

Predicted and Measured Settlement of Peat Loaded by a Reservoir

T.L. Smith, C.D. Gilbert & J.A. Masigan

Riley Consultants Ltd, Christchurch.

ABSTRACT

Te Waihekeora Water Storage Reservoir, completed in 2024, stores 3.2M m³ of water within a 43 Hectare geomembrane lined basin located 15km south of Dargaville. The site topography is dominated by dune formations of the Kariotahi Group, with recent organic deposits infilling valley sections. The adopted design solution involved installation of a high-density polyethylene (HDPE) liner over natural soils, which included organic deposits up to 12m deep, with only nominal surface preparation. To support the assessment of liner deformations due to reservoir loading, a range of tests were undertaken including in-situ and laboratory techniques. Upon completion of construction, high-resolution bathometric surveys have been undertaken at prescribed reservoir levels. The comparison of available settlement prediction techniques with measured deformations over an extended area provides a range of insights around their applicability and accuracy. Derived settlement coefficients are presented, which may be of interest to those working with similar ground conditions.

1 INTRODUCTION

The Te Waihekeora Reservoir, located 15km south of Dargaville, provides 3.2M m³ of water storage for the Kaipara Water Scheme. The reservoir is designed to support up to 1100 Ha of new horticultural development on the Poutō Peninsula. One high potential impact classification (PIC) dam and four low PIC dams were built to form the reservoir, with a maximum retained height of 11m.

The work was commissioned by the Te Tai Tokerau Water Trust, which has the objective to develop water schemes to enable the establishment of commercially viable and environmentally sustainable horticulture, providing economic and employment opportunities in the region. The Trust has received funding assistance from Kānoa - Regional Economic Development & Investment Unit - the Northland Regional Council and Far North District Council.

2 GROUND MODEL

The dunes of the North Kaipara Barrier that dominate the topography and geology of the area are formed from sand transported by prevailing south-westerly winds, and supply of sediment from the coast. The Institute of Geological and Nuclear Sciences 1:250,000 scale geological map of the area ('Whangarei', QMAP 2, 2009) indicates three phases of dune formation in the region since the Pliocene (5.3M to 2.6M years ago), with the site being underlain predominantly by materials from the middle phase, which are referred to as Karioitahi Group Dune deposits (KGD). These deposits form fixed, parabolic dunes, comprising weakly cemented partly consolidated bedded dune sands with intercalated paleosols, lignite and mudstone and lignite of early to med Quaternary-age (0.128M to 1.8M-years old).

Additional to the KGD dune formations, Holocene (10,000 years ago to present day) deposits infill valley floor areas with alluvial, swamp and lacustrine materials, comprising unconsolidated mud, sand, gravel, and peat of recent age (<12k-years old).

All dams were founded on relatively competent in-situ KGD cemented sand. Within the reservoir area however, alluvium mostly comprised of geologically young fibrous peat was encountered up to 12m deep. The peat distribution within the reservoir area was estimated with consideration of the geomorphology of the valley, together with the results of a subsurface investigation programme. The originally estimated peat depth contours, along with the geotechnical test locations, are shown in Figure 1.

Regional groundwater level was deep, inferred to be around 40m below ground level within the KGD sand unit. Locally perched groundwater horizons were encountered within the peat, which was variably logged as moist to wet. Arising from its partially saturated state, the peat has undergone a degree of decomposition and consolidation. It was not deemed feasible or desirable to remove the peat from the reservoir area, and a design solution was developed that involved lining over this material with a minimum of surface disturbance.

