Geotechnical Construction Issues on Leeder Landfill (Cape Horn Industrial Park, Coquitlam, B. C.)

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Abstract: Over a 15-year period, the Leeder Landfill was used for disposal of waste materials including construction debris, wood waste and domestic rubbish. The landfill material typically varies from about 1.5 to 8 m in thickness. During later years of operation, it was reported that the landfill was partitioned into cells for fire control. On decommissioning, the landfill was capped with material from local construction excavations and river sand. Twenty-one lots were created in the Cape Horn Industrial Park, which was developed on the reclaimed Leeder Landfill. Commercial and light industrial buildings have been constructed on 17 of these lots. Building foundation systems include piles, conventional shallow footings constructed after preloading, and weight-compensated foundations constructed on Lightweight Cellular Concrete (LCC).

The major geotechnical issues in foundation analyses and design in this industrial park are associated with the magnitude and distribution of post-construction settlement. Methane generation is also a major issue. Other geotechnical issues include bearing capacity and soil liquefaction potential. Bearing capacity is generally a function of the thickness and characteristics of the soil capping of the landfill. With few exceptions, the soil capping is competent for a maximum allowable soil bearing pressure of 100 kPa. Potential for soil liquefaction is limited to saturated sand underlying the landfill at a depth of at least 13 m below ground surface.

Post-construction settlement is related to the landfill materials and native organic silt underlying the soil capping and consists of two components: mechanical consolidation, and subsidence due to biodegradation of organic matter in the landfill. Initial preparation of the industrial park recognized the settlement issue and included general preloading in the expectation of being able to market lots which could be directly developed with light warehouse and commercial buildings supported on conventional spread footings without further preparatory work. However, the preload was of insufficient thickness and/or was removed too soon to be fully effective. Extrapolation of the preload data indicated that, for an effective preload height of 2.35 m left in place for a further 30 years, between 200 and 300 mm of additional settlement due only to consolidation of the landfill material and underlying compressible silt would occur. It was also determined that biodegradation of the organic matter in the landfill under anaerobic conditions would result in additional subsidence of the ground surface of between 125 and 250 mm over the same 30 year time span. After preload removal, total long-term settlements were estimated at 300 to 400 mm. Larger settlements over a much shorter timespan would occur if the landfill environment became aerobic. This paper discusses additional foundation improvement and alternate foundation support systems, including appropriate methane control systems, which were required to deal with the potential large post-construction settlements.

Introduction

The Leeder Landfill in Coquitlam, B.C. was constructed with the intention of future development as an industrial park. The use of landfill materials to raise the general site grade has resulted in a combination of issues that create special geotechnical challenges to construction of warehousing and multi-tenant buildings on the subdivided lots. The main issues are related to post-construction settlement and methane generated as a by-product from the biodegradation of organic material deposited in the landfill.

