterised by its relatively small size (6 x 14 mm), with an active measuring zone of 3.5 mm in diameter (black 'dots' in Figure 1 b) (Schleicher et al., 2025). Individual *TPS* units can be arranged to form waterproof grids with custom layouts. The data can be stored on a local data logger, connected directly to the *TPS* or sent via Bluetooth to any nearby device.

The sensor was used in two centrifuge model tests to assess its performance. The sensors were calibrated in a pressure chamber by the manufacturer beforehand. Therefore, their use in the centrifuge simulated typical conditions on a construction site, where calibration is usually not possible with a given soil under varying stress conditions. This allowed realistic assessment of the measured earth pressure development under changing load conditions.

2 PHYSICAL MODELLING

Centrifuge model tests allow a 1:N scaled model to be tested under stresses representative of the prototype, where the g-level is increased by a factor of N (Schofield, 1980; Madabhushi, 2014). The sensors were installed in two different test setups at different g-levels to test their performance. Table 1 summarises the two test setups BLOCK and NAIL, which are described in detail below. N describes the g-level factor in the test, d_{60} and d_{max} refer to the grain size distribution of the sand used, and S_r describes the relative saturation (0 = dry; 1 = saturated). The sensor performance should not be influenced by the grain size distribution for the two given sands, as the ratio of d_{max}

to the diameter of the measuring zone is sufficiently small (Schleicher et al., 2025).

Table 1: Test and soil property overview

ID	N [-]	Sand	d_{60} [mm]	d_{max} [mm]	S_r [-]
BLOCK	30	Perth	0.31	0.50	1
NAIL	60	Geba	0.12	0.40	0

BLOCK: As part of a research project investigating the load-bearing behaviour of block foundations (*BF*) (Arnold et al., 2024), centrifuge model tests were carried out at the ETH Zurich Geotechnical Centrifuge Centre (GCC) beam centrifuge under 30*g* in saturated Perth sand (Nater, 2006). The test setup (Figure 1 a) and the foundation with the sensor grid (Figure 1 b, excavated after the test) are shown schematically in model scale.

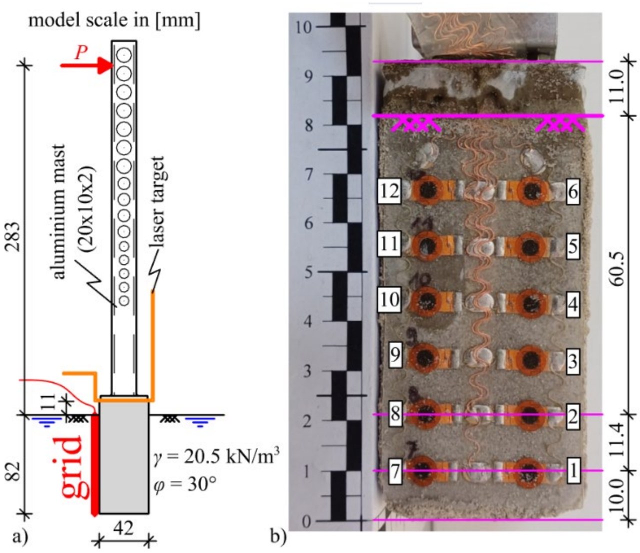

Figure 1: BLOCK: (a) Test setup in model scale and (b) block foundation with sensor grid after the test.

The foundation was concreted directly against the partially saturated sand under 1*g* with the sensor grid inserted between soil and concrete. The grid was coated with spray adhesive (3M Display Mount) and a thin layer of Perth sand to ensure sufficient roughness between grid foil and soil and good bonding between foil and concrete. The sand was re-saturated after the concrete had cured. Finally, a pushover test was carried out under 30*g*, in which the mast was loaded at a constant horizontal velocity of 0.05 mm/s.

The sensor grid's positioning was selected to enable the measurement of changes in earth pressure as the load *P* increases.

