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Staged construction of surcharged embankments over peat for a national road in Co. Donegal, Ireland

Construction etagé pour des remblais surchargés sur des sols tourbe pour un route national à Donegal en Irlande

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ABSTRACT: The paper describes innovative geotechnical methods to implement staged construction of surcharged embankments up to 5.5 m high on very soft blanket peat soils in north west Ireland. Shear wave velocities, CPT ball tests and direct simple shear tests were used to assess the undrained strength of the peat. Intermediate hold periods and consolidation benefits were exploited to optimise the filling schedule. Changes to instrumentation, basal reinforcement, anchorage detailing and filling rates were implemented to assure stability. Detailed interpretation of settlement and pore pressure responses during loading and unloading at instrument clusters is presented, including back-calculated field coefficients of consolidation and observed deformation ratios.

RÉSUMÉ: L'article décrit des méthodes géotechniques innovantes pour mettre en œuvre la construction par étapes de remblais surchargés jusqu'à 5,5 m de haut sur des sols tourbeux très mous dans le nord-ouest de l'Irlande. Les vitesses des ondes de cisaillement, les essais à la bille CPT et les essais de cisaillement simple direct ont été utilisés pour évaluer la résistance non drainée de la tourbe. Les périodes de détention intermédiaires et les avantages de la consolidation ont été exploités pour optimiser le calendrier de remplissage. Des modifications apportées à l'instrumentation, au renforcement basal, aux détails d'ancrage et aux taux de remplissage ont été mises en œuvre pour garantir la stabilité. Une interprétation détaillée des réponses au tassement et à la pression interstitielle pendant le chargement et le déchargement au niveau des groupes d'instruments est présentée, y compris les coefficients de consolidation sur le terrain rétro-calculés et les taux de déformation observés.

Keywords: Peat soils, Observational Approach, Multistage construction, Surcharge

1 INTRODUCTION

The N56 national road forms the major transportation corridor along the remote, north-west coast of Co. Donegal, Ireland. Route upgrades require maintenance of existing 'lifeline' traffic and provision of new alignments. Much of the route is underlain by Atlantic Blanket Bog peat and shallow Caledonian Granite bedrock. The paper describes works on a 4.1 km two-lane road located just north of Glenties, the southern half of which falls within the Owenea River Freshwater Pearl Mussel catchment. Concerns about potential impacts of mass excavation of peat on this protected aquatic species led to a solution involving crushed rock fill and surcharge (Figure 1).

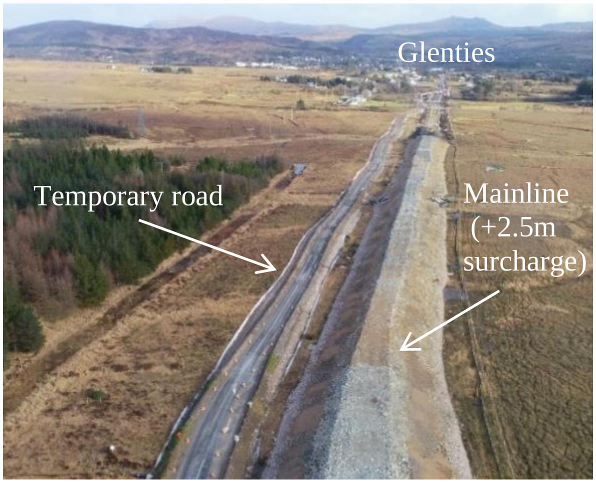

Figure 1. Looking south towards Glenties: temporary diversion on left and main embankment at surcharge level.