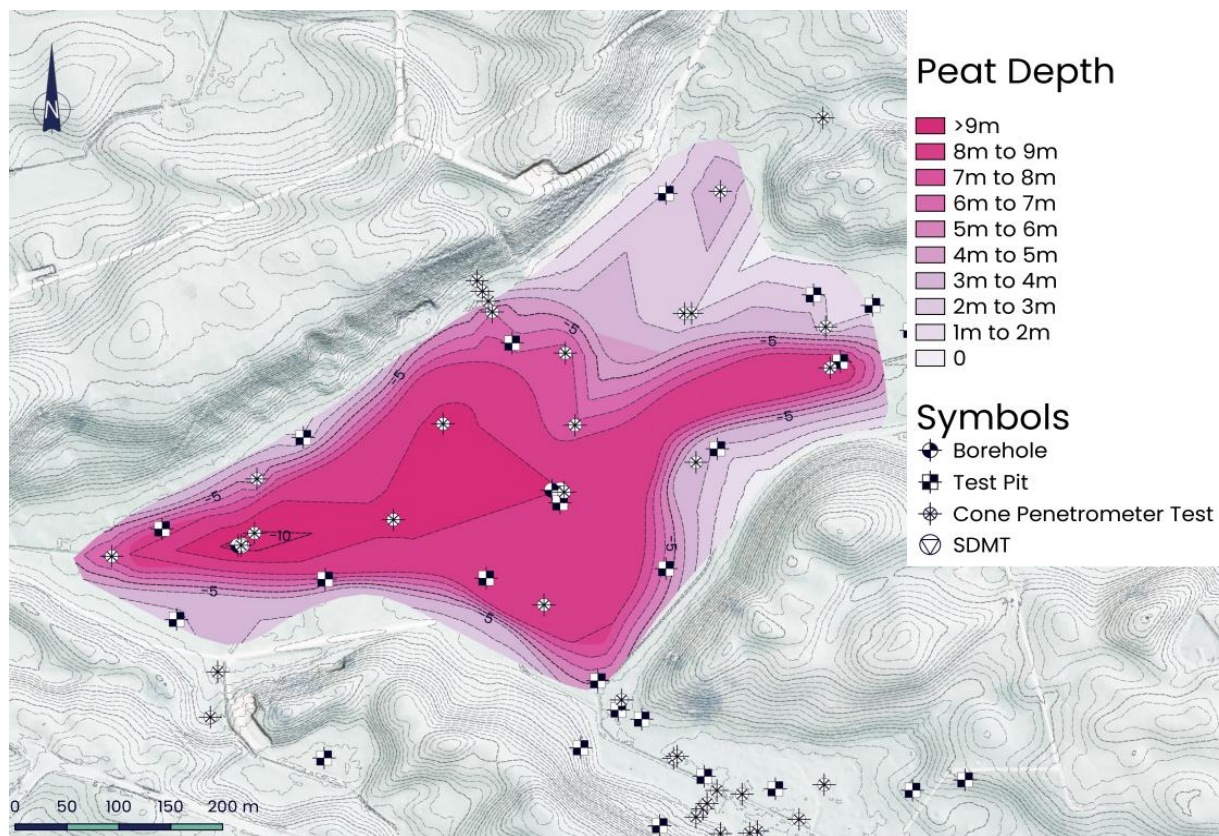


Figure 1: Investigation plan and interpreted peat depth contours

3 PEAT ALLUVIUM - TESTING AND PROPERTIES

To support assessments of the necessary strength, flexibility and durability of the lining system, a programme of in-situ and laboratory testing was undertaken. In-situ tests targeted at estimating ground deformations included Cone Penetration Tests (CPTu) and Dilatometer Tests (DMT). A suite of laboratory tests was completed including oedometer tests undertaken from push tube samples taken at various depths within four machine boreholes. To facilitate comparison with other sites, relevant index results are summarised in Table 1. In addition, two preload pads were constructed and monitored within the reservoir area.

