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CHAPTER 11

Case studies of Vacuum Consolidation Ground Improvement in Peat Deposits

Brendan C. O'Kelly
Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland

11.1 VACUUM CONSOLIDATION TECHNIQUE

The vacuum consolidation (preloading) ground improvement technique, originally proposed by Kjellman (1952), has, over the past three decades, evolved to become a viable, more cost-effective solution for projects worldwide. Vacuum consolidation involves applying a vacuum pressure into ground that has been protected from pressure losses at its surface, usually using a sealing membrane (Fig. 11.1). The vacuum pump produces a negative pressure (with respect to atmospheric pressure) in the permeable soil cushion, located immediately beneath the sealing membrane, and along prefabricated vertical drains (PVDs) installed within the ground under treatment. The PVDs serve a dual purpose; they aid in the balanced distribution of vacuum pressure over the soil treatment depth while discharging pore water up to the permeable soil cushion at ground surface level. Because of pressure losses via holes in the sealing membrane, pipe connections, and from peripheral sealing trenches, a preload pressure equivalent to atmospheric pressure cannot be achieved in practice. Vacuum pressures as high as 90 kPa may be achieved for soft clays, although a value of 80 kPa is typically considered for design (Chu et al., 2008).

The combined surcharge and vacuum preloading mechanisms can be explained using a piston and spring analogy (Fig. 11.2). Since geotechnical analysis is usually based on mean effective stress p', atmospheric pressure ($p_a \approx 100$ kPa) tends to be disregarded in stress calculations. However it must be considered for an understanding of the theory underlying vacuum consolidation. When a vacuum pressure is applied using vacuum pumps, the total stress remains the same but a decrease in the pore pressure by p_a causes a corresponding increase in the mean effective stress ($\Delta p'$) to occur, generally without increasing the shear stresses. Accounting for

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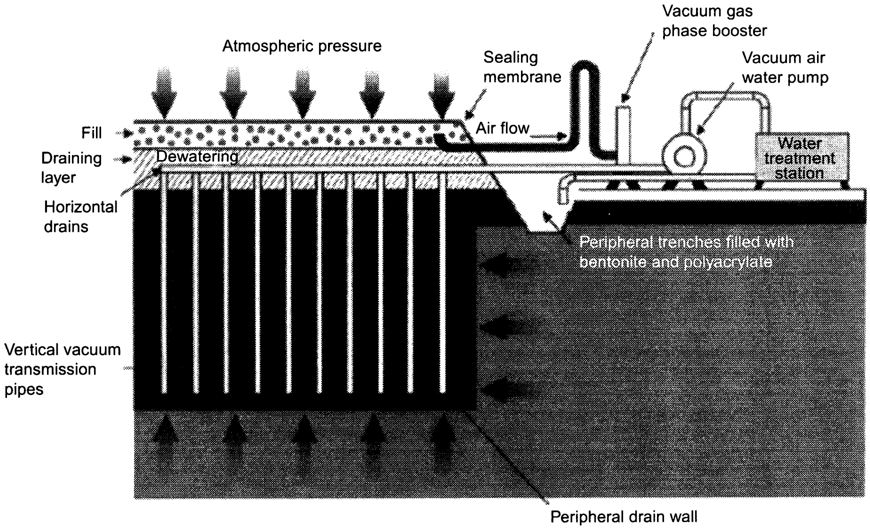


Figure 11.1 Schematic diagram of typical membrane vacuum consolidation system. *(Source: Adapted from Masse et al. (2001)).*

the vacuum pump efficiency (η), normally 70–80% of atmospheric pressure (Chu et al., 2008), the increase in mean effective stress is given by:

$$\Delta p' = \eta \bullet p_a \tag{11.1}$$

The effective stress path experienced by a soil element undergoing vacuum consolidation varies with depth (Chai et al., 2005). For a soil element at or near the ground surface, the effective stress path is close to isotropic consolidation, whereas it is closer to 1D consolidation for deeper locations. The superposition principle can be applied when surcharging is combined with vacuum preloading; that is, the resulting pore pressure equals the excess pore water pressure generated by the surcharge plus the pore pressure reduction induced by vacuum preloading. Thus, the maximum induced pore water pressure is smaller, compared with surcharge preloading alone.

The vacuum technique is considered to be environmentally sustainable compared to alternative ground improvement techniques (Indraratna et al., 2011; Indraratna et al., 2012; Griffin and O'Kelly, 2014b). Significant improvements in geosynthetic/PVD and vacuum pump technology have also occurred over recent decades (Griffin and O'Kelly, 2014a). Compared with surcharging alone, vacuum-assisted preloading can potentially reduce the cost of ground improvement works by 30% (TPEI, 1995, Yan and Chu,

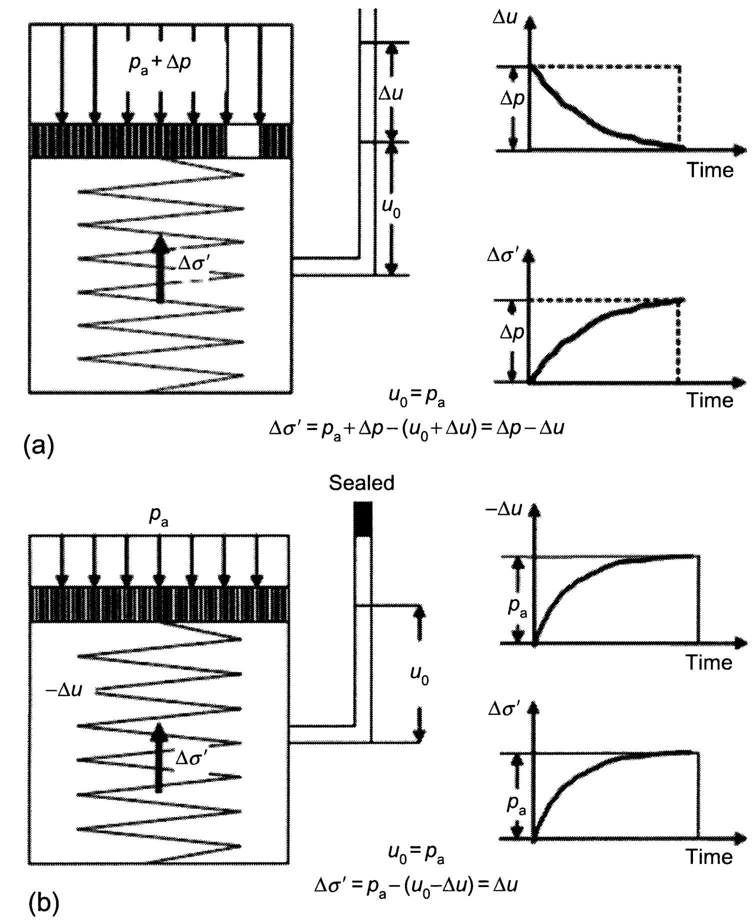


Figure 11.2 Spring and piston analogy of consolidation response: (a) surcharge pressure, Δp, (b) vacuum pressure, $-\Delta u$. *(Source: From Chu and Yan (2005a)).*

2003); for example, reduced surcharge loads means less fill material must be transported to site.

The major advantage of the vacuum preloading technique is that the full vacuum pressure can be instantaneously applied, without risk of adversely affecting the factor of safety on slope instability. Chemical residues are not introduced and left in the soil, although the PVDs remain in the ground posttreatment. The design drain spacing is a function of the vertical and horizontal consolidation properties and effective drainage lengths and also the time period targeted to achieve the desired average degree of consolidation under combined vertical and radial drainage. Drain spacing of 1.2–1.3 m is considered adequate for design in highly compressible clay, with a reduction in the consolidation rate likely to occur for drains placed at closer spacing on account of the intersection of smear zones (Indraratna et al., 2011).

When vacuum consolidation has to be performed over an extensive area, the installation of the drain system can become a significant challenge. This occurs because the vacuum treatment would need to be performed consecutively for different subareas and this approach leads to inefficiencies (Chu et al., 2008). This challenge may be overcome by connecting the vacuum line directly to each PVD using a tubing system, such as that proposed by Seah (2006). Thus, the permeable soil cushion and sealing membrane are not required since the connection from the top of the PVD to the vacuum line is completely sealed. However, unless the system provides an airtight condition for the entire treatment area, the efficiency may be quite low, with vacuum pressures conceivably no greater than 50 kPa (Seah, 2006).

Interbedded, more permeable layers can also produce some practical problems. For deposits open to two-way vertical drainage, the PVDs should only partially penetrate the layer under treatment to mitigate against vacuum pressure loss via the bottom drainage boundary (Chai et al., 2005) as well as inhibiting upward flow from underlying (possibly more permeable) deposits, which would result in additional discharge volume for the vacuum pump. In the case of deep soft soil deposits open to one-way vertical drainage, it may not be feasible to install PVDs over the full depth although partial penetration makes anchoring of PVDs during installation more difficult. Field monitoring usually encompasses measurements of the pore water pressure and the vertical and lateral displacements at different soil depths. Whether the average degree of consolidation is evaluated based on settlement or pore water pressure data is relevant and should be made clear in design work (Chu and Yan, 2005b). The average degree of consolidation achieved can often be underestimated because instruments monitoring the pore water pressure response are typically installed where the highest values of these parameters are likely to occur (Chu et al., 2008); for example, pore pressure transducers are usually installed equidistant from neighboring PVDs.

