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Settlement behaviour of peat underneath a sand and sawdust embankment: centrifuge modelling

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ABSTRACT: Peat soils, when impacted by external loads, compress and experience settlement. Infrastructure such as roads founded on peat may suffer serviceability issues when settlement predictions are incorrect. Nevertheless, most predictions build on results from laboratory tests on small samples which could be misleading. Using the results of three identical, plane-strain centrifuge tests, this paper examines the settlement behaviour of a natural peat layer of 7.5 m thickness in prototype scale during construction of a 1 m high sand and 1 m high sawdust embankment. The embankment loading was replicated by increasing the centrifuge acceleration level to 50 times gravity. Measured pore pressure changes and peat deformations, obtained by image-based deformation techniques, indicate that the fibrous peat was very permeable and that laboratory-based settlement predictions were overly conservative. The settlement patterns observed in the three tests agreed well, but the heterogeneity of the natural peat samples affected the magnitude of the measured displacements. A comparison to full-scale field tests suggests that the centrifuge tests captured the prototype performance well.

1 INTRODUCTION

Peatlands store large amounts of carbon dioxide. Replacing peat soils by granular materials or draining peat to develop infrastructure, such as roads, is thus no longer accepted. Although several examples of constructing directly on peat exist, assessing the response of peat to applied loads remains a concern.

A potential sustainable solution to develop low trafficked roads on peatlands is the combination of locally sourced sand and sawdust to form the road embankment. The design of such embankments relies on the sawdust layer settling beneath the water table to remain its condition. Results from 60-year-old full-scale field tests of such sand and sawdust embankments on two different peats showed promising results (i.e., well preserved 57- to 58-year-old sawdust), but unexpectedly high dissipation of the pore water pressure was measured during the embankment construction (Gautschi, 1967; Long et al., 2023). There remains uncertainty if settlement predictions from standard laboratory tests on small samples reliably describe the peat behaviour underneath embankments. This implies that in practice uncertainty still exists about the required thicknesses of the sand and sawdust layers.

This paper presents a centrifuge test series which investigated the interaction between a natural peat and a sand and sawdust embankment. The full scope of these experiments included also to study failure mechanism in the peat during external loading and cone penetration tests with pore water pressure measurement (CPTu). However, due to length constrictions this paper focuses on settlements due to embankment construction only. The next section describes the peat used and the adopted experimental setup. Subsequently, the experimental results are presented and compared to settlement predictions and field trials. Finally, key findings are listed.

2 EXPERIMENTAL SETUP

Three geotechnical centrifuge tests were performed at Deltares to study the settlement behaviour of a natural peat underneath a sand and sawdust embankment. Figure 1 shows the centrifuge model. The layout of each test was kept identical to isolate the effect of the heterogeneity of the natural peat. In addition to the instrumentation shown in Figure 1, two digital cameras (L-VIT 2500) were used to obtain images of the peat, sand, and sawdust layers. The digital image correlation (DIC) software GeoPIV-RG (Stanier et al., 2015) was used to calculate soil displacements.

Block samples of natural peat were obtained close to the Norwegian Geo-Test Site Tiller-Flotten for quick clay (L'Heureux et al., 2019). The sampling followed the procedure described in ISSMFE (1981). First, the topsoil was carefully removed using an excavator. Second, a wooden template and a serrated knife were used to cut block samples with dimensions of 930 x 280 x 215 mm (length x width x height). Third, the samples were sealed using cling film. Finally, pre-made wooden boxes were used to transport the samples to The Netherlands.

Table 1 lists the main properties of the peat block samples used which are representative of typical Norwegian peats. The water contents were determined when preparing the peat model using excess peat material. Throughout the block sampling and sample preparation, water drained from the peat samples. For this reason, the reported water contents must be interpreted with caution. The parameters initial void ratio, e_0, constrained modulus, M_0, yield (or preconsolidation) stress, p_{vy}', and Janbu's modulus number, m, were derived from oedometer tests carried out on Tiller-Flotten peat and supported by the database of results for Trondheim peat (Paniagua et al., 2021; Long et al., 2022). These mechanical properties of the peat provide the basis for the subsequent settlement predictions.

Table 1. Peat samples properties.