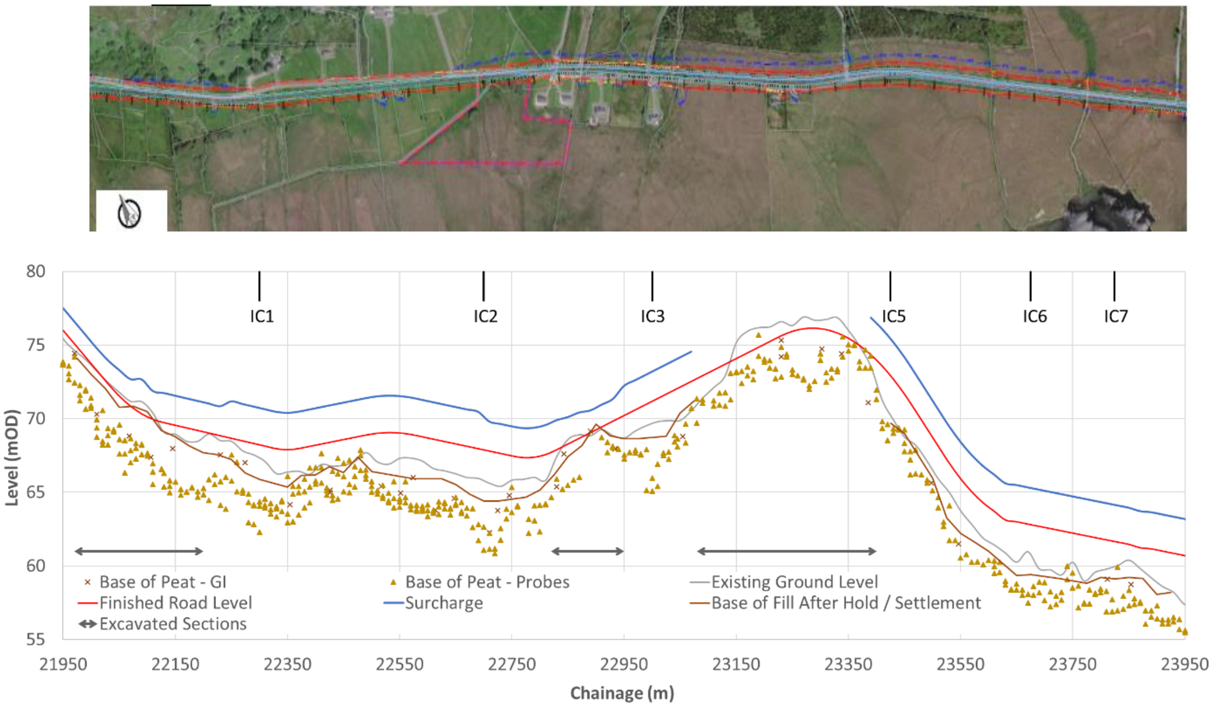

Figure 2: Aerial map of alignment and profile of peat and fill levels (surcharge and final settlements).

A 1.25 km long section was constructed directly onto extremely low-strength soils, using geosynthetic basal reinforcement, multi-stage construction and 1.5–2.5 m high temporary surcharge (Figure 2), informed by extensive instrumentation. The full surcharge height was achieved in all of this section with the exception of Chainage 23080 to 23400.

Construction commenced in early 2021, diverting traffic onto a 1.5 km single-lane temporary road (Figure 1), with supplemental investigations and refinements to the proposals prior to multi-stage embankment construction. Just under 50% of the surcharge material brought to site was used efficiently after completion of the hold period, filling excavations where peat removal was necessary (where at-grade or in cutting into peat). Geosynthetic reinforcement of the pavement foundations was also provided to mitigate differential creep movements. The completed works were opened to traffic in late 2022.

2 INVESTIGATING PEAT PROPERTIES

2.1 Peat Probing

The construction contract required confirmation of peat thicknesses at 10 m intervals upon possession of the site. The contractor, Wills Bros. Ltd., provided the peat probes, noting depths in the range 0.3 m to 5.2 m, as shown in Figure 2. This probing provided more useful information in several areas than previous investigations, which were confined to locations close to the existing road embankments, typically 1.0 m in height above surrounding peat and prone to long-term deformation. Upwelling of pore pressures from the base of some probes was also observed, which was consistent with high ground water levels and low (hand) shear vane strengths at these locations.

2.2 Temporary Road Hand Vane Data

Construction of the temporary road (Figure 1) provided an opportunity to review some design assumptions from the perspective of risk avoidance, as disastrous peat slides had been initiated elsewhere in the county in the months prior to commencement.