11.2 PEAT DEPOSITS: GEOTECHNICAL PROPERTIES

Peat deposits cover large areas of the world's landmass and are formed by the accumulation of partially decomposed and disintegrated plant material (such as mosses, sedges, and grasses) in wetland areas where unfavourable conditions, including lack of oxygen supply, inhibit complete decay (Hobbs, 1986; O'Kelly and Pichan, 2013). Peat material can range from coarse fibrous, showing little or no humification, to highly humified (amorphous) peat. In situ water content can vary greatly, from a few hundred percent of dry mass to greater than 2000%. Virgin peat generally has very low shear strength (typically <15 kPa) and undergoes large consolidation and creep settlements under loading. The botanical composition of the peat also has an important influence on its engineering properties.

Heterogeneity and anisotropy usually mean that geotechnical and hydraulic properties can vary considerably within a peat deposit, even over short distances (Landva, 1980; O'Kelly and Pichan, 2013). Fibrous peat tends to exhibit a high degree of strength and permeability anisotropy, with the ratio of the permeability coefficients for the horizontal to vertical flow directions typically ranging 1.7–7.5 initially. Compared with fine-grained mineral soils, significant fabric and structural differences (including the porous cellular structure and compressible nature of the organic solids themselves) make the direct application of classical soil mechanics strength models doubtful for peat (O'Kelly and Orr, 2014; O'Kelly, 2015).

Therefore, peat deposits present difficult ground conditions for construction, necessitating high initial costs and (or) frequent maintenance, and design. Some particular challenges can be seen, for example, from recent failures of dykes at Wilnis, the Netherlands (van Baars, 2005), canal embankments at Edenderry, Ireland (Pigott et al., 1992), peat bunds and dams at Raheenmore bog, Ireland (McInerney et al., 2006), and also excessive deformation in road subgrade causing serviceability failure of pavements (Osorio et al., 2008). Often surcharging with PVDs is not adequate, particularly when dealing with deep peat deposits, as the period required to achieve substantial completion of consolidation settlements can be excessive (Ariyarathna et al., 2011) and PVDs are unlikely to help in accelerating the secondary compression (creep) rate.

Creep settlement is significant for peat, producing dramatic reductions in permeability, and can often account for the majority of the total settlement over the design life. Peat initially tends to have relatively high permeability, comparable to fine sand, but its void ratio reduces significantly under modest loading such that its permeability becomes similar to that of soft intact clay (Wong et al., 2009). Other important considerations in settlement analysis are the large strain (deformation) response and significant changes in soil parameter values under loading, even for a constant state of effective stress.

11.3 REVIEW OF VACUUM CONSOLIDATION IN PEAT DEPOSITS

The majority of vacuum consolidation projects to date have been performed on soft clayey deposits and hydraulic fills for land reclamation (see Griffin and O'Kelly, 2014a). This section summarizes the limited application of the technique in peat and other highly organic deposits (see Table 11.1).

Vacuum consolidation treatment (setup shown in Fig. 11.3) was applied, in combination with stage-constructed surcharge embankments, to a peat layer (water content, $w = 110$–470%) during a highway construction project in Sri Lanka (Ariyarathna et al., 2011). The amorphous peat layer (H_8–H_{10}) extended from 4.7–7.7 m depth and was underlain by loose to medium-dense sand, with the groundwater table located close to the ground surface. The construction and monitoring of four vacuum consolidation field trials for the project have been described by Karunawardena and Nithiwana (2009).

The PVDs were arranged in a square-grid pattern at 1.0 m spacing. Although the vacuum pump was supposed to generate suctions of ~90 kPa, the maximum vacuum pressure achieved under the sealing membrane was only 55 kPa, developed shortly after commencement of pumping. Under the average vacuum pressure of 35 kPa actually achieved and 11.6 m high embankment surcharge applied, the thickness of the peat layer was reduced by between 47% and 70%, with the measured undrained strength increasing from ~7–22 kPa initially to 38–79 kPa posttreatment. The trials demonstrated that 95% of the primary consolidation settlement could be achieved within an economically viable time period of ~8 months.

Table 11.1 Summary of ground improvement projects in the literature involving vacuum consolidation with PVDs

Project, country	Soil type(s)	System	Vacuum pump	Vacuum pressure (kPa)	Treatment area (m^2)	Reference
Northeast New Railway, China	Peat, silt	Membrane	NR	93	1950	(Qian et al., 1992)
Pilot test of highway embankment, Ambès, France	Peat, highly organic clay	Membrane along with surcharge	25 kW water-air pump backed by Venturi pumps	150 for combined vacuum and surcharge	390	(Cognon et al., 1994)
Oil depot, Ambès, France	Peat, silt, organic clay	Membrane along with surcharge	NR	NR	NR	
Embankment stabilization, Ishikari, Japan	Peat, peaty clay, silty clay, silty sand, sand	Membrane along with surcharge	NR	60–70	20,870 (divided into 13 sub units)	(Shiono et al., 2001)
Embankment construction, Route 337, Sapporo, Japan	Peat, clayey peat, clay, sand	Membrane along with surcharge	Two vacuum pumps	60	3200	(Hayashi et al., 2002)
Road at Tianjin Port, China	Silt, silty clay	Membrane	Jet pump with centrifugal pump	80	18,590	(Yan and Chu, 2003)
Test embankment, Kushiro City, Japan	Peat, clay, sand	Membrane along with surcharge	NR	60	1350	(Tran and Mitachi, 2008)
Field test, Ballydermot raised bog, Ireland	Pseudofibrous peat	Membrane	Jet pump, liquid ring pump	80 initially, 71 sustained	100	(Osorio et al., 2010)
Southern Expressway near Colombo, Sri Lanka	Amorphous peat	Membrane	NR	55 initially, averaging 35	NR	(Ariyarathna et al., 2010)

Note: NR = not reported.
Source: Adapted from Griffin and O'Kelly (2014a).

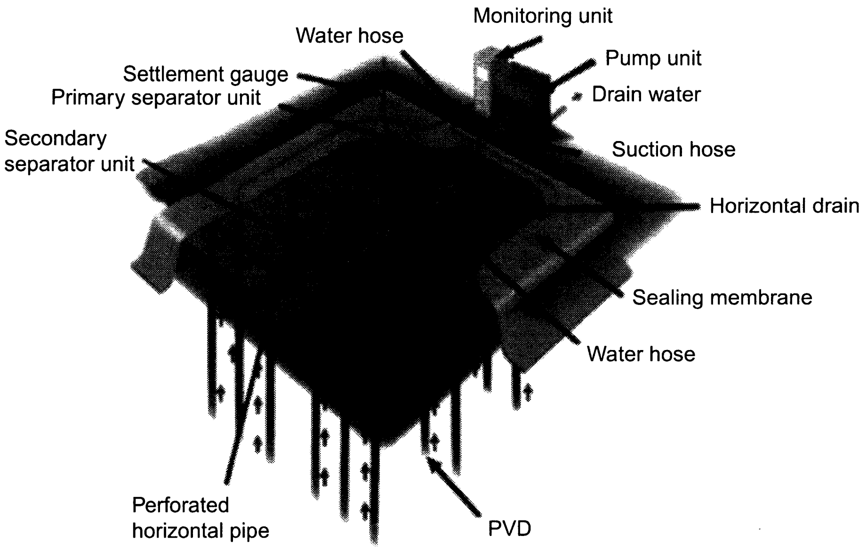


Figure 11.3 Schematic diagram of vacuum preloading setup for Sri Lankan trial embankments. *(Source: From Ariyarathna et al. (2011). Reproduced by permission of the Institution of Engineers, Sri Lanka).*

Cognon et al. (1994) reported a vacuum-assisted preloading trial performed in Ambès, France, for the construction of a highway embankment over a 1.7 m deep peat layer, having a water content of 430–860%, which was underlain by a 2.0 m deep highly organic clay layer (w = 140–210%) over muddy sand. The trial was comprised of a two-stage embankment surcharge followed by vacuum preloading, with the settlement–time response shown in Fig. 11.4. For the first stage, a 0.8 m deep sand blanket was placed on the ground surface, acting as a hard standing and drainage layer. After 3.5 weeks, PVDs were installed in a square-grid pattern at 1.4 m spacing. After 5 weeks, the second surcharge layer, a 0.5 m deep granular bed, was placed. Vacuum pressure was applied from the beginning of week 7.

The 0.7 m settlement ($\varepsilon_z = 18.9\%$, where ε_z is the vertical strain) achieved over the 3.7-m-deep highly compressible layers by the end of the 3-month monitoring period was reported equivalent to that for a 4.5 m high embankment surcharge. An average degree of consolidation of 80% was achieved for the peat layer and 50% for the underlying organic clay layer. After removing the vacuum pressure, the ground surface heaved by 0.03 m within the first 48 h, before stabilizing. Based on the success of this trial, the vacuum consolidation technique was chosen over embankment surcharging as the better solution for preloading the highway footprint.