Peat property	**Test A**	**Test B**	**Test C**
Water content, w (%)	788	1137	639
Density, ρ_p (Mg/m^3)		1.05*	
Loss on ignition, LOI (%)		95-98*	
von Post H** (-)	3	4	3-4
Initial void ratio, e_0 (-)	11.8	17.1	9.6
Constrained modulus, M_0 (kPa)	150	110	175
Yield stress, p_{vy}' (kPa)	9.5	7	11
Janbu's modulus number, m	6	5	7

*Typical values for the Tiller-Flotten peat
** H = degree of decomposition (1-10).

The model preparation included the installation of the pore pressure sensors in the back plate of the strong box (Figure 1). While preparing the peat model, the pore pressure sensors were kept saturated using a sponge. The peat samples were carefully taken out of the wooden boxes and cut to the required dimensions using steel plates and clamps for guidance. Throughout this sample trimming process, it was ensured that the in-situ vertical orientation of each sample was maintained. After a peat sample was placed in the strongbox, the front face of the peat was artificially seeded using yellow modelling flock. This procedure increased the natural texture of the peat to improve the precision of the DIC.

Baskarp B25 sand (Ibsen and Bødker, 1994;) and a sawdust supplied by Moelven, Norway, were used to form the embankment. Bjertness and Sponås (2021) conducted a detailed laboratory investigation on the used sawdust ("SdMn" in Bjertness and Sponås (2021)). The sawdust was sieved using a 4 mm sieve. Subsequently, approximately 30% of the sawdust was coloured using black textile colour to add artificial texture. The same artificial seeding was carried out for the sand. Wooden moulds were used to build the embankment on top of the peat. The moist sawdust and sand were compacted by hand. Table 2 lists the obtained densities.

Table 2. Densities of the sand and sawdust embankments.

Embankment densities	**Test A**	**Test B**	**Test C**	**Mean**
Sand, ρ_s (Mg/m^3)	1.68	1.77	1.79	1.75
Sawdust, ρ_{SdMn} (Mg/m^3)	0.26	0.23	0.31	0.27

All tests were performed at a final centrifuge acceleration level, N, of 50 times gravity, g. The spin-up phase replicated the loading of the peat during the embankment construction and was conducted in $N = 10$ g increments. At each 10 g increment, the remaining excess pore pressures were evaluated based on the pore pressure measurement. Spin-up was continued when the pore pressure values remained almost stable. Throughout a test, the water level was kept coincident with the peat surface using a water level control and drainage system.

3 EXPERIMENTAL RESULTS

Figure 2 shows the LVDT measurements at the different 10 g increments for Test A. As expected, the vertical displacements increased with the centrifuge acceleration level and the LVDT closest to the embankment boundary (i.e., LVDT1) typically showed the largest vertical displacements. With distance from the embankment centreline, the