Table 1: Summary of index testing for Holocene Peat Alluvium encountered on site

Test	Unit	No. of Tests	Min	Max	Mean
Natural Moisture Content	%	7	212	395	292
Organic Matter Content	%	7	55	85	64
Dry Density	t/m ³	2	0.30	0.48	N/A
Plasticity Index	-	5	46	295	163

3.1 Coefficient of Volume Compressibility Estimates

Settlement modelling using the Coefficient of Volume Compressibility (M_v) has been adopted for this study, as it is widely used in industry, and a range of empirical relationships exist for estimating its value from different in-situ tests. Care is required in the selection of M_v values, as for a given soil, unique values of M_v apply for each initial and final effective stress combination. Values for M_v obtained from various test methods and correlations are summarised in Table 2. Note that Oedometer, CPT and DMT tests selected for presentation were conducted adjacent to the two preload pads prior to placement, where the peat was 9.5m and 10.5m deep respectively.

3.2 C_v Estimates and Secondary Consolidation

Values for coefficient of vertical compressibility (C_v), which relates to the rate of settlement, were estimated from Oedometer and preload testing. A C_v of 3.39-4.49m²/year was adopted based on Oedometer testing, and this was included for all settlement analysis cases apart from those which reference the preload. For the preload trial, C_v was back calculated to be between 90 - 300m²/year, and in this case the upper range has been modelled to give a conservative settlement total, especially when considering secondary settlement.

As the encountered peat layers are underlain by permeable sands, a persistent water table was not encountered during the investigation. Perched water tables were encountered within the peat aligning with areas of lower permeability or logs/stumps. As such measures of C_v in this instance do not relate to permeability and the ability to dissipate porewater pressure, rather this relates to a rate of consolidation.

Secondary consolidation parameters (C_α) were obtained from the extended Oedometer tests and ranged between 0.0035 and 0.026. A value of 0.02 was assumed during the assessments of the reservoir liner. For the comparisons in this paper, secondary consolidation has been ignored given the limited timeframe of load application and monitoring.

Table 2: Coefficient of Volume Compressibility (M_v) estimates by various methods

Test	Initial Effective Stress (kPa)	Low (M2/MN)	High (M2/MN)	Selected (M2/MN)
Laboratory Oedometer	50	0.4	0.9	0.7
Laboratory Oedometer	100	0.5	1.5	1.44
CPT Test ¹ (averaged over relevant length)	N/A	0.24	0.39	0.39
DMT Test (averaged over relevant length)	N/A	0.30	0.35	0.3
Preload Trial (back calculated from settlement)	N/A	0.21	0.23	0.22

4 ANALYSIS

Settlement modelling was undertaken utilising the proprietary software package Settle3 (Rocscience) to assess anticipated future settlements and assess the risk of damage to the polyethylene liner. A model was produced of the underlying peat depth, based on interpretation of subsurface investigation, and imported into Settle3 as a series of boreholes. This included inclusion of imaginary boreholes to better define the subsurface profile. The reservoir was modelled in 12D Model and water contours were produced in 0.25m increments to be imported into Settle3 (aligning with 2.5kPa increments of applied stress). For comparative purposes in this paper, load contours were limited to the actual reservoir fill height during the period of monitoring. These load contours were imported into Settle3 in a stacked manner.

For the purpose of this paper, the model was assessed in a time-dependant manner where all loads were applied at $T_0 = 0$ days. Settlement was queried at 27, 58, 93 and 195 days to align with the surveyed settlement monitoring instances. The assessed predicted settlement (preload parameters case) over the monitoring period is presented in Figure 2.

5 POST CONSTRUCTION MONITORING

As part of the reservoir commissioning procedure, regular bathymetric surveys of the liner level are required. These utilise a dingy-mounted Seafloor HydroLite Echosounder sensor linked to a GPS survey staff. The system is understood to have an accuracy of 10mm or 0.1% of depth in the vertical direction.

A series of 30 evenly spaced sections have been established across the reservoir footprint, and each section line is traversed in each survey.

Reservoir filling commenced in August 2024. The water level has been a relatively constant RL78.1m since October 2024 until the time of writing. This corresponds to a nominal water depth of around 3m in the middle of the reservoir. Full supply level is RL84.5, so the reservoir has been currently around one third of full depth during this time.