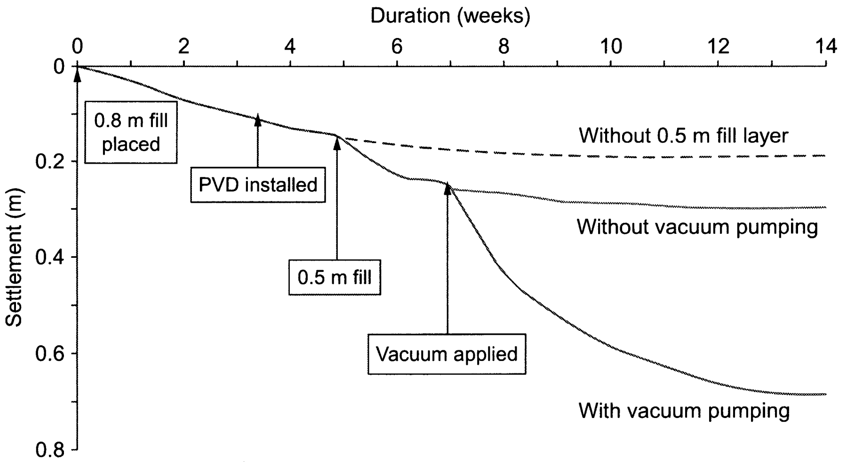


Figure 11.4 Settlement response for trial involving two-stage embankment surcharge followed by vacuum preloading in Ambès, France. *(Source: Adapted from Cognon et al. (1994)).*

Hayashi et al. (2002) reported on vacuum-assisted preloading for the construction of a highway embankment over fibrous peat (w=200–700%) underlain by a clayey peat layer described as having an organic content of 10–60%. PVDs were installed in a square-grid pattern at 0.8 m spacing. Negative pressures of 50 kPa were achieved in the fibrous peat layer, close to the design suction of 60 kPa. Vacuum pressures of only 20 kPa were measured in the underlying deposits. The settlement responses of the underlying layers were also delayed relative to the upper peat layer. The consolidation rate was very sensitive to PVD spacing, from which Hayashi et al. (2002) concluded that significant ground improvement could not be achieved for greater than 0.9 m PVD spacing. In practice, however, minimum spacing is more relevant as a design guide as too close a spacing may result in some overlapping of smear zones, causing a decrease in the consolidation rate.

11.4 VACUUM CONSOLIDATION TRIAL AT BALLYDERMOT BOG IN IRELAND

11.4.1 Introduction

A significant part of Ireland's road network has been constructed across peatlands, with 17.2% (Hobbs, 1986) of the overall land surface of Ireland covered with peat. Historically, peat harvesting in the vicinity of bog roads for use as domestic fuel was a common practice in Ireland and created what are known as bog ramparts or rampart roads (Osorio et al., 2008). The purpose of the Trinity College Dublin (TCD) Ballydermot vacuum consolidation field trial was to investigate the feasibility of implementing the vacuum consolidation technique in (pseudo) fibrous peat deposits and its effectiveness for use in road construction and widening of existing roads over peat deposits (NRA, 2007).

The trial was performed at the Ballydermot (South) bog, County Offaly; geographically located in the Irish Midlands. This is a raised bog, with details on the formation of such bogs provided in numerous publications (e.g., Moore and Bellamy, 1974, and Hobbs, 1986). Since the mid-1940s, the peat layer at Ballydermot bog had undergone a reduction in thickness due to industrial peat harvesting and consolidation due to drainage via manmade ditches/channels. Accordingly, the peat depth had been reduced from approximately 8–9 m to 4 m between 1935 and 2014. The resulting apparent preconsolidation pressure for the in situ peat has been established as 14 kPa (Pichan and O'Kelly, 2013).

Different aspects and stages of the vacuum consolidation field trial, including the original ground investigation and measured soil properties, have been reported by Osorio et al. (2010), Farrell et al. (2012), and Griffin and O'Kelly (2015). The vacuum consolidation field trial formed the basis for a dissertation by Osorio-Salas (2012). Further details on the geotechnical and hydraulic properties, and the effects of decomposition on same, have been reported for the Ballydermot peat by Pichan and O'Kelly (2012, 2013) and O'Kelly and Pichan (2014). The oven-drying characteristic of the same peat for water content determinations have been reported by O'Kelly and Sivakumar (2014) and profiles of water content against depth for the untreated test area have been reported by O'Kelly and Pichan (2014) and O'Kelly and Sivakumar (2014). Using published literature, this section presents a summary compilation of the field trial along with new water content and field vane strength against depth profiles. The importance of understanding the bog hydrology in the assessment of the field data is demonstrated.

From the various ground investigations at the Ballydermot test area, a consistent picture emerged indicating a ~4 m deep pseudofibrous peat layer overlying glacial deposits. Over the depth of the peat layer, the bulk density ranged 0.98–1.08 Mg/m^3, specific gravity of solids 1.39–1.54, void ratio 6.8–14.8, loss in dry mass on ignition 93–98%, pH 4.5–5.6, and degree of humification according to the von Post scale (Landva and Pheeney, 1980) of H_5–H_7, where H_1 refers to peat that has undergone no decomposition and H_{10} to completely decomposed peat. From visual inspection, Pichan and O'Kelly (2013) reported that the peat was mainly composed of *Sphagnum* (S) mosses, which are the dominant plant species found in most raised bogs in temperate regions. The parental vegetation also included *Carex* (C), *Lignidi* (W), and *Phragmites* (Ph). Based on the degree of humification of the plant structures (H_5–H_7), water contents ranging 500–2000% (B_{3-4}), high fine fiber content (F_3), moderate coarse fiber content (R_2), and generally no or little wood/shrub remnants present, O'Kelly and Pichan (2014) classified the peat as SCWPh-H_{5-7}-B_{3-4}-F_3-R_2-W_{0-1} material according to the modified von Post classification system (Landva and Pheeney, 1980).

11.4.2 Setup and performance of Ballydermot vacuum consolidation trial

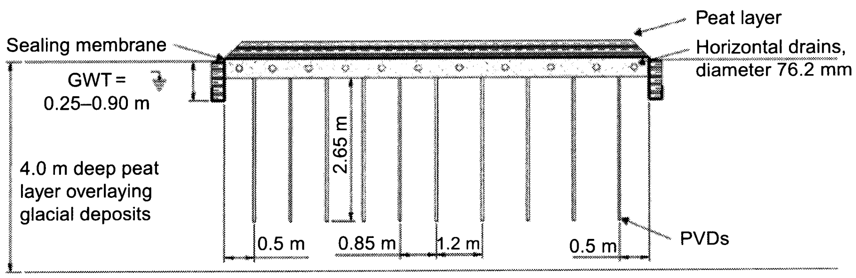
Figure 11.5 shows schematic diagrams of the vacuum consolidation setup for the 10 m × 10 m treatment area. The construction sequence, described by Osorio et al. (2010) and Farrell et al. (2012), is summarised below. From probing of the ground, the initial depth of the peat layer was established as 4.0 m across the test area. Over a 12 m × 12 m area, 0.4 m depth of peat was excavated. For half of this area, flexible (band) PVDs were installed in a square grid at 0.85 m spacing and for the other half at 1.20 m spacing (Fig. 11.5(b)). The former fits the conclusion by Hayashi et al. (2002) that significant ground improvement in peat could not be achieved for greater than 0.9 m PVD spacing; the latter in the range for the successful field trials in peat using PVD spacings of 1.0 (Karunawardena and Nithiwana, 2009; Ariyarathna et al., 2011) and 1.4 m (Cognon et al., 1994).

Using the bucket of a bog digger and an aluminum box section as a lance, the PVDs were pushed vertically into the peat to a depth of 2.65 m; that is, 3.05 m below the original ground level (bgl). In this manner, vacuum pressure losses by way of the bottom boundary would be reduced by the initial ~1 m gap between the bottom of the PVDs and the underlying higher-permeability glacial deposits (Fig. 11.5(a)), in agreement with recommendations by Thevanayagam et al. (1994). According to Farrell et al. (2012), the underlying deposits of very clayey sandy gravel (~30% fines) overlying slightly clayey sandy gravel (4–11% fines) had permeability coefficient values of the order of 10^{-5}–10^{-6} m/s, determined from in situ falling head tests.

A permeable bed, 10 m × 10 m in plan and comprising a 0.30-m-deep gravel layer overlying a 0.15-m-deep sand cushion, was placed above the peat layer, applying a surcharge of ~9 kPa. Referring to Fig. 11.5(b), corrugated and perforated flexible pipes, 76 mm in diameter, were embedded horizontally within the gravel layer. The vacuum line connection was located along the central transect B–B, offset 0.75 m from the orthogonal axis to tie in with the nearest horizontal drainage pipe. The natural groundwater level in the untreated area was recorded at between 0.25 and 0.90 m bgl, fluctuating with prevailing seasonal and climatic conditions. A 0.3-m-wide by 1.0-m-deep perimeter trench was dug around the 10 m × 10 m test area and a heavy duty polythene membrane (1200 gage polythene) rolled out over the entire test area. Its edges were keyed at the bottom of the trench, with the excavated peat backfilled to secured the membrane in place and provide an airtight peripheral seal (Osorio et al., 2010).