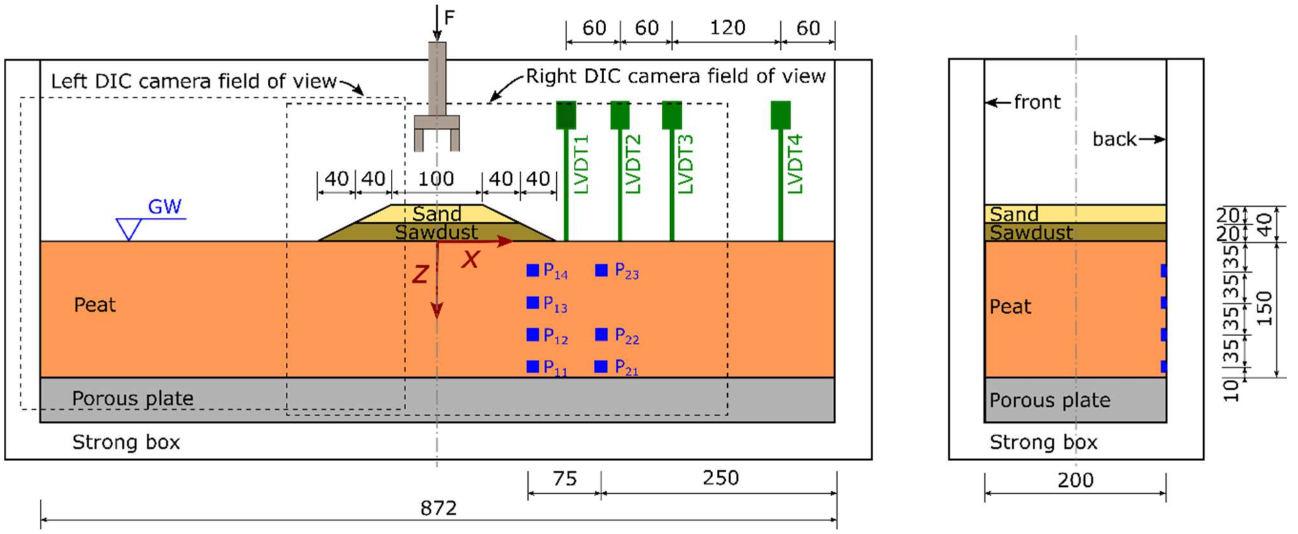

Figure 1. Centrifuge model: F = load cell, LVDT = linear variable differential transformers with footings (diameter of 40 mm) and P = pore pressure transducers. Dimensions in mm and model scale.

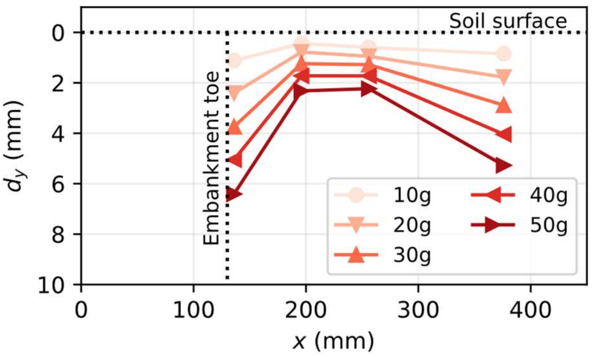

Figure 2. Vertical displacement, d_y, profiles during spin-up of test A measured with linear variable differential transformers (LVDTs). x = 0 corresponds to the embankment centre.

vertical displacements generally reduced. Surprisingly, the LVDT closest to the right boundary of the peat model (i.e., LVDT4) measured considerably larger displacements. Considerable tracks of the LVDT footings into the peat surface were observed after each test. This observation indicates that the LVDT measurements likely overestimated the peat displacements.

The pore water pressures measured by the sensors P_{11} to P_{14} (Figure 1) were plotted during the spin-up and consolidation phase in Figure 3. For comparison, the theoretical, hydrostatic values are shown for each sensor position. The measured pore water pressures were in good agreement with the hydrostatice ones.

Figure 4 provides the change of pore water pressure measured by P_{11} after reaching a centrifuge acceleration level of 50 g. The x-axis shows a normalised time, $t_{n,50g}$, which is the ratio between the time after reaching 50 g and the total time at 50 g, to better compare the different tests.

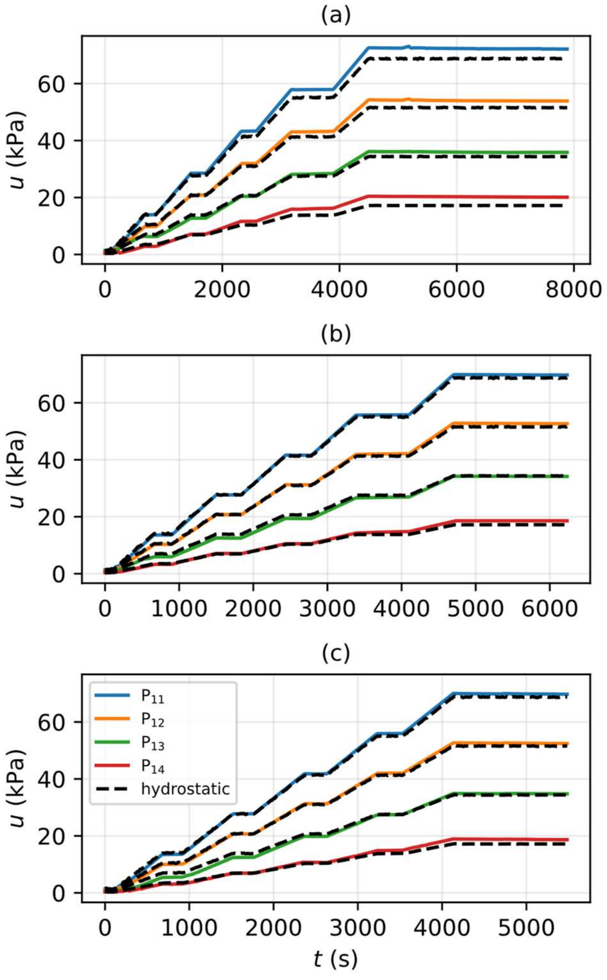

Figure 3. Pore water pressure, u, versus spin-up time, t: (a) test A, (b) test B and (c) test C.