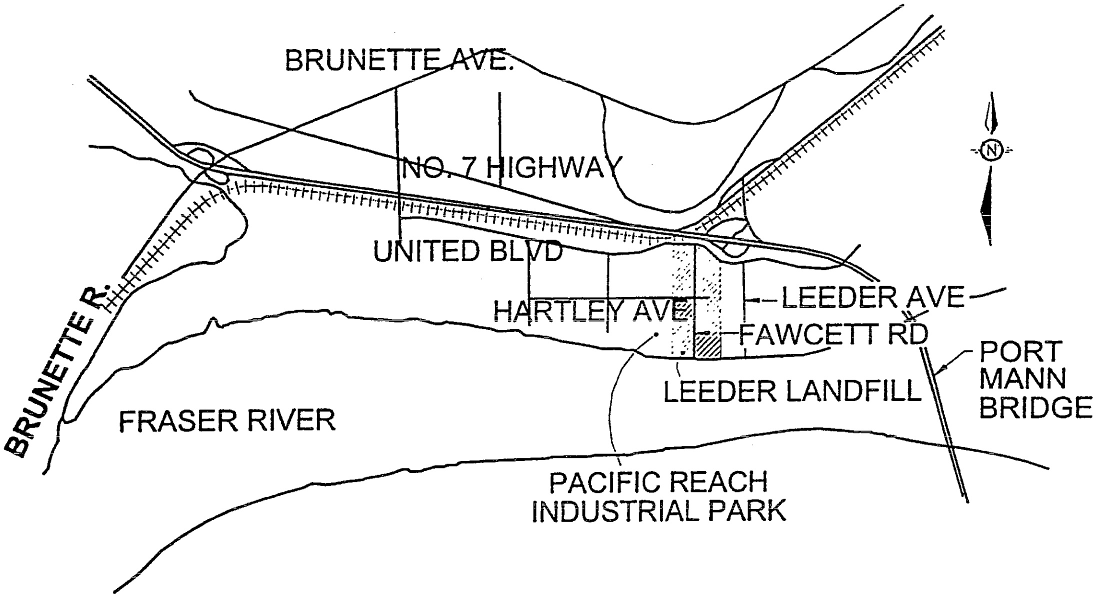
By the nature of the landfilling operation, the distribution of materials is random both in space and in composition. This leads to uncertainty in predicting the long-term performance of the subgrade materials.

Site description

The Cape Horn Industrial Park is located on the north bank of the Fraser River about 1 km west of the Port Mann Bridge on the site of the former Leeder Landfill as shown on Fig. 1. The site encompasses about 27 hectares bounded between United Boulevard on the north and by the Fraser River on the south side. To the west, the site is bounded by the Pacific Reach Business Park.

The site slopes gently down from north to south. The finished surface of the industrial park is approximately 4 m above the properties to the east and west. The eastern and western edges of the industrial park are marked by slopes as steep as 35 degrees.

Fig. 1 – Location Plan



The Cape Horn Industrial Park has been developed with a north-south access road (Fawcett Road) through the centre of the site and an east-west road (Hartley Avenue) connecting into the Pacific Reach Business Park to the west. Services including water, sewer, gas and telecommunication are buried below the streets or the boulevards flanking the streets.

The subsurface conditions are relatively consistent in terms of the materials encountered, but the thickness of the individual units is quite variable. The surface layer over most of the site investigated consists of mineral fill between 2.75 and 4.25 m thick. The upper 1.2 to 1.5 m of the fill consists of brownish grey, loose, medium grained river sand. The remaining fill consists of grey, compact silty fine sand and gravel and firm sandy or clayey silt with gravel; both these materials are of till-like origin and were obtained from construction excavations.

The fill overlies landfill debris, which typically has an upper layer of 0.3 to 0.6 m of wood-waste overlying a random mixture of construction debris, wood-waste and other assorted debris. The landfill has a strong organic odor. Throughout the industrial park, the landfill layer was observed to vary from 1.5 to 8 m in thickness. The average thickness is about 5.5 m.

Below the landfill material is native stiff sandy silt or compact silty sand. Along the northern perimeter of the industrial park, a discontinuous band of peat generally 0.3 m or less in thickness was encountered above the sandy silt or silty sand. The silty zone becomes increasingly sandy with depth and, by about 13 m below ground surface, the soil consists of compact to dense fine to medium sand with occasional thin lenses of siltier material. The sand extends to a depth of about 30 m, where it is underlain by clayey silt toward the river and glacial till at shallower depth toward the north end of the property.

Groundwater

In addition to localized, perched water tables encountered in the soil capping above the landfill, two aquifers have been identified during various investigations. The upper aquifer is located at a depth of about 5 m below ground surface. The deeper aquifer is associated with the sand zone beneath the landfill.

Landfill Operation

The Leeder Landfill was active between 1965 and 1979, and received mainly commercial and industrial wastes. Between 1965 and 1970, the landfill was operated by uncontrolled end-dumping of wastes. The waste materials were spread in layers and compacted with a crawler tractor. The main contents of the landfill are reported to be construction debris, hogfuel, wood waste, demolition waste, garbage and glass. Materials specifically excluded after 1970 are reported to be oils, creosote, PCB's, spent catalysts, drywall, tires and wood stumps.