A 0.5-m-deep peat layer placed over the sealing membrane helped maintain the seal and prevented damage from weathering/prolonged exposure to UV light. Surface settlement monitoring points (SM1–SM7) were installed as shown in Fig. 11.5(c), and leveled relative to a site datum (reference elevation). Two different vacuum-generating systems were investigated over the course of the project. First, between November 30, 2009 (start of the trial) and June 23, 2010, a 38-mm-diameter jet pump connected to a 1.5 kW centrifugal pump produced a maximum suction of 80 kPa under the sealing membrane (Farrell et al., 2012), although this value could not be consistently achieved on account of calcification problems with the pumps. The regional geology is Carboniferous Limestone.

Second, between July 29, 2010 and October 29, 2010 (end of the trial), a 2.2 kW liquid ring pump in combination with the jet pump was found to produce a more stable vacuum (Farrell et al., 2012; Griffin and O'Kelly, 2014a). To these applied vacuum pressures must be added the surcharge load due to the 0.45-m-deep granular bed and 0.5-m-deep peat covering layer; that is, ~14 kPa initially reducing to ~4.5 kPa when the underlying peat had



(a) *Cross section (adapted from Osorio et al., 2010).*

Figure 11.5 Schematic diagrams showing setup of Ballydermot vacuum consolidation field trial.

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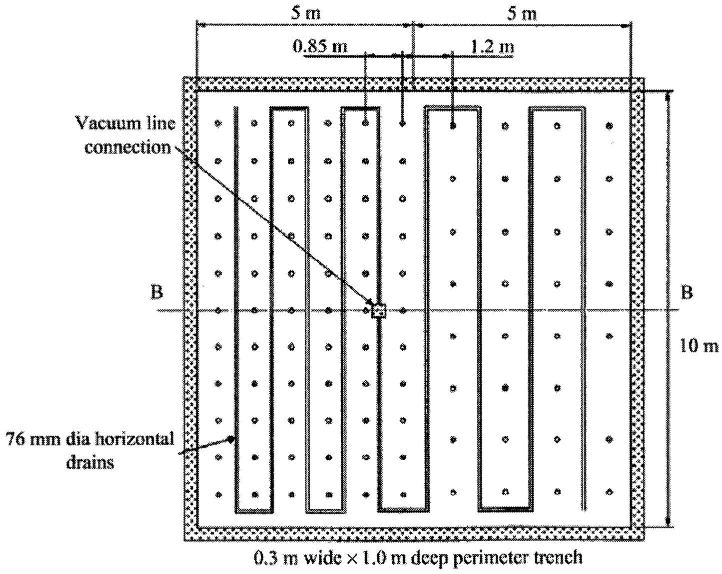
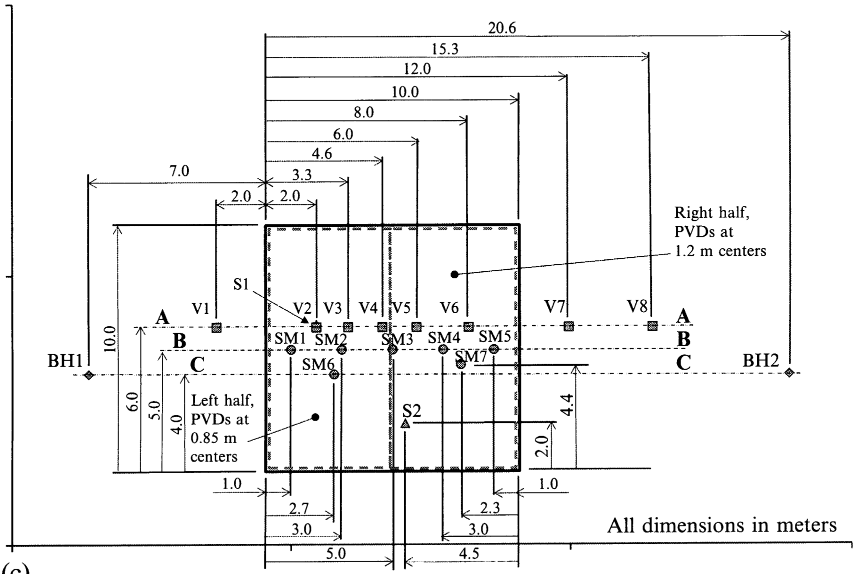


(b) Plan arrangement of PVDs and horizontal drains (adapted from Osorio et al., 2010).



(c) Locations of sampling points and settlement monitoring points. Note: BH, cable-percussion borehole; SM, surface settlement monitoring point; S and V, gouge auger samples. BH1, BH2 and SM1–SM7 after Farrell et al. (2012), S1 and S2 after Osorio-Salas (2012) and V1–V8 from present study.

Figure 11.5 cont'd

consolidated sufficiently for these layers to become submerged. Over the 11-month vacuum pumping period, the average suction achieved by the jet pump–centrifugal pump combination (first phase) was 50 kPa, with higher suctions of 50–70 kPa achieved in combination with the liquid-ring pump (second phase) (Farrell et al., 2012). These values are considerably below reported vacuum pressures of up to 90 kPa achievable for soft clays and 80 kPa typically considered for design (Chu et al., 2008), but are in broad agreement with the maximum (initial) vacuum pressure of 55 kPa for the Sri Lankan vacuum consolidation field trial in peat reported by Ariyarathna et al. (2011) and Karunawardena and Nithiwana (2009).

At the Ballydermot site, a piezometer located 5 m away from the perimeter of the test area did not show any reduction relative to the local groundwater table level (Osorio et al., 2010), indicating that the peripheral seals were effective. However, boundary effects were significant on account of the small treatment area and relatively deep peat layer, resulting in the formation of a concave depression, evident from Fig. 11.6. As expected, considerable tension cracking occurred around the test area perimeter near ground-surface level (Farrell et al., 2012) on account of the lateral inward displacement of the upper peat layer (Chai et al., 2005). At the lateral boundaries, the horizontal stresses gradually reduce due to the consolidation movements, with vertical tension cracks forming when tension stresses are reached. The large (differential) settlements/strain (Fig. 11.6) and manner

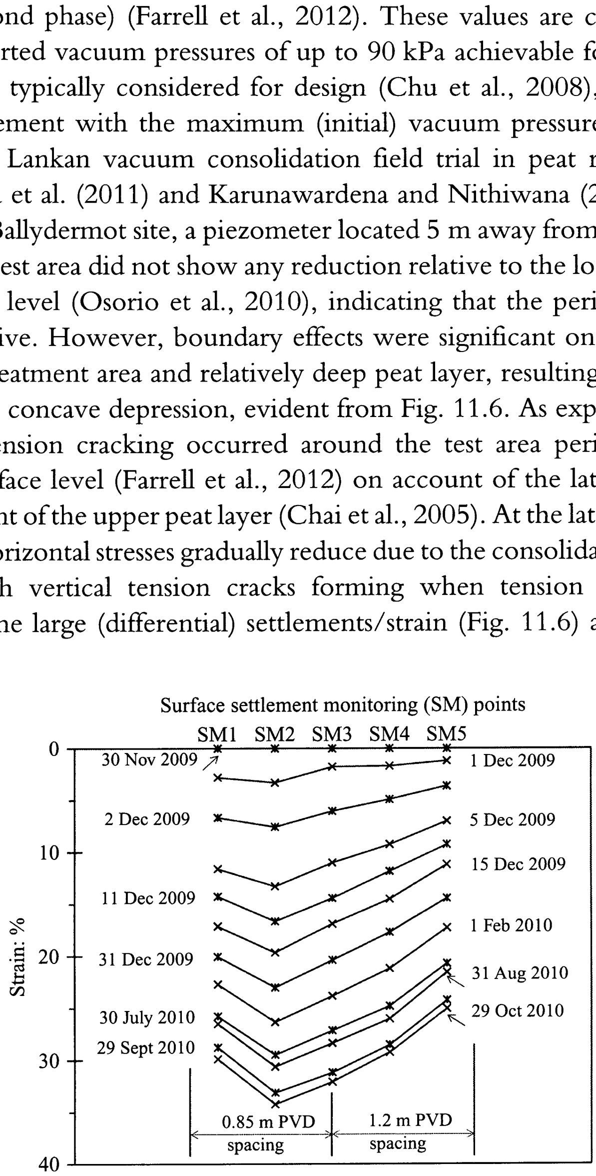


Figure 11.6 Ground surface profiles along section B–B at different stages during the Ballydermot vacuum consolidation field trial. *(Source: Adapted from Farrell et al. (2012)).*

in which the edges of the sealing membrane were restrained in the perimeter trench meant that this membrane was vulnerable to tearing/rupture (as transpired intermittently for large (differential) settlements), significantly reducing the vacuum pressure transmitted to the ground.