Hand vane tests performed at shallow depths of 0.3 m to 0.6 m gave undrained strengths (c_u) typically in the range 5–50 kPa along the subgrade of the temporary road prior to its construction. Failure by extrusion at the edges of the temporary road was observed in the softest deposits, coincident with saturated conditions due to a shallow rock profile. It is likely that the filling rate was greater for the temporary road than for the mainline, with approximately 1.0m placed directly onto 30 kN grade geogrids.

2.3 Peat Moisture Contents and Humification

Peat moisture contents (w) range from 600-1500% across the site, averaging ≈1000%. The degree of humification, according to the Von Post (1922) classification, generally increases with depth from H3 to H6/H7. Most of the peat incorporates fine and coarse fibres, with a significant timber content observed at the northern end of the site.

2.4 Shear Wave Velocities & Direct Simple Shear Laboratory Testing

In-situ shear wave velocities (V_s) in the range 14-40 m/s were measured at critical locations on site. An innovation on this project was the use of V_s profiles to infer c_u values, using the following established correlation: $c_u = 55.8(V_s/w)^{0.683}$ (Trafford and Long 2020). This confirmed extremely low strengths of the order of 4-6 kPa. These values fall slightly below Direct Simple Shear (DSS) test results conducted at normal stresses of between 6 and 7 kPa. Peat samples used for the DSS tests were retrieved from block samples at 0.6m depth. Both sets of strength data are shown in Figure 3.

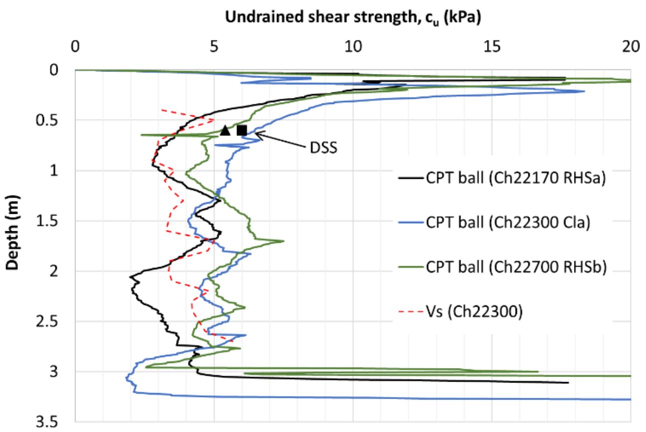

Figure 3: Undrained shear strengths derived from DSS tests, CPT ball tests and shear wave velocities

2.5 CPTu / Ball Cone Penetration Testing

In-situ cone penetration testing (using a lightweight rig, Figure 4) was undertaken with standard piezocone and ball-cone apparatuses suited to lower strength organic peat soils at critical locations between the temporary road and the previous N56. Profiles of c_u values inferred from the CPT ball data (adopting $N_{t\,ball}$ = 15) are also shown in Figure 3 and are in keeping with those derived from shear wave velocities and DSS data.

2.6 Laboratory Oedometer Testing

A total of six maintained load oedometer tests were performed on 80 mm diameter, 19 mm high peat specimens obtained from serrated edge, thin-walled tubes. Sample depths ranged from 0.5 m to 2.4 m and natural moisture contents from 520% to 1136%. Load stages, each 24 h in duration, were 2.5, 5, 7.5, 10, 20, 40, 80, 120 and 80 kPa. The unloading generated an effective surcharge overload ratio (also known as Adjusted Amount of Surcharge or AAOS; Ladd 1971) of (120-80)/80, i.e. 50%, for the final stage. Two tests showed evidence of a yield pressure in the peat of between 5 and 10 kPa. Coefficients of consolidation c_v typically varied between 2 and 5 m^2/yr at initial load stages, reducing to 0.2 to 0.6 m^2/yr above 40 kPa. These values are at the lower end of those reported by Long & Boylan (2013) for Irish peats.

Figure 4. Lightweight CPT rig using ball-cone apparatus

An extended (7-month duration) oedometer test with a maximum load of 100 kPa and AAOS of 69% was carried out on a block sample with natural moisture content 1030%. At maximum load, the normally consolidated creep strain rate was C_{sec}=0.017 with corresponding C_α=0.26 (assuming specific gravity G_s=1.5; initial void ratio e_0=15.5). This value is consistent with values quoted by Long & Boylan (2013). After reloading, a much-reduced secondary creep coefficient C_{sec}=0.001 was observed. However, this improvement was short-lived; the normally consolidated creep rate was re-established after a period of 2 months. This post-surcharge creep strain behaviour was also observed in research on Norwegian peats (Keary, 2020).