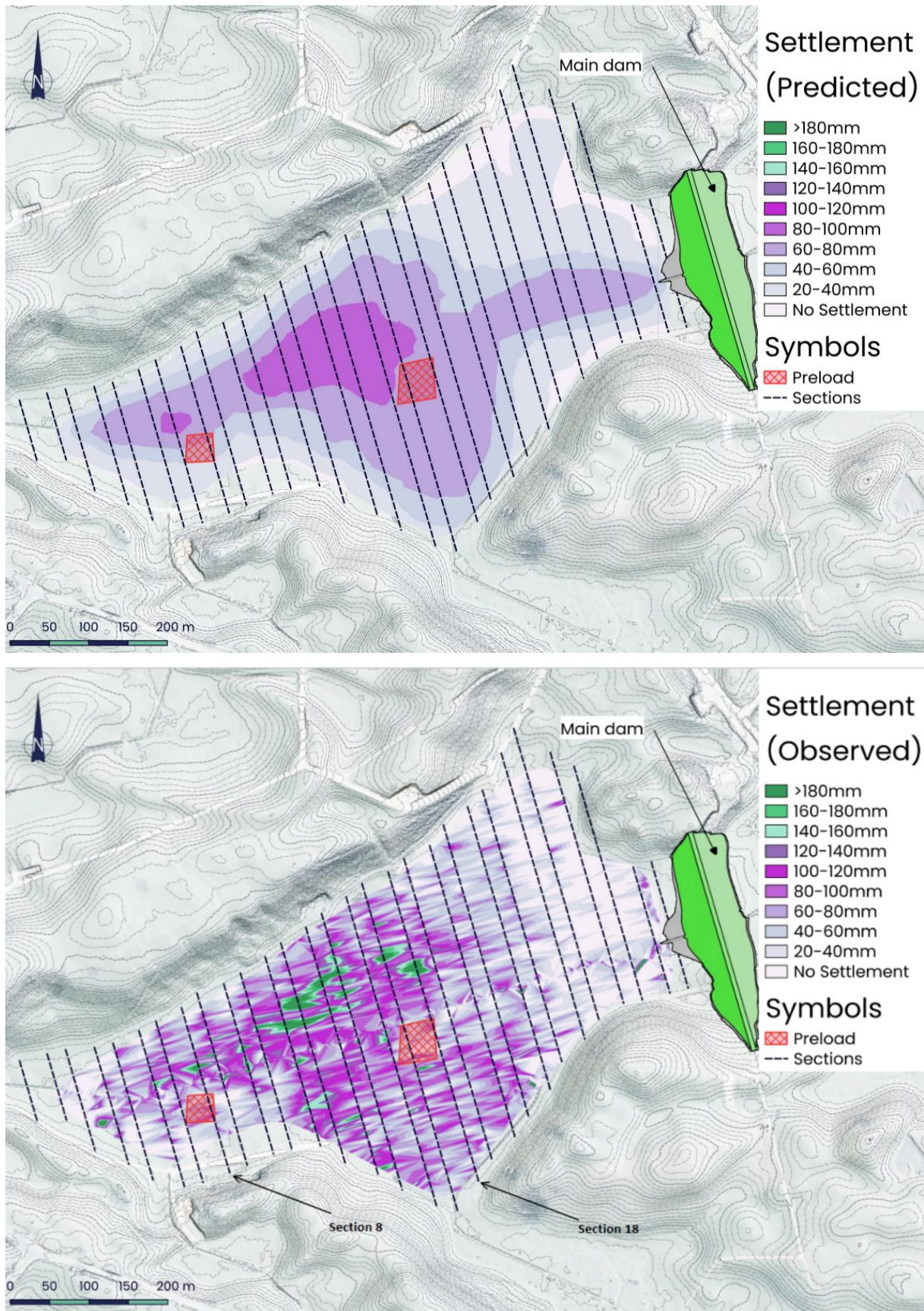


Figure 2: Predicted settlement (top) and observed settlement (bottom)