In this project, vacuum pumping commenced during the winter months, and early on in the trial, the uppermost peat layer and groundwater froze due to harsh weather. The water inside of the vacuum lines also froze periodically over the course of an 11-week period (Farrell et al., 2012; Griffin and O'Kelly, 2014a), rendering the vacuum system inoperative. Adequate thermal protection fitted to exposed hoses and pipes may have prevented the vacuum lines from freezing, which would have allowed the system to remain in continuous service (Griffin and O'Kelly, 2014a) and caused consolidation of the deeper (unfrozen) peat. Along with seasonal effects and prevailing climatic conditions, these events were responsible for some erratic responses in the ground monitoring data. Because bogs are dynamic ecohydrological systems, their morphology changes on an annual cycle. All of the settlement markers were leveled periodically relative to the local site datum (Farrell et al., 2012), from which the respective settlement (strain) responses were calculated (Figs. 11.6 and 11.7).

Consistently, throughout the 11-month vacuum consolidation period, the ground settlement was greater for the 0.85 m PVD spacing than for the 1.2 m spacing (Fig. 11.6). From Figs. 11.6 and 11.7, the consolidation settlement rate was also higher, and by the end of the first month, ~66% and 59% of the total (maximum) measured settlements at end of pumping had occurred for the 0.85 and 1.2 m PVD spacing areas, respectively. Note that settlement markers SM6 and SM7 were not located along the axis of symmetry (see Fig. 11.5(c)), but were offset by 1.0 and 0.6 m, respectively. Thus, their settlements were comparatively less on account of the concave depression. As described earlier, the vacuum line connection along central transect B–B was offset 0.75 m, within the 0.85 m PVD spacing area (Fig. 11.5(b)), although given the highly permeable nature of the granular bed, its impact on the settlement response across the treatment area would not have been significant. The difference in the early stage settlement rates was expected as, in theory, the degree of consolidation is inversely proportional to the square of the effective drainage length. The maximum ground surface settlement of 1.22 m ($\varepsilon_z \approx 34\%$ based on the initial 3.6-m peat depth) was recorded for SM2, located near the center of the 0.85-m PVD spacing area.

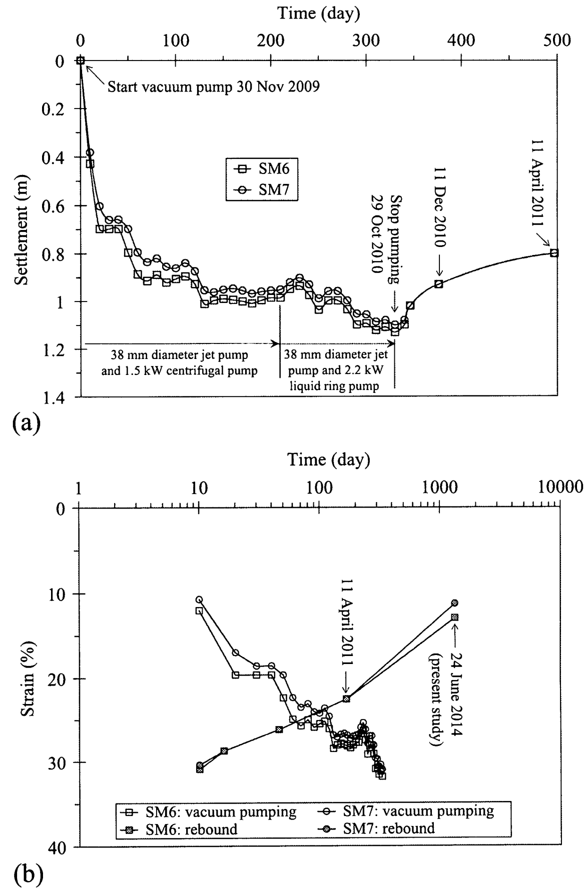


Figure 11.7 Ground surface settlement/strain against time responses for Ballydermot vacuum consolidation field trial: (a) linear time, (b) logarithm time. *(Source: Adapted from Farrell et al. (2012)). For locations of surface settlement monitoring points SM6 and SM7, refer to Fig. 11.5(c).*

Assuming Terzaghi's 1D consolidation theory applied for the peat material, the duration of the primary consolidation stage was estimated at 3.3 months from standard curve fitting of the settlement against square-root of elapsed time plot. The coefficient of volume compressibility (m_v) value was estimated at 4.2 m^2/MN, based on the corresponding "end of primary" settlement of ~0.90 m, initial 3.6 m deep peat layer, and stress increment of ~60 kPa. Based on this "end of primary" settlement value and the SM1–SM5 readings, the average degree of consolidation values achieved by the end of the first month of pumping were 83% and 63% for the 0.85 and 1.2 m PVD spacing areas, respectively. From the logarithm of time plot in Fig. 11.7(b), the creep deformation rate was significant. After switching off the vacuum pump on October 29, 2010, monitoring continued until April 11, 2011, with a measured 0.33 m rebound ($\varepsilon_z \approx 9.2\%$) for the saturated peat layer over this unload period (Fig. 11.7). For safety reasons, the depression in the ground was later backfilled with peat, level with the original ground surface, with the sealing membrane and 0.45 m granular bed remaining in place. The resulting surcharge loading on the overconsolidated peat layer due to the (submerged) granular bed, its overlying peat cover, and peat backfill was ~9.5 kPa.

11.4.3 Postconstruction ground investigation

The vacuum consolidation test area remained undisturbed, and more than three years after completing the trial (June 23–24, 2014), a ground investigation was performed to determine water content and strength against depth profiles, with the objective of quantifying the amount of ground improvement achieved. From reviewing the literature, one case study exists, namely the Sri Lankan trial embankments on peat deposits reported by Ariyarathna et al. (2011), which presents the general improvement achieved for combined vacuum–surcharge preloading. The author is not aware of other field case studies in the literature that quantify the strength improvement in a peat deposit achieved by vacuum consolidation alone.

At the Ballydermot site, "undisturbed" peat cores were recovered in successive 1.0 m lengths from locations V1 and V8 (outside of the test area, see Fig. 11.5(c)) using a 25-mm-diameter gouge auger. From the recovered cores (and with the peat backfill in place above the permeable layer), the top of the underlying glacial deposits were located at 4.3 m bgl across the test site. Samples from these cores were bagged, labeled, and returned to the geotechnical laboratory for the determination of water content and degree of humification (von Post number) against depth profiles for the virgin peat. The water content tests involved oven drying the samples at a temperature of 105–110 °C for a 48-h period. Although some organic matter in peat is susceptible to slight charring/oxidation at these elevated temperatures, measured water content values are nevertheless sufficiently accurate (O'Kelly and Sivakumar, 2014).

In practice, difficulties in obtaining samples for laboratory tests often make the in situ assessment of peat strength a more favorable option. Despite known problems with the test in peat (Landva, 1980; Boylan and Long, 2014), the field vane remains the most commonly used test device in the United Kingdom and Ireland for the determination of the "undrained" strength (s_{uFV}) of peat deposits. Deduced strength values are generally higher and may grossly overestimate the undrained shear strength of peat deposits due to partial drainage effects, an assumed failure surface (from which s_{uFV} is calculated) that is quite different from the actual failure surface and the interaction of the fibers with the vane, which often wrap around the vane during rotation, especially for fibrous peat.

In the present investigation, profiles of peak and remolded field vane strengths were determined at eight locations along transect A–A in Fig. 11.5(c). A GEONORH-70 field vane (vane height/diameter of 151.6/75.8 mm) having an accuracy of ±3% of full scale was used. A GEONOR H-10 field vane (vane height/diameter of 110/55 mm) was also trialed but was found to produce erratic results for this pseudofibrous peat. Within the 10 m × 10 m treatment area, the depth to the sealing membrane was established using a tape measure and the gouge auger, which could not easily penetrate into the top of the granular bed.

The vane was driven down, punching through the sealing membrane and 0.45-m-deep granular bed, to the required depths in the underlying vacuum-consolidated peat layer. Across the area, the depth to the standing groundwater table was determined from standpipes in the peat layer using an electric dip meter. At ground surface level, it was observed that peat material backfilled over the 10 m × 10 m treatment area was soggier than the surrounding virgin ground. This was explained by the embedded (concave profile) vacuum sealing membrane preventing downward flow, resulting in a perched water table locally, the posttreatment effect of which must be considered in design practice.

11.4.4 Ground improvement achieved and effect of bog hydrology

Figure 11.8 shows the profiles of natural water content, field vane strength (s_{uFV}), and von Post number against depth recorded for the virgin peat. Overall, the peat layer was moderately to strongly decomposed (H_5–H_7), with some slightly decomposed (H_4) peat present near the bottom of the layer (Figs. 11.8 (d, e)). The gouge auger was able to penetrate to a depth of ~10 cm into the top of the underlying glacial deposits, with the recovered material classified as firm light brown sandy silt with some gravel (V1) and soft light brown silty sand (V8). From the earlier cable-percussion boring investigation, this thin inorganic layer was underlain by very clayey sandy gravel (~30% fines) overlying slightly clayey sandy gravel (4–11% fines) (Farrell et al., 2012). In other words, the peat layer at the Ballydermot site could drain vertically to the underlying deposits.