NAIL: This research project investigated the load-bearing behaviour of anchored excavation pit closures at the TU Delft geotechnical centrifuge (Allersma, 1994). Tests were conducted in dry Geba sand (Maghsoudloo et al., 2018) at 60*g*. The original plan was to apply the grid to the excavation pit closure. However, the data presented here only refer to the installation shown in Figure 2. The grid was positioned horizontally and not coated with adhesive and sand in this installation. After being carefully placed at the desired level, the grid was buried in sand using dry pluviation.

Approximately one minute after the model reached 60*g*, a push-down load *P* was applied at a speed of 0.01 mm/s. *TPS* 1 to 4 were located near the strongbox wall, while *TPS* 18 to 23 were closer to the load *P*. The 127 mm of soil coverage in the model corresponds to a vertical load on the sensor of σ_v = 105 kPa at 60*g*. In theory, all sensors should indicate this stress once the *g*-level is reached, before stresses increase as a result of *P*.

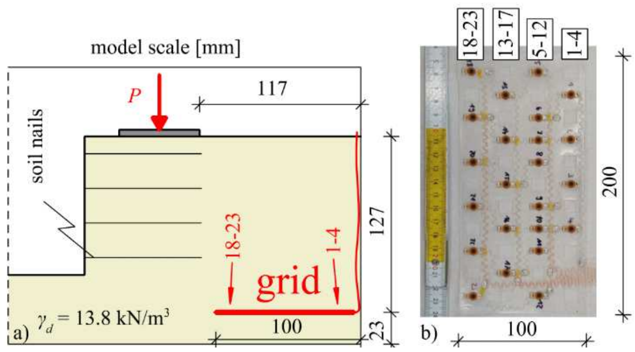

Figure 2: NAIL: (a) Test setup in model scale and (b) sensor grid.

3 FIRST RESULTS

BLOCK: The readings from *TPS* 3-6 & 9-12 cannot be meaningfully evaluated, as they either did not register any pressure (*TPS* 6, 9, 10 & 11) or the measured values for *TPS* 3, 4, 5 & 12, which are between 0 and 35 kPa, show abrupt changes and noise.

The measurement results of the lower four *TPS* (1, 2, 7 & 8) over time are shown in Figure 3. The pushover load *P* from the model-scale test is plotted on the second *y*-axis over time to enable a clearer understanding of how the stresses measured by the *TPS* develop over time. The centrifuge reaches 30*g* at approximately -600 s, after which the displacement-controlled pushover test begins at t = 0 s (increase in load *P*). Finally, the mast/foundation is unloaded at t = 1500 s.

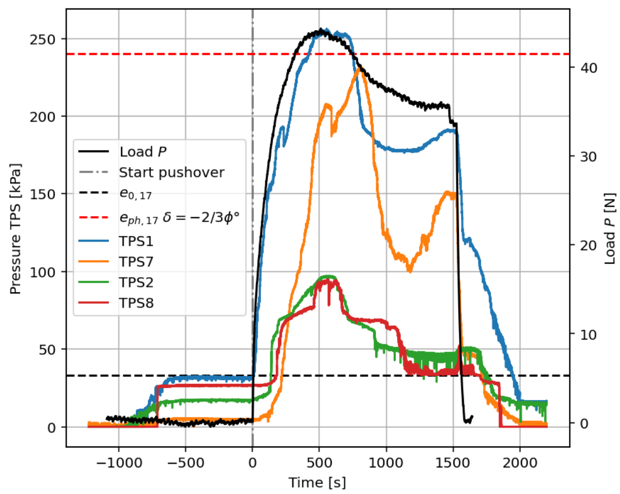

Figure 3: TPS measurement over time from the BLOCK experiment.