The pattern of settlement between the deformation survey of February 2025 and the as-built reservoir floor prior to filling, is shown in Figure 3. Comparing the estimated and measured surface, there is reasonable agreement on the total quantum and general pattern of settlement. The following observations are possible:

1. An infilled paleo channel was inferred in the eastern portion of the site, following the natural surface drainage pattern of the valley between two dunes and through the Main Dam site. This feature does not appear in the measured liner response.
2. While the estimated primary settlements generally resemble the magnitude and pattern of the measured values, the estimated maximum was exceeded in a small area which appears to comprise a linear feature running parallel to the toe of the prominent dune bounding the reservoir to the northwest. This is inferred to be a local deepening in the peat basin, perhaps related to an ancient progression pattern of the sand dune.

5.1 Detailed Sections

Two sections are presented in Figure 3 (section locations are as shown in Figure 2). Notable features include:

1. The location of the two preload trials can be observed in the two sections. As expected, the preloaded portion of the reservoir floor is undergoing significantly less settlement than the surrounding ground due to the prior surcharging.
2. The marked location of maximum settlement suggests that a greater depth of peat may be present locally at this location. This corresponds to the dune progression pattern suggest in the previous paragraph.
3. There is noise in the data, with some points being re-surveyed slightly higher or lower in successive surveys. This is a function of the survey approach, which relies on the boat reproducing a similar path through the reservoir each time. The boat is guided using GPS and the prescribed section lines but cannot exactly reproduce its original path. Variations are visible in the data at the relatively steep and narrow central drain, which runs northeast/southwest through the site.

6 REVIEW OF PARAMETER ESTIMATES

The reliability of the compressibility parameter estimates in this study would be expected as follows:

1. Preload trial (large scale loaded area, test loading arrangement closely matches final loading)
2. Oedometer test (direct measurement of relevant parameter in controlled laboratory conditions, at small scale)
3. DMT (in-situ test, direct measurement of compressibility, but is measured in a horizontal orientation while final loading is vertical)
4. CPT (in-situ test, indirect correlation based on tip resistance)

Assuming single values for settlement parameters across the entire site, back analysing the observed settlements on the basis of the originally inferred peat depths provided a best estimate M_v value of $0.3 \text{ m}^2/\text{MN}$, C_v of $100 \text{ m}^2/\text{year}$ and C_α of 0.001 . An overlay of monitored settlement data and back analysed settlements is shown in figure 4.

The most accurate parameter estimates were from the DMT tests, which estimated M_v to be in the range 0.3 to 0.35 . CPT tests also provided good M_v estimates against expectation, however with a wider range of values (~ 0.2 to $0.4 \text{ m}^2/\text{MN}$).