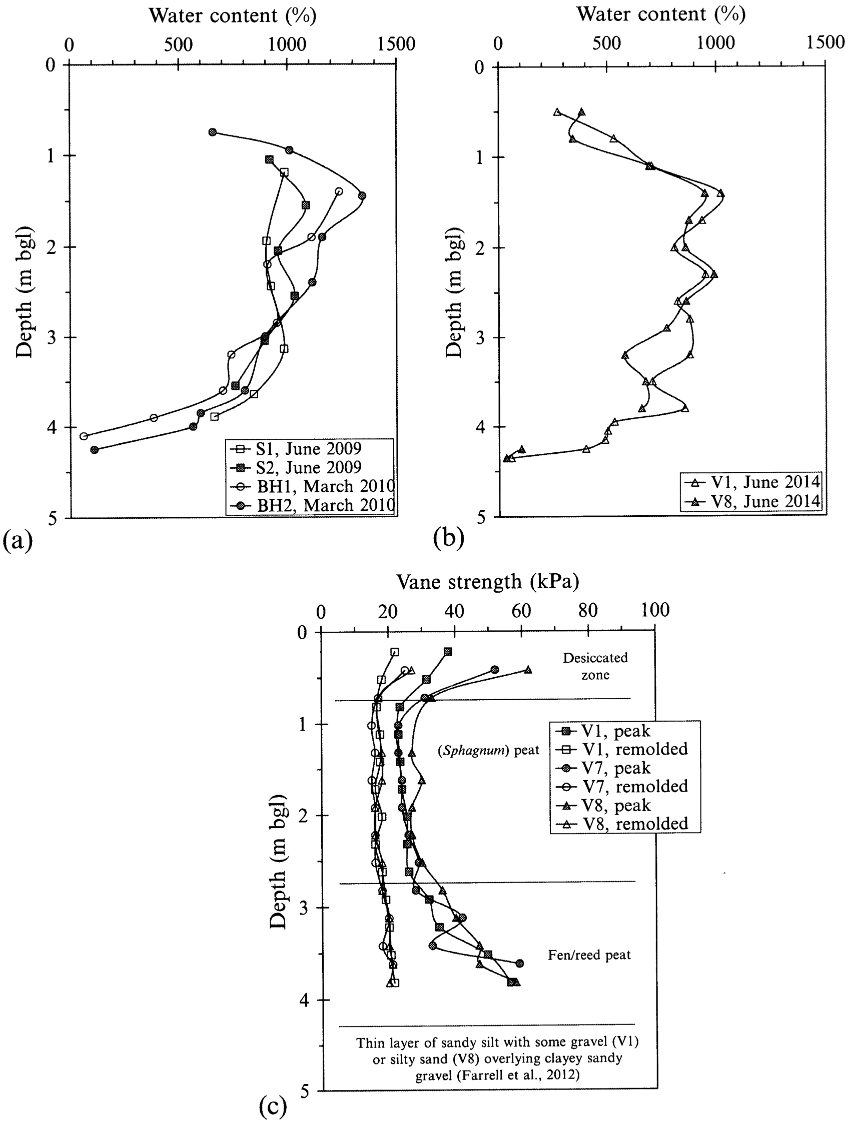


Figure 11.8 Natural water content, in situ vane strength, and von Post humification number against depth for virgin peat at the Ballydermot vacuum consolidation test area: (a) water content (adapted from Osorio-Salas, 2012), (b) water content (present study), (c) field vane strength (present study),

(Continued)

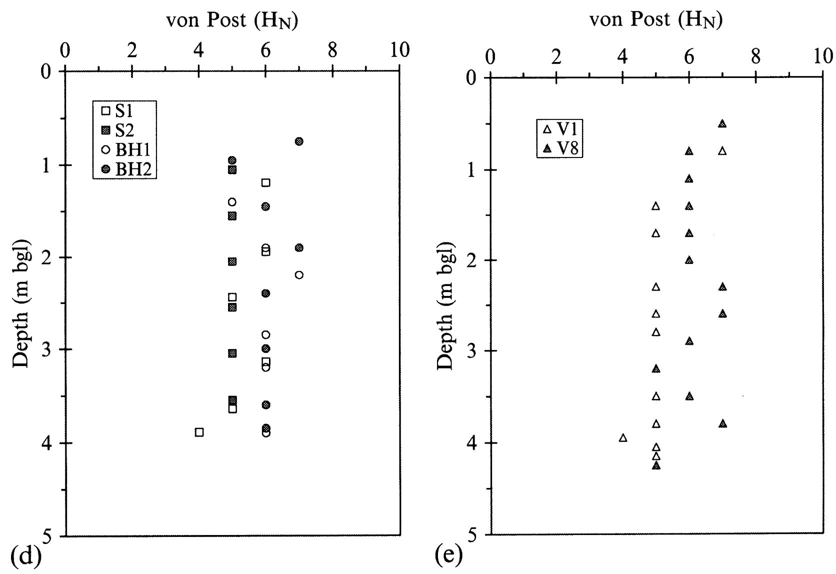


Figure 11.8 cont'd (d) von Post (adapted from Osorio-Salas, 2012), (e) von Post (present study). *Note:* BH, piston samples recovered on March 11, 2010; S and V gouge auger samples recovered in June 2009 and June 2014, respectively. Refer to Figure 11.5(c) for locations of sampling/testing points.

On June 14, 2014, the water content within the peat layer reduced approximately linearly from ~950% to 700% with increasing depth from 1.5 to 3.9 m bgl (Fig. 11.8(b)). For shallower depths, the water content reduced approximately linearly toward the ground surface (e.g., to ~300% at 0.5 m bgl). The standing groundwater table was located at 0.5 m bgl. From profile V1 in Fig. 11.8(b), the water content reduced from ~500% to 400% over the lowermost 0.4 m of the peat layer (i.e., 3.9–4.3 m bgl). The same general trends are evident in Fig. 11.8(a) for the June 2009 and March 2010 data, although seasonal effects and prevailing climatic conditions must be considered. The bog morphology changes on an annual cycle, effectively swelling during the wintertime and consolidating during the summertime, producing relatively higher and lower water content values, respectively.

The June (summer) 2009 and 2014 profiles were approximately similar. As expected, the end-of-winter (March 2010) data show significantly higher water contents, especially at shallower depths within the peat layer; for example, reducing approximately linearly from ~1250% (compared with ~950%) to 700%, with increasing depth from 1.5 to 3.9 m bgl (Fig. 11.8(a)). This would suggest that the lower 2.0 m thickness of the

Sphagnum peat layer was responsible for the greater proportion of the measured ground settlements/rebound. It must also be considered, and has been well documented (Landva, 1980; Hobbs, 1986; O'Kelly and Pichan, 2014), that the water content profile of peat deposits can vary sharply, even over short distances. For instance, Landva (1980) found that measured water content values for a given depth within a 75 m × 15 m test area at the Escuminac bog (New Brunswick, Canada) varied by at least 600%. This occurs because plants of different character live in communities and their decomposition rates are not uniform throughout the bulk mass, particularly during the early stages of decomposition. This natural heterogeneity was also evident for the Ballydermot site.

The field vane strength profiles shown in Fig. 11.8(c) are consistent with the water content profiles. In terms of strength, it would appear that the peat deposit was comprised of three distinct sublayers: a desiccated zone (crust) to 0.75 m bgl; a low-strength peat *Sphagnum* peat with peak s_{uFV} increasing marginally (22–26 kPa) to 2.75 m bgl; and low to medium strength fen/reed peat, for which the peak s_{uFV} increased substantially by 23 kPa/m depth increase. The fen peat layer was underlain by higher-permeability deposits that acted as a bottom drainage layer, inducing downward flow. This resulted in a reduction in pore water pressure (from hydrostatic condition) over the lower part of the fen peat layer. The increased consolidation/creep and more fibrous nature of the less decomposed peat (H_4) near the bottom of the peat layer can account for the recorded increase in shear strength. Botanical differences between the Sphagnum peat and underlying fen peat were also determining factors for the mobilized strengths. Increases in remolded s_{uFV} values with depth were insignificant for the *Sphagnum* peat and marginal for the fen peat (3 kPa/m depth for the latter), with remolded to peak s_{uFV} ratios of ~70% and 37–67% for the *Sphagnum* and fen peats, respectively.

Figure 11.9 shows the settlement profile for the base of the granular bed (top of vacuum-consolidated peat layer) 3.7 years after stopping the vacuum consolidation treatment. Note that in these calculations, the top horizon of the underlying glacial deposits was used as a reference datum in calculating settlement/strain responses. Most striking was the degree of swelling that occurred under the maintained ~9.5 kPa surcharge loading, with the trend in the data suggesting that the treated peat layer would continue to rebound. The vertical strains reduced approximately uniformly across the central transect (section B–B), from a maximum ε_z of 34% to ~14% for SM2 (Fig. 11.9), which was located in the 0.85 m PVD spacing area.