According to Atwater (1980), a fire apparently occurred in the landfill in 1970, and, following the fire, operation of the landfill was changed to deposition in bermed cells. It was further reported that the cells were constructed by excavating 1.8 to 2.4 m into the native subgrade and casting the soil around the perimeter of the excavation to form berms. Material in excess of that required for the berms was used as the initial cover for previous cells. The dimensions of the cells were reported to vary from about 30 m to 60 m in plan. Air photos taken in 1976 indicate excavation for one cell on the eastern half of the property that appears to be about 60 m wide and over 250 m long.

Initial industrial park preparation

The soil cover over the landfill was constructed progressively as the landfill advanced. There are no records to describe the sequence of construction of the soil cover, but it is believed that the initial layer was composed of sandy silt and clayey silt excavated during cell construction. Final grading to raise site grade to the design level involved importation of material from construction excavation and dredged river sand to cover the capping. In 1989, a geotechnical investigation was completed by Golder Associates Ltd., which resulted in the construction of a general preload. River sand was used to build a preload fill 3 m above the existing site grade. The fill height resulted in an average effective preload height of 2.35 m after allowing for preload settlement. This was established for typical warehouse structural loads and a floor load of 15 kPa.

Geotechnical considerations

Soil Bearing

Initial investigations indicated that the sand fill covering the property had unadjusted Dynamic Cone Penetration blow counts varying from 2 to 15. The river sand is amenable to compaction, and, after proof-rolling, the sand fill provides an adequate bearing stratum for conventional spread footings.

The underlying sandy silt fill appears to have been spread with only minimal compaction, and is generally classified as firm based on unadjusted blow count data. However, as a lower subgrade material, the silty fill is satisfactory to support the loads of a typical warehouse structure.

For footing design purposes, a maximum allowable soil bearing pressure varying from 100 to 125 kPa is assigned to the sand fill, depending on the actual thickness of the layer. For slab design, a modulus of subgrade reaction, k, of 30 MPa/m is appropriate. Perched water in the sand fill has been determined to not require reduction in soil bearing values.

The landfill occurs in an area where the firm ground horizontal acceleration due to an earthquake with a return interval of 475 years would be about 0.22g. At this level of acceleration, liquefaction potential would be moderate to high in saturated granular soils between 10 and 15 m below surface across the site. The crustal soils and landfill materials were deemed to be non-susceptible to liquefaction. The non-susceptible soils were of sufficient thickness to preclude a punching failure of footings into the subgrade soils in the event of liquefaction of the deeper granular soils.

The potential for lateral spreading of non-liquefied soil crust during a design seismic event was judged to be low to moderate for buildings within less than 100 m from the banks of the Fraser River. No measures are known to have been implemented to resist lateral spreading, other than reinforcement of some of the slabs.

Settlement Evaluation

The entire Cape Horn Industrial Park, except for strips along the northern and western edges, was preloaded between September 1989 and January 1990. The preload fill was designed and monitored by Golder Associates Ltd.

The industrial park was surveyed before and after preloading by Matson, Peck and Topliss Land Surveyors. According to the survey information, site grade prior to preloading varied from about El. 8.3 m to El. 10 m. The top of the preload varied from about El 11.5 m to El. 12.7 m. Over 40 settlement gauges were installed to monitor the progress of preload settlement, and during the 4-month preload period, total settlements varying between 520 to 915 mm was recorded. Typical curves of the progress of preload settlement during initial site preparation are shown on Fig. 2a; for comparison, preload settlement curves for later, building-specific foundation preparation are shown on Fig. 2b – a lot with about 5 m of landfill. Fig. 2c is for a lot where landfill is absent and the settlement is due to native clayey silt. At the time the original excess preload fill was removed, the rate of settlement, as estimated on a semi-log plot, varied from 100 to 200 mm per log cycle. This inferred that, if the net preload of about 2.35 m were to be left in place for another 30 years, between 200 and 400 mm of additional settlement would likely occur due only to consolidation of the organic material in the landfill and the underlying cohesive soils. After removal of the preload, long-term settlement would be less. With building loads, the net effect would be that post-construction settlements of 100 to 200 mm could be expected

