Best Available Science Report For
Peat Settlement-prone Geological Hazard Areas

The report was prepared by Brennon Staley, MUP in Urban Planning, and reviewed by Susan Chang, Ph.D. in Civil Engineering, P.E.

Overview

Peat is an accumulation of partially decayed organic plant material that typically forms in wetland where lack of oxygen and acidic conditions inhibit complete decay. Unconsolidated peat deposits are generally characterized by a fibrous structure exhibiting weak compressive strength and high void ratios (i.e., containing significant void space).

Peat deposits are subject to settlement when loaded with additional weight or when groundwater levels are lowered. Lowering of the groundwater level reduces the buoyancy of overlying soils, thus increasing the pressure on the peat deposit and potentially resulting in compression. Settlement can occur where new fill or structures load soil or where groundwater levels are lowered due to sump pumps, temporary construction dewatering withdrawals, or other drainage projects. Because settlement can be induced by lowering of the groundwater table as well as by direct loading of the soil, settlement of peat deposits can occur a significant distance from the originating development activity because water withdrawals can influence the water table off-site.

Seattle Context

In the City of Seattle, peat deposits have typically formed in topographical basins created during the most recent glacial retreat and in the nearshore areas of lakes, the floodplains of the Duwamish River, depressions along modern streams, and marine estuaries. The lowering of Lake Washington by nine feet in 1916 also exposed significant areas of former lake bottom that contain peat deposits. As the City developed, these boggy areas were often filled to reclaim marshy areas considered to be a nuisance due to standing water and odors as well as to provide more developable land. Consequently, some of the many peat deposits have been buried and now support development throughout the City.

Urban development in these areas has led to further alterations which have impacted the peat deposits and their settlement potential. Drainage projects were initiated in some areas of the City to drain wet areas and redirect stream flows. Installation of storm drains and sewer systems, sump pumps, and impervious surface have reduced the amount of groundwater recharge through diversion of stormwater and groundwater inflow. Regrading projects and public utilities may also have changed water flow directions and created new flow corridors where granular fill has created new pathways of increased permeability. Together, these modifications have led to significant cumulative impacts where altered hydrology has created new equilibrium states, as well as acute impacts where individual development projects adversely affected nearby properties.

Mechanics of Peat Settlement

The magnitude of settlement occurring in a particular location is based on a number of factors including:

- Geotechnical characteristics of the peat
- Thickness of the peat deposit
- Existing pressure on the peat
- Change in pressure on the peat
- Historic loading of the peat

These relationships can be expressed in the following equation:

$$\text{Expected Total Settlement} = s_t = s_i + s_c + s_s$$

where s_i = immediate settlement
s_c = primary consolidation
s_s = secondary compression.

Immediate settlement is only of concern during fill or structure loading. Because these concerns are adequately addressed by existing building code standards, they are not a topic for this paper, which remains focused on potential off-site impacts.

Primary consolidation is a time-dependent settlement process that occurs in saturated fine-grained soils that have low permeability. The settlement is due to water slowly being forced from the void spaces of the soil due to increases in load on the soil. For soils such as peat and other highly organic soils with high natural water content and high void ratios, primary consolidation settlements can be large.

Primary consolidation is made up of a recompression component (settlement due to loading up to the maximum past pressure experienced by the peat) and a virgin compression component (settlement due to loading greater than the maximum past pressure experienced by the peat). Primary consolidation can be estimated with parameters from laboratory testing using the following equation (Holtz and Kovacs, 1981):

$$s_c = C_r * \frac{H}{1+e_o} * \log\left(\frac{p_p^{'}}{p_o^{'}}\right) + C_c * \frac{H}{1+e_o} * \log\left(\frac{p_f^{'}}{p_p^{'}}\right)$$

where s_c = primary consolidation
C_r = recompression index
C_c = compression index
H = thickness of the peat
e_o = initial void ratio (volume of voids divided by volume of solids)
p_o' = initial effective stress on the peat
p_p' = maximum past pressure on the peat
p_f' = final effective stress on the peat

Primary consolidation settlement can take several months to complete.

Secondary compression is a continuation of the volume change that starts during primary consolidation, but it occurs at a much slower rate. It constitutes a major part of the total settlement of peats and other highly organic soils, and it may continue for an indefinite time period, creating a continuing hazard. Secondary compression can be estimated with parameters from laboratory testing and the following equation:

$$s_s = C_\alpha * \frac{H}{1+e_p} * [\Delta \log(t)]$$

where s_s = secondary compression
C_α = secondary compression index
H = thickness of the peat
e_p = void ratio at end of primary consolidation
t = time period being considered for design

Once consolidation has occurred, peat deposits will never return to their original state, although minimal rebound is possible if weight is removed or the water level increases.