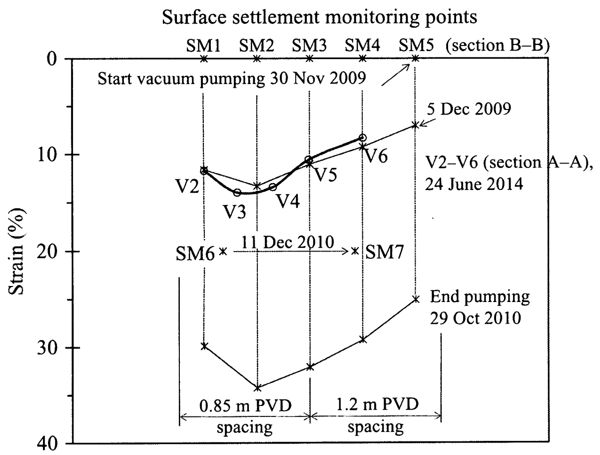


Figure 11.9 Vertical strain profile for the top of the vacuum-consolidated peat layer at the Ballydermot test area. For locations of surface settlement monitoring (SM) points and probing for in situ vane (V) tests, refer to Fig. 11.5(c). *Note: data for December 5, 2009 and October 29, 2010 adapted from Farrell et al. (2012); V2–V6, present study.*

The rebound profile for June 2014 closely matched the vacuum settlement profile for December 2009 (i.e., only 5 d after the start of vacuum pumping). With the treated peat layer in a rather heavily overconsolidated state ($OCR \approx 6$ arising from the ~60 kPa combined vacuum–surcharge preload and reduced surcharge load of ~9.5 kPa remaining in place), it was somewhat unexpected that the peat layer had swelled so much. From analysis in Section 11.4.2, the maximum settlement recorded at location SM2 was comprised of ~0.9 m primary consolidation settlement and 0.32 m secondary compression settlement ($\varepsilon_z \approx 25\%$ and 9%, respectively). Thus, the measured strain recovery was within the possible range for swelling to occur. Furthermore, heavy overconsolidation of peat layers for low embankments/ overburden, whether achieved by vacuum consolidation or other preloading technique, may not prove a wise ground improvement strategy. This is because significant swelling of the saturated peat layer is likely to occur (and as evidenced for the present case study, over a relatively short time frame), if the local bog hydrology remains intact.

Figure 11.10 shows peak and remolded vane strengths across the treated area, albeit measured 3.7 years after removing the vacuum preload. Considering that the treated ground had swelled significantly during the intervening period, the shear strength would have been higher (and water contents considerably lower) at the end of the vacuum pumping. Overall, the treated

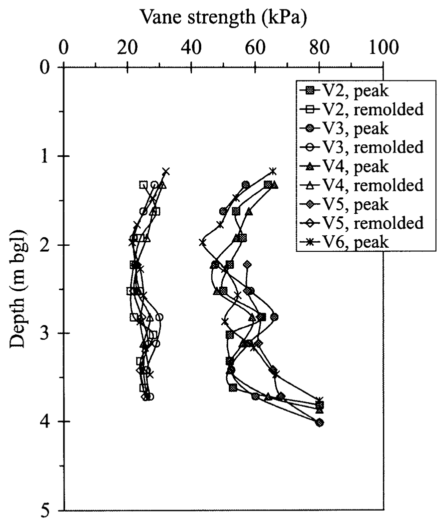


Figure 11.10 Field vane strength plotted against depth for the Ballydermot vacuum consolidation test area.

peat layer had medium undrained strength (peak $s_{uFV} = 45–65$ kPa), increasing to >80 kPa for the fen peat nearing its lower drainage boundary. Again, the strength profiles suggested that the peat deposit was comprised of three distinct layers, identified earlier in Fig. 11.8(c). Figure 11.11 compares the strength profiles for treated and untreated areas. In assessing the level of strength improvement, a strain adjustment was applied to the untreated soil profile, assuming a triangular strain distribution occurred over the peat depth; that is, maximum settlement occurring at ground surface, reducing to zero settlement at the base of the peat layer. In this manner, the vacuum-treated profile could be approximately compared against the consolidated profile but for no strength improvement (Fig. 11.11(b, d)).

Based on this approach, the strength improvement was greatest for the *Sphagnum* peat, with its peak s_{uFV} increasing almost uniformly by ~30 kPa over the layer depth, producing a strength gain of 105–150%. The gain in strength was not as great for the uppermost (crustal) and lowermost (fen) peat layers, both initially having greater strength than the *Sphagnum* layer. For the crustal layer, the increase in peak s_{uFV} ranged 15–30 kPa, corresponding to a strength gain of 30–105%, both increasing with depth. For the fen peat layer, the increase in peak s_{uFV} ranged 16–30 kPa, corresponding to a strength gain of 25–110%, both decreasing with depth.

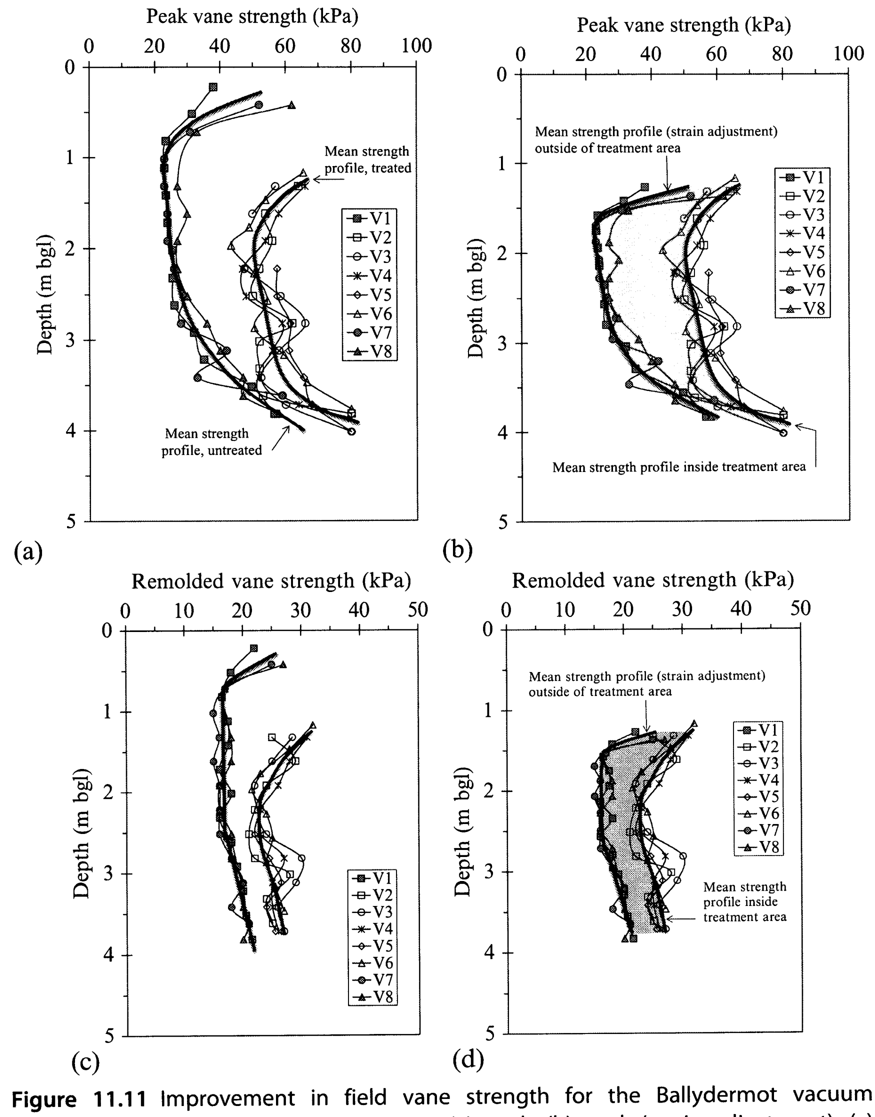


Figure 11.11 Improvement in field vane strength for the Ballydermot vacuum consolidation test area on June 14, 2014: (a) peak, (b) peak (strain adjustment), (c) remolded, (d) remolded (strain adjustment).

The rates of increase in peak s_{uFV} with depth were 5.6 and ~45 kPa/m depth for the *Sphagnum* and fen peats, respectively, although the latter value was strongly dependent on its proximity to the underlying drainage boundary. The ground treatment also increased the remolded s_{uFV} approximately uniformly by 6 kPa over the depth of the treated peat layer (Figs. 11.11(c, d)), equivalent to strength gains of 25–65%, 35–40%, and ~30% for the crustal, *Sphagnum*, and fen peat layers, respectively. The respective values of the ratio of remolded to peak s_{uFV} were ~48%, 40–48%, and ~48%; reduced from corresponding values for the untreated peat of ~70% (*Sphagnum*) and 37–67% (fen). These trends are consistent with the overconsolidated state of the treated deposit.

As described in Section 11.4.3, vane tests in peat may give misleading and nonconservative results for stability assessments. Thus, the field vane data presented herein should be treated with caution. Mesri and Ajlouni (2007), for instance, suggested a correction factor of 0.5 to be applied to the results of vane tests in peat. Nevertheless, other factors being equal, the relative increase in field vane strength determined over the depth profile is a good indicator of the strength improvement achieved.

11.5 DISCUSSION

From the published case studies by Cognon et al. (1994), Hayashi et al. (2002), Ariyarathna et al. (2011), and Farrell et al. (2012), it would appear that vacuum pressure of typically 80 kPa considered in design for soft clays (Chu et al., 2008) cannot be consistently achieved for vacuum consolidation in peat deposits. For the Ballydermot pseudofibrous peat, the average vacuum pressure of 50 kPa produced by the jet pump–centrifugal pump combination (Farrell et al., 2012) were in line with the negative pressures of 50 kPa achieved for fibrous peat (Hayashi et al., 2002) and maximum vacuum pressure of 55 kPa for amorphous peat (Karunawardena and Nithiwana, 2009; Ariyarathna et al., 2011). From these data, the maximum vacuum pressure was achieved shortly after the commencement of pumping, and as the ground deformations increased with elapsed time, the vacuum pressures decreased; an average of 35 kPa was reported by Ariyarathna et al. (2011). It is postulated that under the very large (differential) settlements of peat deposits, the likelihood of ruptures or tears in the sealing membrane, pipe connections, and peripheral sealing trenches increases, leading to greater pressure losses.