From Figure 4 it can be seen that small changes in pore water pressures (< ±0.5 kPa for a period exceeding 15 min) were measured. These data suggest that small excess pore water pressures were generated. In other words, the peat samples were very permeable. Similar findings were reported by Mesri and Ajlouni (2007) for fibrous peat and in the field trials (Long et al., 2023), which inspired this work.

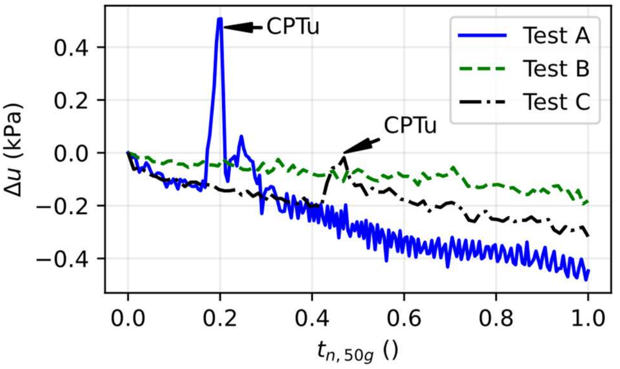

Figure 4. Change of pore water pressures, Δu, measured by pore pressure sensor P11 at a centrifugal acceleration level of N = 50. $t_{n,50g}$ *is the time for each test after reaching N = 50 normalised with the total time at N = 50. The peaks relate to carried out cone penetration tests (CPTu).*

The displacements in the sawdust and peat layers after reaching a centrifuge acceleration level of 50 g are presented in Figure 5. For the sand layer, reliable DIC data could not be obtained due to insufficient texture. This limitation is likely a result of the moist sand which counteracted the artificial seeding.

Figure 5 indicates that the displacements were predominantly vertical. The horizontal displacements were less than 2.5 mm (12.5 cm in prototype scale) and point from the centreline of the embankment. The measured horizontal displacements imply that the strains below the embankment were not one-dimensional. The plotted vertical displacement contours (Figure 5, right) indicate that considerable settlements (> 0.5 mm) were confined to the area beneath the embankment. These settlements reached a depth of about 100 mm (5.0 m in prototype scale) below the peat surface.

The lines of equal settlements show that the maximum settlements are typically close to the centreline of the embankment. The data reveal that the sawdust layer did not experience sufficient vertical displacements (i.e., 20 mm) to settle beneath the water level. Only for tests B and C, settlements close to this 20 mm threshold were reached at the embankment centre. With distance from the embankment centre substantially smaller settlements were observed. This implies that the design criteria was not met and that future designs should consider embankments with thicker sand layers.

Considerable heave movements at the toe of the embankment were not measured. A comparison with the LVDT data (Figure 2) shows that the DIC measurements were considerable smaller than the LVDT ones. The difference can be explained by the LVDT footings settling into the peat surface.

Different displacement magnitudes were obtained for the three tests (Figures 5 and 6). Notably smaller displacements occurred for Test A, while the displacements of Tests B and C matched well. The different water contents measured for the peat samples (Table 1) cannot completely explain these differences. Likewise, the small difference in the von Post H value (Table 1) cannot clarify these displacement differences. A potential explanation may be the inherent heterogenity of natural peat.

Figure 6 provides vertical displacements at the centre of the sawdust layer and the peat surface as a function of the centrifuge acceleration level. Interestingly, the vertical displacements notably increased at constant G-levels. These time-dependent settlements are a surprising observation considering the small excess pore pressures measured (Figure 4) and may be attributed to long-term creep settlements.

Creep and creep time scaling laws in geotechnical centrifuge modelling have been addressed in literature (e.g., Kutter (1995), Garnier et al. (2007)), but remain controversial. It remains unknown how the modelled periods of constant 10 g increments relate to prototype time. In other words, one must be cautious when comparing the final settlements obtained in the centrifuge tests with long-term settlements measured in the field. Further study is required to investigate how the settlements measured in the centrifuge relate to creep behaviour of peat.