In addition to consolidation, the organic wastes would deteriorate with time due to biological action. The processes involved are discussed in more detail in the next section. Because the landfill had been capped, the environment within the landfill was oxygen-deficient, and under these conditions, the deterioration of the organic matter was anaerobic and relatively slow. For up to 8 m of landfill material, it was estimated that up to 250 mm of subsidence would occur over a period of 30 years due to volume loss caused by the biodegradation.

It was difficult to estimate deterioration rates at specific locations beneath buildings located over landfill debris because the material was a non-uniform mixture of wood products, metals, concrete, organics and miscellaneous debris. The anticipated deterioration would be irregular in time and distribution so that differential subsidence was expected. In addition, consolidation by preloading reduced the air permeability of the landfill material thereby reducing the degradation rate and partially smoothing out differential movements.

Fig. 2(a) – 3m Initial General Preload

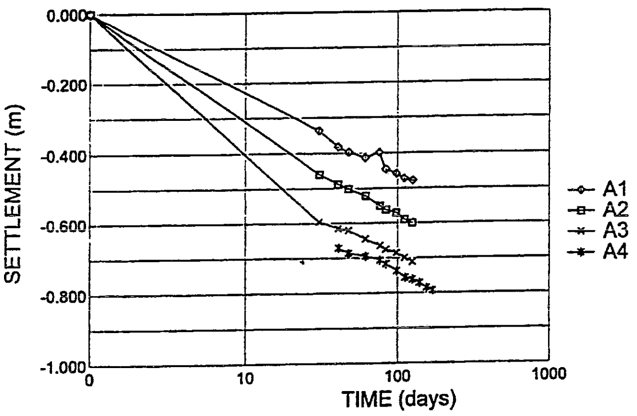


Fig. 2(b) – 4.5m Building Preload

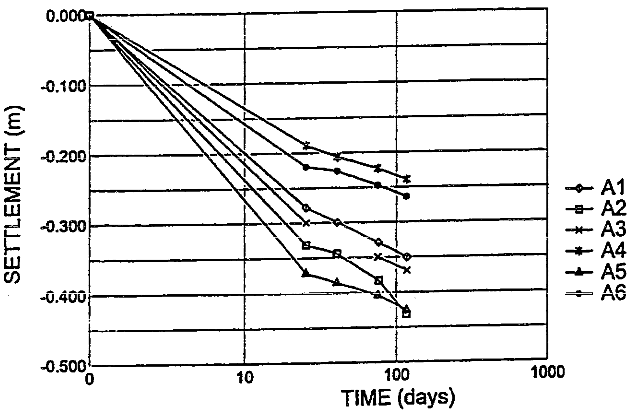
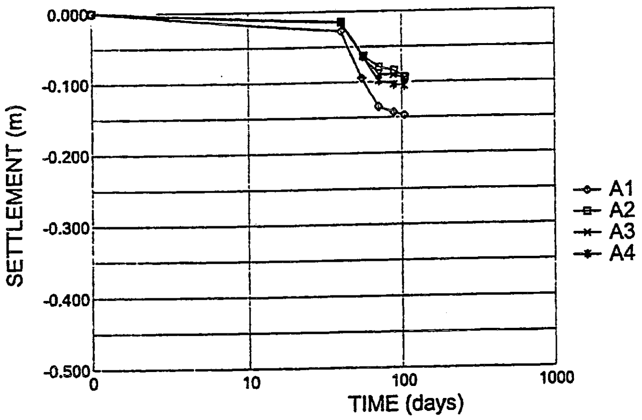


Fig. 2(c) – 3m Building Preload; Landfill Absent



The cumulative effect of consolidation and biodegradation was estimated to result in post-construction settlement in the range of 200 to 400 mm over the service life of a typical warehouse building without further treatment. The corresponding average differential settlement was predicted to be in the range of 100 to 200 mm over a 30 m width of building. Due to variability in the underlying landfill, the distribution of differential settlements was expected to be random. Because of the magnitude of predicted settlements, foundation treatment and design options were reviewed as discussed in a later section.