For the membrane system setup (see Fig. 11.1), the manner in which the edges of the sealing membrane are restrained in the perimeter trench means that the membrane becomes more vulnerable to tearing or rupture toward the later stages of vacuum consolidation. Based on the limited field data, a vacuum pressure of typically 50 kPa would seem appropriate in design for peat deposits. The Ballydermot field trial demonstrated that higher suctions of 50–70 kPa could be achieved using the jet pump–liquid-ring pump combination (Farrell et al., 2012). The perimeter trench must be deep enough, including an allowance for drawdown by the vacuum pumping, to maintain an airtight peripheral seal. A minimum additional 0.4 m depth below the lowest recorded seasonal groundwater level is recommended for keying the sealing membrane in perimeter trenches. A double membrane may mitigate against punching of the (tensioned) sealing membrane by the underlying permeable bed (gravel layer). It was noted that a perched water table could form above this impermeable membrane, the posttreatment effect of which must be considered in design.

In relation to PVD spacing, Hayashi et al. (2002) reported that significant improvement could not be achieved in fibrous peat for PVD spacing greater than 0.9 m. However, the vacuum consolidation technique has been successfully applied in peat using 0.85 and 1.2 (Farrell et al., 2012), 1.0 (Ariyarathna et al., 2011), and 1.4 m (Cognon et al., 1994) PVD spacings. This illustrates the difficulties in comparing projects involving different types of peat. If nothing else, the general success of these projects demonstrates that the vacuum consolidation technique can be applied just as effectively for peat as for soft clay deposits, where the technique has been widely used (see Griffin and O'Kelly, 2014a). The Ballydermot field trial showed that the consolidation rate was greater for closer PVD spacing, as one would expect, with the theoretical degree of consolidation inversely proportional to the square of the effective drainage length.

Based on "end of primary" settlements, average degree of consolidation values of 83% and 63% were achieved by the end of the first month of pumping for 0.85 and 1.2 m PVD spacings, respectively. This demonstrates the effectiveness of the vacuum consolidation technique in achieving a high degree of consolidation in a timely manner. Fibrous peat tends to be highly cross-anisotropic, with horizontal to vertical permeability coefficient ratios of 1.7–7.5 initially, which may explain why the consolidation rate can be very sensitive to PVD spacing (Hayashi et al., 2002). The design drain spacing is a function of the vertical and horizontal consolidation properties and effective drainage lengths and also the time period targeted to achieve the desired average degree of consolidation under combined vertical and radial drainage.

The Ballydermot field trial demonstrated the importance of understanding the bog morphology and hydrology in the assessment of the field data. Bogs are dynamic ecohydrological systems. Posttreatment, significant swelling of the saturated overconsolidated peat layer occurred over a relatively short time frame. At this raised bog site (*Sphagnum* peat overlying fen/reed peat), the deposit was open to two-way vertical drainage, with subartesian conditions below the bottom drainage boundary to higher permeability glacial deposits (Farrell et al., 2012). This may not be the case for other bog formations. Thus, at the Ballydermot site, the PVDs were installed to partially penetrate the peat layer in order to mitigate against vacuum pressure loss and inhibit upward flow via the bottom boundary. Nevertheless, during vacuum pumping, upward flow did occur through the bottom boundary, evidenced by calcification problems with the pumps (Farrell et al., 2012).

Posttreatment, a uniform increase in peak s_{uFV} of 30 kPa was measured for the low-strength *Sphagnum* peat (equivalent to a strength gain of 105–150%). Because the PVDs did not penetrate the full depth of the peat layer, the strength improvement for the bottom 1 m depth of peat was lower (increase in peak s_{uFV} ranged 16–30 kPa), although this was offset by the fact that this zone had significantly higher s_{uFV} pretreatment on account of the reduction in pore pressure (from hydrostatic condition) and hence increased consolidation/creep caused by downward flow to the underlying glacial deposits. Botanical differences and degree of humification also influenced the mobilized strength. Thus, there is significant scope for performing further experimental in addition to numerical studies on the behavior of peat in response to vacuum preloading.

11.6 SUMMARY AND CONCLUSION

Peat bogs are dynamic ecohydrological systems, heterogeneous and anisotropic in geotechnical properties, which are dependent on botanical origin and degree of humification. The bog morphology changes on an annual cycle, effectively swelling during the wintertime and consolidating during the summertime. For instance, within the *Sphagnum* peat layer at the Ballydermot raised bog, $w = 700$–1250% and 700–950% (increasing with depth) for the end of winter and midsummer, respectively. Thus, in assessing field performance, it is important to understand the bog morphology and hydrology. At the Ballydermot bog (*Sphagnum* peat overlying fen/reed peat), the bottom boundary drained to subartesian higher-permeability glacial deposits, which resulted in significantly higher peak s_{uFV} toward the bottom of the peat deposit. This will vary from one bog to another and particularly between bog types.

From the limited field trials reported for the vacuum consolidation technique in peat, the following conclusions have been drawn:

- The technique has proven to be effective in achieving a high degree of consolidation in peat ($w = 430$–860%), amorphous peat (110–470%), pseudofibrous peat (650–1350%), and fibrous peat (200–700%) deposits within economically viable periods of typically 3.3–8 months.
- For jet pump–centrifugal pump systems, an average vacuum pressure of typically 50 kPa seems appropriate in design for peat although higher suctions may be considered for a jet pump–liquid ring pump combination. A double heavy-duty sealing membrane is recommended since the membrane becomes more vulnerable to tearing and rupture under the very large (differential) settlements toward the later stages of vacuum consolidation treatment. A minimum additional 0.4-m depth below the lowest anticipated seasonal groundwater level is recommended for keying the sealing membrane in perimeter trenches to maintain an airtight peripheral seal. To establish this depth, it is recommended that the standing groundwater table level is monitored over an extended period, to include the end-of-summer months. As vacuum pumping progresses, considerable tension cracking in the peat occurs around the perimeter trenches, near ground surface level, although the local groundwater table level outside of these trenches is usually not significantly affected by the vacuum treatment (Farrell et al., 2012). A perched water table can form above the sealing membrane, the posttreatment effect of which must be considered in design. Vacuum pumping should not be scheduled during winter months if the risk of ground freezing is high, otherwise adequate thermal protection to exposed hoses and pipes is recommended to allow the system to remain in service and induce the consolidation of deeper (unfrozen) peat.
- For fibrous peat, the consolidation rate may be very sensitive to PVD spacing on account of the highly cross-anisotropic nature of such deposits. However, contrary to Hayashi et al. (2002), significant improvements have been achieved in (fibrous) peat deposits using the vacuum consolidation technique for 1.0–1.4 m (>0.9 m) PVD spacings. From the Ballydermot trial, as one would expect, the consolidation rate and hence accumulated settlement were greater for closer PVD spacing. In an attempt to mitigate against vacuum pressure loss, the PVDs were stopped 1.0 m short of the bottom of the 3.6-m deep pseudofibrous peat layer, although upward flow to the PVDs still occurred from the underlying glacial deposits, evidenced by calcification problems with the pumps. Nevertheless, for the 0.85 and 1.2 m PVD spacings (and average 60 kPa combined vacuum–surcharge preload generated), the respective average degree of consolidation values achieved by the end of the first month of pumping were 83%

and 63%, with the duration of the primary consolidation stage estimated at 3.3 months. Approximately half of the total measured settlements were achieved within the first two-week vacuum period. This demonstrates the effectiveness of the technique in achieving a high degree of consolidation for peat deposits in a timely manner.

- In terms of the level of ground improvement achieved, for the treated *Sphagnum* peat layer, s_{uFV} increased from 22–26 kPa to 45–65 kPa, equivalent to a strength gain of 105–150%. For the underlying fen peat layer, s_{uFV} increased with depth to greater than 80 kPa (strength gain of 25–110%).
- Posttreatment, significant swelling of the saturated overconsolidated peat layer occurred over a relatively short time frame under the 9.5 kPa maintained surcharge load, with the trend in the monitoring data suggesting that the peat layer would continue to rebound. From this, it is concluded that if the local bog hydrology remains intact, heavily overconsolidating peat layers in order to support low embankments/overburden, whether achieved by vacuum consolidation or other preloading technique, may not prove a wise ground improvement strategy.

11.7 NOTATION

H_N = degree of humification (von Post number)
m_v = volume compressibility coefficient
p_a = atmospheric pressure (≈100 kPa)
OCR = overconsolidation ratio
p' = mean effective stress
s_{uFV} = field vane strength
w = water content
ε_z = vertical strain
Δp = surcharge pressure
$\Delta p'$ = increase in mean effective stress
η = vacuum pump efficiency

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