Figure 6 compares measured and predicted settlements of the peat surface. The predictions are based on hand calculations according to the method by Janbu (1970). For the settlement predictions, the strains, ε_{oc}, for stresses up to p_{vy}' were determined using

$$\varepsilon_{oc} = M_0\left(p'_{vy} - \sigma'_{v0}\right) \tag{1}$$

where σ_{v0}' is the in situ vertical effective stress. The strains in the normally consolidated range, ε_{nc}, were estimated according to

$$\varepsilon_{nc} = \frac{1}{m} ln\left(\frac{p'_{vy}+\Delta\sigma}{p'_{vy}}\right) \tag{2}$$

where $\Delta\sigma$ is the stress increase above p_{vy}'. Only the settlement predictions for the peat samples with the highest (i.e., Test B = upper bound estimate) and lowest water content (i.e., Test C = lower bound estimate) are shown. The data in Figure 6b suggests that the hand calculations are overly conservative.

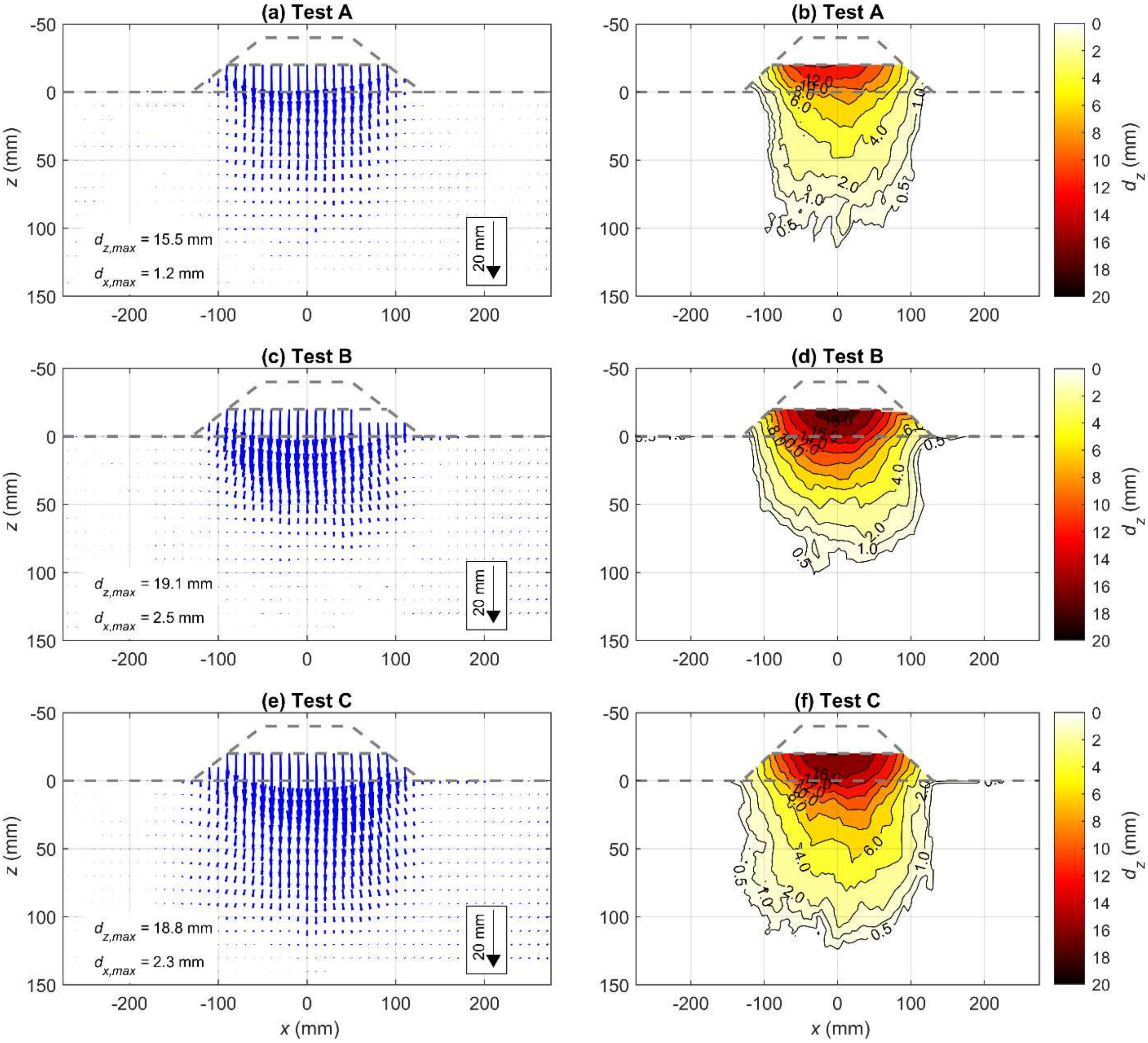

Figure 5. Displacement vectors (left column) and vertical displacement contours (right column) after reaching a centrifuge acceleration level of 50. Dimensions in model scale.