Estimates of the expected settlement due to groundwater table drawdown derived from the preceding formulas are included in Tables 1 and 2. The settlement estimates were based upon the following with the understanding that peat settlement properties can be highly variable:

(1) consolidation parameters from the WSDOT Geotechnical Design Manual of $C_{c\varepsilon} = C_c/(1+e_o) = 0.4$ and $C_{\alpha\varepsilon} = 0.06 * C_{c\varepsilon}$
(2) initial water table at 2 feet below the ground surface drawn down to 7 feet below the ground surface

Table 1: Estimated primary settlement (in inches) expected due to groundwater table drawdown from 2 feet below surface to 7 feet below surface.

Depth to top of peat deposit (ft)	Vertical Thickness of Peat Deposit			
	2 ft thickness	3 ft thickness	5 ft thickness	10 ft thickness
0	0	½	1½	11
5	2	3	5	9
10	1½	2	3½	6½
20	1	1	2	4

Table 2: Estimated total settlement (in inches) expected due to groundwater table drawdown from 2 feet below surface to 7 feet below surface.

Depth to top of peat deposit (ft)	Vertical Thickness of Peat Deposit			
	2 ft thickness	3 ft thickness	5 ft thickness	10 ft thickness
0	0	½	4	16
5	3	4½	7½	14
10	2½	3½	6	11
20	2	2½	4½	9

Effects of Settlement

The impacts of settlement can be significant, particularly where differential settlement occurs due to a peat deposit having variable thickness, groundwater flow directions, slopes, differential loading, or previous compressions. Common damages from settlement include uneven or cracked foundations, cracks in the interior finishes, sticking windows and doors, broken underground utilities, and uneven sidewalks and roads. These problems may cause existing structures to become more prone to damage during earthquakes. Flooding may also occur both as pipes break and settlement lowers the elevation of yards and structures, creating ponding, or even lowering areas below the water table. Because settlement occurs gradually, the impacts of additional loading or groundwater withdrawals may appear gradually after an initial modification.

Historic Settlement in Seattle

Evidence of gradual settlement has been found in many localized areas of Seattle. Areas in Greenwood, the most studied area of peat-rich soils, have been experiencing documented settlement of roads and structures as far back as 1958 (Shannon & Wilson 2004). Union Bay, one of the deepest known peat deposits in Washington State, has also experienced significant recorded settlement (Montlake Landfill Work Group, 1999).

In 2001, sections of the Greenwood neighborhood began to experience unexpected acute settlement. Developed on the location of historic wetlands, substantial subsurface peat deposits have been found under portions of

Greenwood including part of the Greenwood business district and the residential area north and west of NW 85th Street and Greenwood Avenue North. This area, commonly referred to as the “Greenwood Bog,” constitutes a topographical depression bordered by Phinney Ridge to the east and Crown Hill and Blue Ridge to the west. Lowered groundwater levels resulting from development along Greenwood Avenue North appear to be a cause of this settlement, although insufficient data exists to pinpoint an exact source (Shannon & Wilson, 2004).

Data for assessing the effects of settlement in other parts of the City is not readily available.

Peat Studies in Seattle

A number of relevant studies have been conducted in Seattle that have added to the knowledge of peat and peat settlement occurring within the City including the Map of Organic-Rich Deposits developed by GeoMapNW (Troost, 2006) and the Shannon & Wilson Greenwood Subsurface Characterization Study (2004).

The Map of Organic-Rich Deposits (GeoMapNW 2006) project compiled and analyzed boring logs submitted to the City of Seattle in conjunction with permit applications between 1914 and 2006. 33,270 reports were compiled and analyzed to identify subsurface deposits of peat greater than one foot in thickness. These results were then extrapolated based on historic geomorphology and hydrology to estimate the extent of peat deposits as well as other organic-rich geologic units, including wetland, lake, tideflat, and Vashon recessional lake deposits.

Follow-up work completed in June 2007 refined the earlier map and identified discrete bogs. This 2007 map, City of Seattle Identified Bogs, dated June 19, 2007, relied on 34,909 data points. The map shows both discrete bogs and individual borings/data points that indicate a presence of peat in the subsurface. This analysis summarized each of the peat deposits based on four factors that indicate potential risk due to settlement: thickness of peat, depth to peat, depth to groundwater level, and location of groundwater level in relation to peat. This characterization provides a critical resource for determining where much of the City’s peat settlement hazards exist. The map relies on available borehole data, geologic mapping, and geologic interpretation.