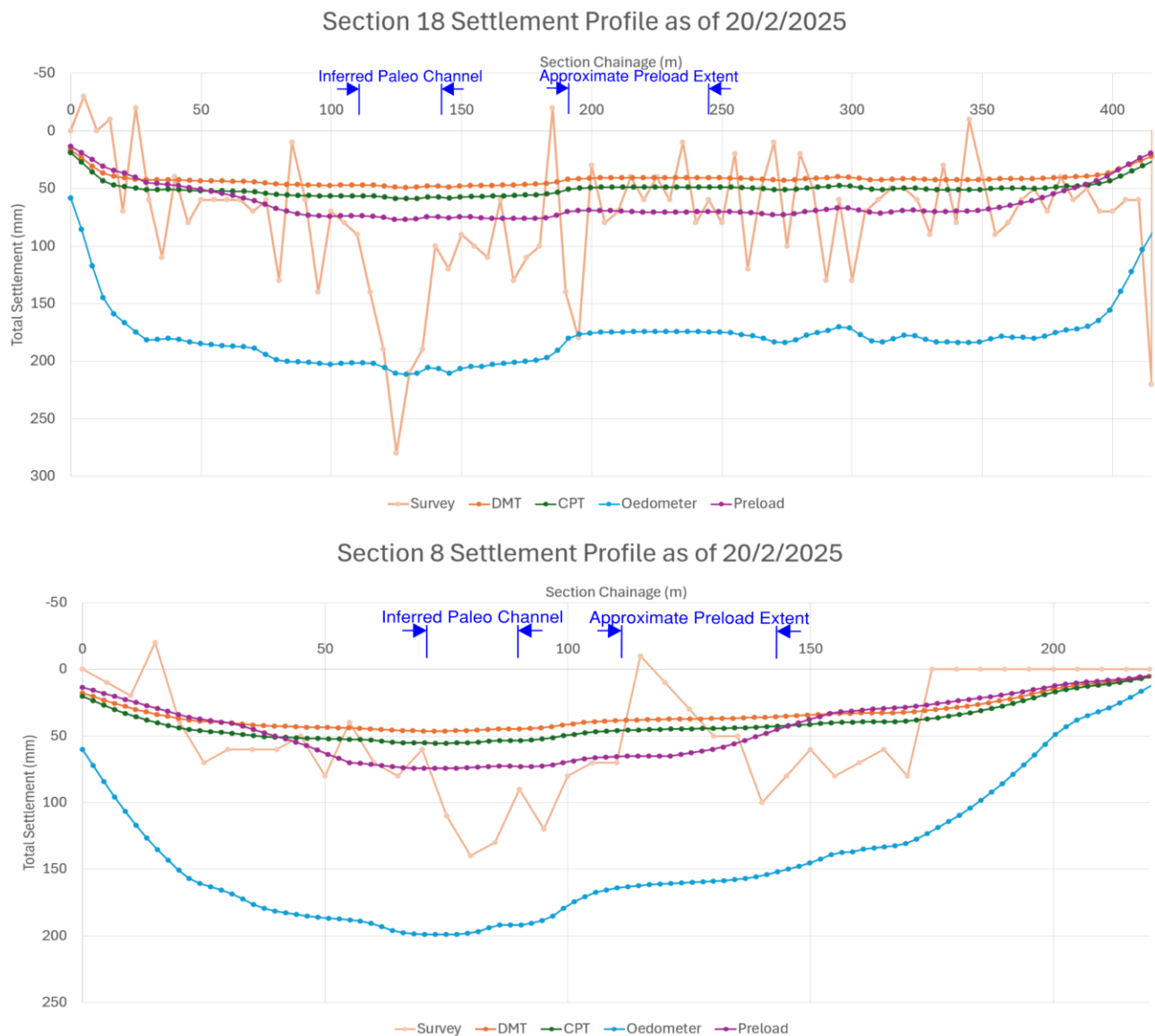


Figure 3: Annotated Sections

The preload pads provided accurate parameters, however a survey mix-up relating to the initial ground level prior to installation of the monitoring pins unfortunately introduced some uncertainty. The derived M_v of 0.22 m^2/MN was still close to the observed value. Additionally, the settlement rate-related parameter C_v was accurately predicted by the preload (though at the lower end of the range).

The outlier in this testing programme is the Oedometer tests. The M_v values were far higher than any other method and consistently over-predicted the settlement by 3 to 4 times. The reason for this over-prediction is not clear but is suspected to be related to drilling and/or sample disturbance effects during retrieval, transport, and extrusion. The natural “springiness” of peat may be a factor, with the sample tending to decompress and lose its structure upon removal from its naturally compressed environment at depth.

Additionally, the Oedometer tests significantly overestimated the rate-related parameter C_v , though this is likely due to another factor; Oedometer tests are conducted with the sample under fully saturated conditions. Groundwater levels on site were low due to vertical drainage provided by the underlying sand dune formations, with only locally perched groundwater horizons within the peat. As the air contained within the pores of partially saturated soil is much more compressible than water, settlement rates for partially saturated peat deposits would be much higher than the fully saturated case tested with the Oedometer.