Comparing the behaviour of the *TPS* with the pushover load over time, the following can be noted:

- The *TPS* generally exhibit a similar behaviour to the pushover load *P*, increasing from approximately 0 to 500 s, followed by a kind of softening or load reduction.
- Start of pushover test: Only *TPS* 1 reacts directly to the increase in load. *TPS* 7 shows a significant delay compared to *TPS* 1. *TPS* 2 and 8 also react with a lag, but this may be due to the sensors being located further up, meaning they start to build up pressure later (depending on the axis of rotation of the *BF*).
- Peak load: The maximum pushover load P is reached at approximately 500 s. In particular *TPS* 7 shows a significant time delay.
- End of test: *TPS* 1 and 7 respond directly to the decrease in *P* at 1500 s. Notably, *TPS* 1 shows a reduction of approximately 60 kPa, while *TPS* 7 shows a reduction of 100 kPa. Since no rotation relative to the mast axis was detected, this difference cannot be directly explained by the test setup. With only the recordings from *TPS* 2 and 8 available, it would not be possible to determine the end of the test (unloading *P*), as they did not seem to respond directly to the load change. Between 1600 and 2000 s, the centrifuge was stopped, which explains the linear decrease of *TPS* 1 and 7.

In order to enhance the evaluation of the measurement results with respect to magnitude, the total horizontal earth pressures *e* for the lower sensor level (*TPS*1 & 7 with z = 71.9 mm) are calculated and displayed in Figure 3:

$$e(z) = N\, z\, (K \cdot \gamma' + \gamma_w) \tag{1}$$

where: N = 30 (see Table 1), K is the corresponding earth pressure coefficient, γ' is the effective bulk density of the soil under buoyancy, and γ_w is the density of water. The earth pressure at rest is estimated using the approach described by Jacky (1944):

$$K_0 = 1 - \sin\, \varphi' \tag{2}$$

Using Equations 1 and 2, along with the values given in Figure 1, the total earth pressure at rest e_0 is calculated to be 32.9 kPa. Comparing this calculated value with the measured data shows that *TPS* 1 exactly matches e_0 before the pushover test (from -600 to 0 s). However, *TPS* 7 measures a lower value, even though this sensor is at the same depth.

In a next step, the total horizontal passive earth pressure is calculated with K_{ph} according to Coulomb's earth pressure theory (e.g., Lang et al., 2004), whereby δ = -2/3 φ' is assumed as a first approximation for the wall friction of the *BF* (the foil was coated with sand as mentioned before):

$$K_{ph} = \left[\frac{\cos\varphi'}{1-\left(\frac{\sin(\varphi'-\delta)\sin\varphi'}{\cos\delta}\right)^{1/2}}\right]^2 \tag{3}$$

With K_{ph} = 5.74 and Equation (1), the total horizontal earth pressure is e_{ph} = 152 kPa. However, this value applies to the plane case (infinitely long foundation). In order to account for spatial effects that increase the passive earth pressure, the approach of Weissenbach (1962) is chosen, which determines an imaginary pressure wall width b_{id} depending on the embedment depth T, the foundation width B and the friction angle of the soil φ'. From the ratio b_{id} to B, a factor λ can be deduced by which K_{ph} is increased:

$$\lambda = \frac{b_{id}}{B} = \frac{B + 0.6 \cdot T \cdot \tan\varphi}{B} \tag{4}$$

For the given geometry, λ = 1.68, which yields a spatial earth resistance coefficient of $K_{ph,R}$ = 9.62, and according to Equation 1 an earth pressure e_{ph} = 240 kPa. Comparing the calculated earth pressures with the measurements of *TPS* 1 & 7, the following can be noted:

- The measured earth pressures appear plausible in terms of magnitude. It seems that the passive earth resistance is mobilised in the lower part of the block foundation due to the load change *P*.
- However, a clear difference is evident between *TPS* 1 & 7. The discrepancy in the measured earth pressure corresponds approximately to the

earth pressure at rest (*TPS* 7 does not measure any pressure at the beginning of the test).