Another important study of peat settlement within Seattle is the Greenwood Subsurface Characterization Study (Shannon & Wilson, 2004). This study was commissioned by Seattle Public Utilities in response to acute settlement occurring in the neighborhood to determine underlying geologic conditions. The study developed a map that delineates the former peat bog area and identifies the depth and thickness of the peat throughout the area. Shannon & Wilson also tested the peat to determine the potential to re-introduce water into the substrata and placed monitoring devices in several locations for a long-term assessment of groundwater flows and levels in the area. The study concluded that settlement in the neighborhood was "likely the result of groundwater removal" occurring due to multiple factors including construction of impervious surface, diversion of stormwater, installation of the 1970s storm drain system, natural groundwater fluctuations, climate change, construction dewatering and permanent drainage systems in subsurface structures. Shannon & Wilson warned that the "continued groundwater removal and the removal of groundwater from other locations within the study area could contribute to additional or new settlement, and should be avoided where settlement could impact structures, utilities, roadways and other improvements." (Shannon & Wilson, 2004)

Implications for Regulation

Development in areas containing peat deposits can result in settlement where new structures or fill compress underlying peat soils or where modification of the groundwater table increases the effective pressure on underlying peat soils.

To avoid negative impacts from development, it is necessary to ensure both that new structures are designed to prevent or accommodate settlement and that they do not cause settlement off-site through modification of the groundwater table. Regulations should specifically seek to minimize modification of the existing groundwater regime because any modification of existing groundwater regime that removes or redirects groundwater even for a short period may lead to local groundwater depressions resulting in settlement. Alternatively, modifications of the groundwater table that increase groundwater levels, although they would not lead to settlement, may also be undesirable as they can not significantly reverse previous settlement activity and may lead to flooding.

Determination of areas that should be included in potential regulations should consider all the variables impacting settlement potential discussed earlier, including geotechnical characteristics of the peat, peat thickness, existing pressure on the peat, potential changes in pressure on the peat (including groundwater levels), and historic loading of the peat. Within regulated areas, protections should be applied even where geotechnical explorations fail to reveal peat deposits on the site of a proposed development because peat deposits may be present on nearby parcels.

References

Berry, P.L., and Vickers, B., 1975, *Consolidation of Fibrous Peat*, Journal of the Geotechnical Engineering Division, ASCE vol. 101, GT 8, August p. 741-753.

City of Seattle Peat Settlement Technical Review Committee, 2007, *Consensus Statements*.

Fox, P.J., et al., 1992, *C sub alpha/C sub c Concept Applied to Compression of Peat*, Journal of the Geotechnical Engineering Division, ASCE vol. 118, GT 8, August, p. 1256-1263.

Holtz, R. D. and Kovacs, W. D., 1981, *An Introduction to Geotechnical Engineering*, Prentice-Hall.

Landva, A.O., and Pheeney, P.E., 1980, *Peat Fabric and Structure*, Canadian Geotechnical Journal, vol. 17, no. 3, August, p. 416-435.

Montlake Landfill Work Group, 1999, *Montlake Landfill Information Summary*, January.

Rigg, George B., 1958, *Peat Resources of Washington*, State of Washington, Division of Mines and Geology Bulletin 44, State Printing Plant, Olympia, WA.

Shannon & Wilson, 2004, *Greenwood Subsurface Characterization Study: Seattle, Washington*, April 21.

Troost, Kathy, 2006, *Map of Organic-Rich Deposits in Seattle*, GeoMapNW, University of Washington, June 14.

Troost, Kathy, 2007, *City of Seattle Identified Bogs*, GeoMapNW, University of Washington, June 29.

Washington State Department of Transportation, 2006, *Publication M 46-03: Geotechnical Design Manual*, Environmental and Engineering Programs, State Materials Laboratory, Chapter 5, p. 21-22, December, <http://www.wsdot.wa.gov/fasc/EngineeringPublications/Manuals/GDM/GDM.htm>.

Technical Review Committee

Steve Erickson; Frosty Hollow Ecological Restoration
Steve Greene; HWA Geosciences
Thomas Kinney; HWA Geosciences
Kathy Troost; University of Washington, GeoMapNW
Mark Varljen; SCS Engineers