3 CONSTRUCTION DETAILING & INSTRUMENTATION

3.1 Stability Analysis and Design Changes

Originally, a 200 kN geogrid was envisaged across the embankment base without any anchorage detail at the toes and a second 400kN layer to be wrapped back fully over and overlapping in the middle of the embankment as part of the next fill stage. Given the lower than anticipated peat strengths, refinements were made by swapping the order of the geosynthetics and providing an anchorage length in Class 6I/6J fill on the basal layer. Side-slopes were reduced from 1:1 (vertical:horizontal) to 1:2, compromising the original goal of maximising the surcharge treatment on the underlying peat for a more stable arrangement. The embankment cross section at IC1 is shown in Figure 5.

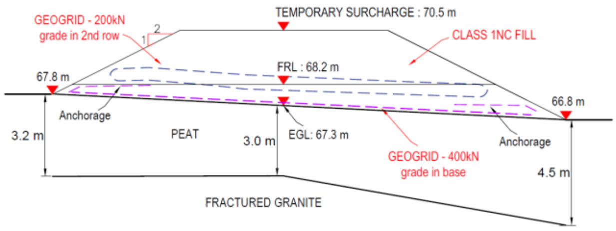

Figure 5: Embankment cross section at IC1, showing levels and geosynthethic reinforcement

3.2 Detailed Instrumentation Clusters

Six instrument clusters (IC1, IC2, IC3, IC5, IC6, IC7), were incorporated along the surcharged embankment (locations shown in Figure 2), each comprising:

(i) a single settlement plate, installed at or close to the centre of the embankment cross section and at the original peat surface,
(ii) a single vibrating wire piezometer, installed at or close to the centre of the embankment cross section, intended for mid-depth within the peat,
(iii) a sub-surface profile gauge (SSPG) spanning transversely underneath the embankment, immediately beneath the original peat surface,
(iv) a pair of inclinometers, located within 1 m on either side of the embankment toes.

The purpose of these clusters was to inform the timing of surcharge release and monitor embankment stability throughout construction, in areas of weakest peat (as observed in geophysics, CPTu ball cone and probing) and considering local maxima in peat depths and fill heights. Regular instruments including settlement plates and Toe Survey Monuments (TSM) were placed at intervals of 25 m to 50 m along the alignment for continuity of measurement between IC locations. Additional peat testing and sampling was undertaken at these instrument cluster locations.

3.3 Staged Filling & Consolidation

Embankment filling stages above peat soils were limited in the contract specification to 0.5 m following a 2-week minimum hold period, equating to a maximum filling rate of 0.25 m/week. In practice, this global filling rate was never exceeded by the contractor, who achieved the maximum temporary surcharge height within 90 to 215 days, with average fill rates from 0.1 to 0.2 m/week. A target of 90% consolidation was specified by the designers for the final surcharge load stage with a minimum hold duration of 90 days at maximum height. Values of AAOS varied from ≈23% to ≈77% from across the six ICs, partly due to local alignment issues and avoiding variability in surcharge heights.

4 ANALYSIS OF MONITORING DATA

4.1 Practicalities for Observational Control

Processing of twice-weekly instrument readings assisted in directing the contractor away from areas with higher deformation ratios or pore pressures in order to control filling in areas of highest risk. This did not result in delays to the contract overall, due to ease of access across the site enabled by the proximity of the new alignment to both the existing alignment and the temporary road.

4.2 Settlements and Consolidation

An example of the vertical settlement response (from the SP and central SSPG measurements) to eight stages of embankment loading at IC1 is presented in Figure 6, at which the peat thickness was ≈3 m. The embankment loading is presented as a total stress increase, corrected for submergence, as the lower portion of the embankment settled beneath the groundwater table (≈0.6 m deep at this location). The early stress increments (Stages 1–3) involved an initially fast becoming slower settlement rate, with a steadier rate from Stage 4 onwards. This is probably due to the cumulative effects of consolidation carried over from previous increments, while also reflecting the dramatic reduction in the coefficient of consolidation (c_v) characteristic of peat at higher effective stress levels (e.g. Carlsten, 1988). There is broad agreement between the SP and (central) SSPG settlements at IC1, with primary consolidation strains of ≈46% and ≈41% respectively at the time of surcharge release.