A comparison to field data of similar embankments (Long et al., 2023) is given in Figure 6b. The two provided trial embankments differ in the thickness of the constructed sand and sawdust layers, but the beneath peat has similar characteristics compared to the peat used in the centrifuge tests. The field site (i.e., Site 1 in Long et al. (2023)) is characterized by three peat layers with average water contents between 1000 to 1675% and average von Post H values of about 3. Embankment I had an initial sand and sawdust thicknesses of about 0.7 and 1.0 m, respectively. Embankment II at Site 1 was constructed with sand and sawdust thicknesses of about 1.3 and 1.2 m, respectively. In situ densities of 1.8 and 0.6 Mg/m^3 were measured for the sand and sawdust layers.

Figure 6b shows that the tests B and C compare reasonably well with the reported settlements for the embankment I at Site 1. This field trial is most similar to the scenario modelled in the laboratory (i.e., peat with von Post H value of about 3 and similar sand and sawdust thicknesses). As expected, the higher embankment II resulted in settlements exceeding the experiment results.

4 CONCLUSIONS

The settlement behaviour of fibrous peat beneath a sand and sawdust embankment was investigated using centrifuge tests. Some findings from this work are:

- The magnitude of the peat displacements varied for the three tests. This difference may be due to the inherent heterogeneity of the used natural block samples. Nevertheless, the displacement patterns observed for the three tests agreed well.
- Measured settlements were lower than the design

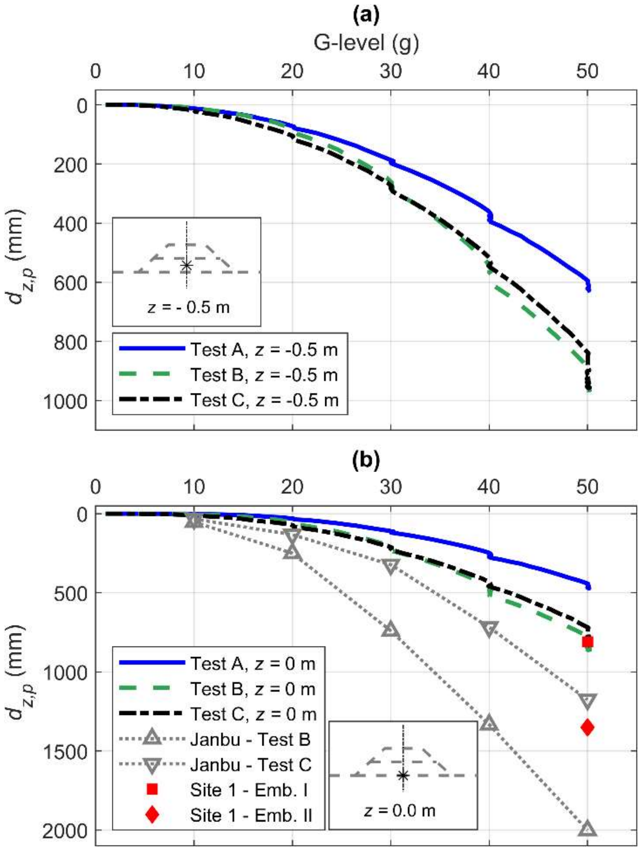

Figure 6. Prototype vertical displacements, $d_{z,p}$, at the embankment centre and at (a) the sawdust centre and (b) the peat surface. Settlement predictions (Janbu, 1970) and data from trial embankments (Long et al. 2023) are given.

criteria. This implies that the sawdust layer was not entirely submerged below the water table; thus, the sawdust condition cannot be preserved with time. The thickness of the sand layer may be increased in practice to overcome this issue.

- A comparison with settlement predictions based on laboratory data suggests that these predictions are very conservative. However, field trials of similar sand and sawdust embankments showed similar performance as the centrifuge tests.
- A high dissipation of excess pore water pressures was observed; the used fibrous peat was very permeable. This finding matches field data (Long et al., 2023) and reported behaviour of fibrous peat (Mesri and Ajlouni, 2007).

Future work will study the performance of the sand and sawdust embankments during traffic loading. In addition, the experimental data will be explored to validate numerical modelling. These combined activities will further evaluate if embankments formed by sand and sawdust layers form a low-cost, sustainable solution to build on peatlands.

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