- In contrast, *TPS* 2 & 8 exhibit very similar behaviour, with the measured peak load being almost identical.

NAIL: The *TPS* measurements over time from the experiment are shown in Figure 4. From 0 to 137 s, the centrifuge accelerates to 60*g* (red vertical line). The load *P* is increased 77 s later (blue vertical line). The experiment's end was not recorded due to a problem with local memory. All *TPS* measurements should display a stress of σ_v = 105 kPa when 60*g* is reached, as described in section 2. The stresses should begin to increase thereafter gradually due to increasing *P* (after 214 s).

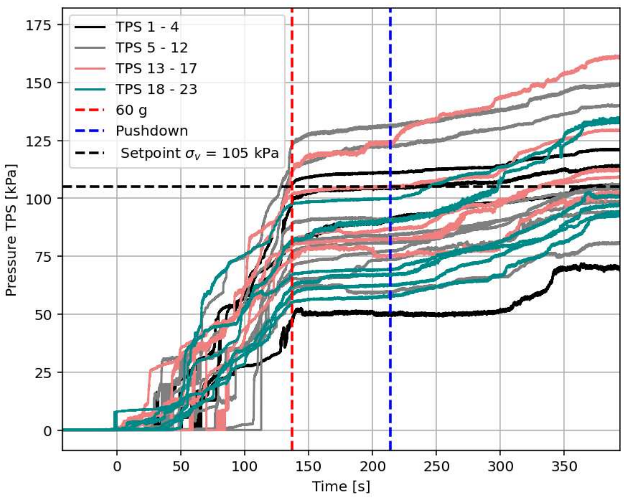

Figure 4: TPS measurement over time from the NAIL experiment.

An examination of the development of the *TPS* measurements over time reveals the following:

- Acceleration to 60*g*: All *TPS* should experience a similar increase in load as a result of the increase in the *g*-field. However, some sensors show an increase in load from 0 s, while others start at 110 s. This clearly indicates that individual *TPS* start to output a measured value above an arbitrary load level, whereby the load increase then occurs abruptly.
- 60*g* reached: Based on the measurement data, the point at which 60*g* is reached can be determined relatively accurately, as all curves show a kink at this point. Once 60*g* has been reached and before the load is increased, all *TPS* should display a constant measured value. However, this is not the case: some *TPS* show an increase in load and others show a decrease, which cannot be explained by the test setup. The deviation is significant based on the setpoint σ_v, which is only measured by two *TPS*. It amounts to 75 kPa (ranging from -55 to +20 kPa compared to σ_v resulting in a Mean Absolute Error *MAE* of 25 kPa). 75% of all *TPS* measure a value that is too low.
- Pushdown: Most *TPS* show an increase in load, with those at the same distance from the pushdown load *P* doing so in a similar manner. *TPS* 1–4, which are further away from the load plate than *TPS* 18–23 (see Figure 2), tend to show a later and less pronounced increase in load, which can be considered a plausible result due to load distribution.

4 CONCLUSIONS

It can be concluded that using the tested *TPS* may be adaptable to be further included into centrifuge model testing. Advantages include the flexible arrangement of the individual *TPS* in grids, their water resistance and their low sensitivity to the effects of grain size distributions commonly used in centrifuge tests (little to none influence for $d_{max} < 2$ mm according to Schleicher et al., 2025).

However, there are several findings which may be considered for further development of the *TPS* sensors:

- Small stresses (approximately 0 to 50 kPa, depending on the test) cannot be reliably detected.
- Each *TPS* appears to have an individual threshold value below which no stress changes are registered, which must be determined beforehand future testing, to take this effect into account.
- The *TPS* show a high scatter of measured values despite prior calibration. This is most likely due to limits in calibration or the need to calibrate the sensors with the material used, as the qualitative measurements seem to be logical. Further research is necessary.
- In some cases, individual *TPS* also exhibit a time lag that cannot be explained by the test procedure.