The corresponding degree of consolidation (U_v) at this time, estimated by applying the Asaoka (1978) method to the settlement plate data, was 96–100% at all ICs. An overall c_v was computed for the entire construction process, assuming that the full embankment height was attained instantaneously at the midpoint of the staged loading period. Double drainage was assumed based on ground investigation data, and a reducing peat layer thickness as a result of settlement was modelled. The values of c_v ranged between 2 to 8.5 m^2/yr across all ICs, corresponding to effective stress ranges from 38 to 97 kPa.

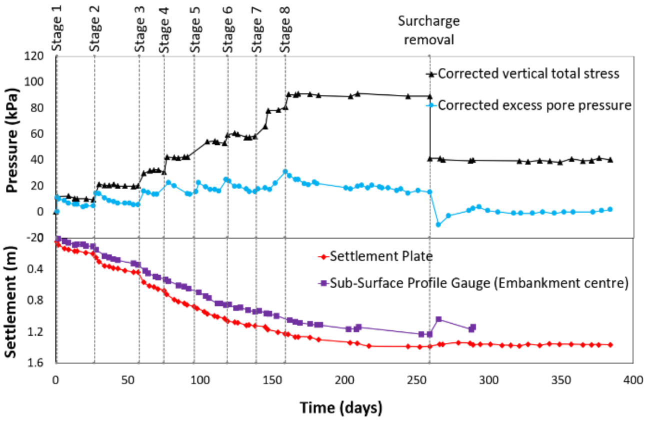

Figure 6: Excess pore pressure and settlement response to embankment loading at IC1.

Values of the compression index (C_c) were back-figured from the SP data, using settlements from Stage 3 onwards, at which stage the yield stress will have been exceeded. The average water at each IC location was used to calculate e_0. C_c was typically found to fall in the range 4 to 15.8, broadly in keeping with values for other Irish peats (Long and Boylan 2013).

4.3 Pore Pressures

The large strains in Figure 6 also had implications for the pore pressure interpretation, with the piezometric datum changing as a consequence of piezometer settlement. For example, at IC1, it was assumed that the piezometer settled by 42% of the surface settlement, given (i) its initial depth of ≈1.75 m within the peat, (ii) that the stress increase within the central peat imposed by the embankment decayed little over the peat depth, and (iii) the uniformity of the peat itself, evidenced from water contents and shear wave velocity profiles. Excess pore pressures, corrected on this basis, are also shown in Figure 6. Temporary negative excess pore pressures were measured for a period of ≈3 weeks after surcharge removal, in tandem with minor swelling, before reverting to ≈0 kPa.

The increments in corrected total stress and excess pore pressure at the start of each of the stages were examined; the sums of each over the entire eight stages were found to be approximately equal (when allowance was made for the time lag between filling and the first piezometer reading). Therefore, the maximum excess pore pressure corresponding to instantaneous embankment construction was assumed to be equal to the corrected total stress reached by Stage 8. U_v values were corrected to relate to the mean of the entire peat layer, rather than at just the piezometer level; these ranged from 64–88% across all ICs with corresponding values of c_v ranging from 0.5–2.1 m^2/yr, lower in general than the Asaoka-derived values and requiring more assumptions. Possible reasons for discrepancies between c_v values derived from laboratory, pore pressures and settlements will be explored in a later publication.

4.4 Deformation and Stability

The concomitant interrogation of inclinometer and SSPG data at the IC locations on this scheme was considered a novel means of monitoring embankment stability on peat. The ratio of the lateral deformation at the toe of the embankment on both sides of the mainline (ΔY), inferred from the inclinometer pair to the maximum settlement of the embankment (ΔS) at any time deduced from the SSPGs was computed. For single-stage embankments constructed on deep, soft mineral soils, a global trend of $\Delta Y/\Delta S < 0.3$ is considered acceptable (Jardine, 2002), but it is recognised that this might vary for shallow peat soils. In Figure 7, it can be seen that the deformation ratio history falls within this limit for IC1. The 'jagged' nature of the ratio observed in the early load stages may be because the lateral position at which the maximum SSPG settlement occurred varied.