The maximum observed settlement values locally exceed their predicted values, likely arising from variation in the geological model (peat depth) rather than the compressibility of the materials. Re-estimating the expected total liner strains associated with the deformation pattern measured in this local area, they are still well within allowable design limits for this geomembrane type.

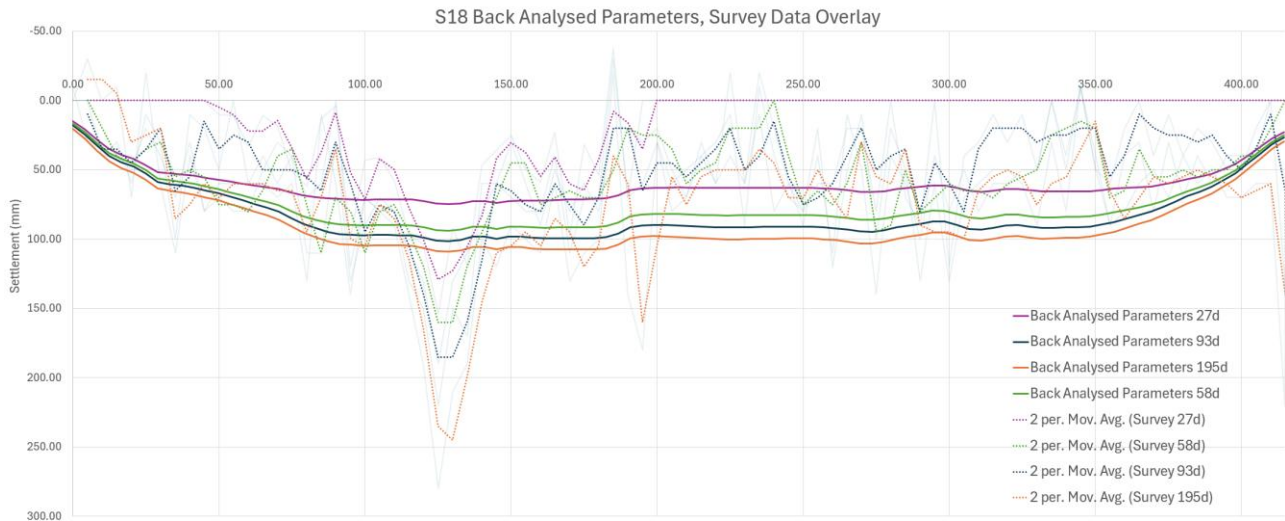


Figure 4: Back analysis section

7 CONCLUSIONS

1. A fundamental limitation to the ability to accurately predict primary and secondary settlement across a large and variable site such as the subject site, is the accuracy and resolution of site geological model. As always, the services of an experienced engineering geologist are essential.
2. Settle 3D (RocScience) is able to analyse and present extensive and complex site and loading geometries, though some “workarounds are required”.
3. In-situ DMT testing stood out as the most accurate predictor for primary settlement parameters.
4. The large-scale preload trial remains the “gold standard” for such analyses as it considers the full soil profile. However, in this case, and more broadly in the experience of the authors, these site trials require careful supervision and can be undermined by the practicalities of constructing and monitoring them.
5. CPT based settlement correlations provided relatively accurate parameter estimates in this case.
6. Laboratory Oedometer testing significantly overestimated settlement in this case. Sample disturbance was suspected as a leading cause for inaccuracy, and this may have been exacerbated by the high fibrous peat content of the samples.
7. Traditional approaches to C_v estimation relate to permeability and the ability of soil to dissipate porewater pressure. This approach is not applicable to the partially saturated peat being assessed. This was confirmed by the preload trial, which more accurately estimated time related effects.