In summary, it can be concluded that the *TPS* can be used to measure pressures in centrifuge model testing, presupposing a further optimisation including hardware, preparation, calibration and handling.

ACKNOWLEDGEMENTS

The authors are grateful for the support of ETH Zurich and TU Delft (Prof. Miguel Cabrera) as well as for the financial support provided by “Allianz Fahrweg”, the Swiss Federal Office of Transport (*FOT*) and the Swiss Public Transport Association (*VOEV*) for the

BLOCK experiments and the contractor company Ghelma AG Spezialtiefbau for the NAIL experiments. The authors thank Angelo Botrugno for the opportunity to evaluate the sensors in the test setup (NAIL) he developed in the framework of his MSc-thesis. The development and adaptation of the *TPS* used is part of the research project SG4SSI (Sensor Grid for Soil-Structure Interaction) funded by the Austrian Research Promotion Agency (FFG).

REFERENCES

Allersma, H.G.B. (1994). *The University of Delft geotechnical centrifuge.* Int. Conf. Centrifuge 94. Balkema, Rotterdam: 47-52

Arnold, A., Herzog, R., Portmann, G. & Anastasopoulos, I. 2024. Block foundations for railway infrastructure – First centrifuge model tests. *Proc. of the 5th European Conference on Physical Modelling in Geotechnics*, Delft. https://doi.org/10.53243/ECPMG2024-7

Jaky, J. (1944). Coefficient of Earth Pressure at Rest. *Journal of the Society of Hungarian Architects and Engineering*, *78*(22), Article 22.

Lang, H.-J., Huder, J., Amann, P., & Puzrin, A. M. (2011). *Bodenmechanik und Grundbau: Das Verhalten von Böden und Fels und die wichtigsten grundbaulichen Konzepte, Soil mechanics and foundation engineering: The behaviour of soils and rock and the most important foundation engineering concepts* [in german], (9th edition). Berlin: Springer.

Madabhushi, G. (2014). *Centrifuge modelling for civil engineers*. Boca Raton: Taylor & Francis

Maghsoudloo, A., Askarinejad, A., De Jager, R. R., Molenkamp, F., & Hicks, M. A. (2018). Experimental investigation of pore pressure and acceleration development in static liquefaction induced failures in submerged slopes. In *Physical Modelling in Geotechnics, Volume 2* (pp. 987-992). CRC Press.

Nater, P. (2006). *Belastungs- und Verformungsverhalten von geschichteten Bodensystemen unter starren Kreisfundationen, Load-bearing capacity and deformation behaviour of layered soil systems under rigid circular foundations* [in german]. PhD thesis, ETH Zurich. https://doi.org/10.3929/ethz-a-005166336

Rebhan, M., Schleicher, J., Daxer, H-P. Tschuchnigg, F., Wirthl, D. & Arnold, A. (2024). SG4SSI Sensor Grid 4 Soil-Structure-Interaction (in german). In *VÖBU-Forum,* Association of Austrian Drilling, Well Construction and Special Foundation Engineering Companies (VÖBU), T. Pirkner (ed.), Issue 55, June 2024, pp. 22 – 24. Vienna, Austria: VÖBU.

Schleicher, J., Rebhan, M.J., Daxer, HP., Pamminger, V., Arnold, A., Tschuchnigg, F. (2025). Tactile Pressure Sensors to analyse Anchor Wall Behaviour in mid-scale Experiments. *Proc. of the 13th International Conference on Structural Health Monitoring of Intelligent Infrastructure*, Graz. http://dx.doi.org/10.3217/978-3-99161-057-1

Schofield, A.N. (1980). *Cambridge geotechnical centrifuge operations.* Géotechnique 20(1) 227-268.

Weissenbach, A. (1962). Der Erdwiderstand von schmalen Druckflächen, the earth resistance of narrow contact surfaces [in german]. *Die Bautechnik, 37*(6), 204-211