Considering the broader dataset, the range of lateral movements per 0.5 m incremental loading stage were in the range of 50-70 mm on average, but extrema of the order of 100-200 mm were observed on the first and second fill stages. Higher ΔY/ΔS ratios arose where instruments were sited close to the previous load alignment (pre-compressed ground), in which case low central SSPG readings were compared with modest lateral displacements in softer ground along the margins. This was unrepresentative of the material behaviour overall.

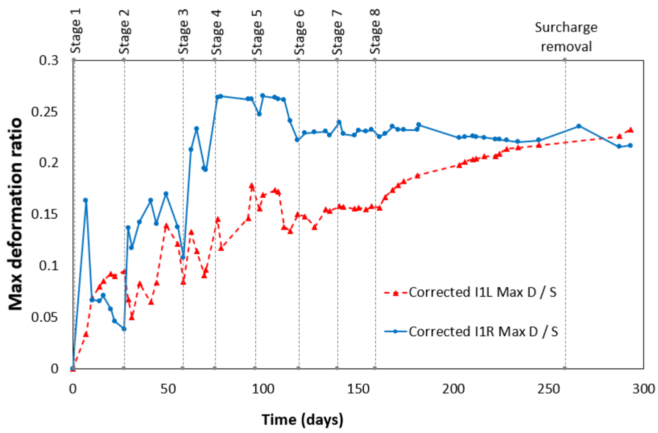

Figure 7: Maximum deformation ratio for IC1

4.5 Lessons Learned on Monitoring Equipment and Informing Stage/Surcharge Releases

Continuous pore pressure monitoring would have been preferable to capture more reliable baseline pore pressures and for greater resolution on the response to each fill increment. A companion extensometer would have been useful to establish the exact position of each piezometer as consolidation of the peat progressed.

Movement trends in TSMs and settlement plates were effective in informing the range of deformations along the embankments in addition to the detailed ICs. The TSM readings were more useful for detecting lateral movements in the early stages, predominantly because of the closer spacings (25 m) and size of dataset. The settlement plates were reliable but did not give as good a picture of overall deformations across each section and tended to be influenced by previous road embankment/field accesses in some locations. Hence the collective view afforded by concentrated (IC) and longitudinal (TSM/SP) data was vital.

Also, when fill becomes buoyant upon settling below the water table, there is effectively a very modest unloading phase during each intermediate hold if sufficient time is allowed. Observations of slight recovery in lateral movements close to release points were noted. These helped to signal a suitable point to recommence filling, if also confirmed using the other instruments, particularly the piezometers. This behaviour requires further research.

Consolidation targets were difficult to validate at two ICs; excess pore pressures upon surcharge release were ≈10 kPa higher than baseline levels. This topic will be explored in a future publication.

5 CONCLUSIONS & FUTURE RESEARCH

Innovative investigation techniques and sampling methods were utilised to establish extremely low peat strengths and refine the proposed embankment design configurations to be implemented at the N56 site. Building embankments up to 5.5 m high on very soft peat up to 5 m deep was challenging but was successfully executed without failures, primarily due to adoption of slow, controlled filling rates, geosynthetic basal reinforcement and substantial specialised ground information and instrumentation monitoring.

A total duration of 8–10 months was required to perform the earthworks related to embankment plus surcharge construction, hold and removal. This is approximately 6–8 months longer than standard excavate and replace methods in peat of similar depths. Some further optimization of geosynthetic reinforcement and construction filling rates could potentially reduce costs and construction durations by 1–2 months. It should be noted that the surcharge strategy boasts significantly better carbon credentials than an excavate-and-replace approach.

Analysis of settlement data interpreted by the Asaoka (1978) method showed that consolidation was achieved generally between 80 and 100 days. These field rates of consolidation are significantly faster than implied by laboratory oedometer tests.

In a novel research project led by the University of Galway, long term settlements are being monitoring at the N56 site with a view to quantifying by how much (and for how long) the surcharging process reduces the secondary settlement rate in the peat.

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