Methane

Methane (CH_4) is most commonly formed as a by-product of biodegradation of organic material. Optimum methane production in landfills occurs when the following conditions exist:

1. High moisture content: 60 to 80 percent;
2. Anaerobic conditions are maintained: oxygen is highly toxic to methane-producing bacteria;
3. Inhibiting chemicals are absent: high salt content, toxic wastes, etc;
4. Methane production may proceed within the pH range of 6.5 to 8.0, but the optimum range is narrow: 7.0 to 7.2; and,
5. Temperature falls within the range of 29 to 38° C.

At sites within the Leeder Landfill, excavation has exposed wood waste in the upper layer of the landfill beneath the soil capping, and measurements indicated pH to be in the order of 5.8. Although no temperature measurements were made, there were no apparent "hot spots", nor any evidence of rising steam from the excavation. Ambient temperature at the time was estimated to be about 15° C; it was therefore assumed that the temperature of the wood waste did not exceed about 20° C. Examination of the recovered samples did not indicate any apparent or significant degradation of the wood fragments after at least 20 years of burial.

Landfills go through several stages in the aging process. Unless interrupted, the stages progress naturally and sequentially. The initial phase at the time of deposition is an aerobic composting phase in the presence of oxygen wherein carbon dioxide and water are the principal by-products. As the oxygen is consumed, and provided there is not a source for additional oxygen, the environment shifts to an anaerobic condition, and methane is generated. This latter phase continues until the biodegradable materials have been consumed.

It is estimated that wood waste may yield up to 200 litres of methane per kilogram dry weight of the wood waste. The volume loss after the total yield of the gaseous by-products including methane is estimated at 25 to 30 percent. The rate of methane production at landfills stabilizes at between approximately 1.2 to 5.6 litres per kilogram per year. Because conditions in the Leeder Landfill are less than the optimum listed above, it is estimated that the actual methane production may range from 0.2 to 0.4 litres of methane per kilogram dry weight of wood waste per year. For the upper limit, methane production would last approximately 500 years with an anticipated volume loss of 30 percent. This translates into an annual volume loss of 0.06 percent or a subsidence rate of 2.5 mm per year for a 4.5 m thick layer of landfill. Total subsidence over 30 years would therefore be approximately 80 mm.

Decomposition under aerobic conditions is a more rapid process than anaerobic degradation, and can proceed to completion in as short a time as 6 to 9 months under ideal conditions. The composting process leads to a volume reduction of between 30 and 35 percent. This rapid volume loss translates into a maximum subsidence rate of 1800 mm per year for a landfill 4.5 m thick.

In landfills, methane occurs in combination with other soil gases and the resulting mix may be lighter or heavier than air depending on the relative quantities of methane and carbon dioxide. As a general rule, methane rises from the point of generation toward the ground surface. The soil gas will move from areas of high pressure to low pressure, and will also move by diffusion. The rate of flow depends on the permeability of the soil through which the gas moves, and the direction of flow is defined by the pathways of least resistance as well as the gradients giving rise to the flow. Rates of methane movement are also influenced by changes in atmospheric pressure and changes in groundwater level.

Buildings constructed on landfills are impermeable features that can trap upward migrating methane beneath the floor slab. Without appropriate measures, methane can then enter the building through cracks in the concrete of the slab, through construction joints and through services constructed through the slab. If methane concentrations reach the flammable or explosive range, any spark or open flame in the vicinity of the methane accumulation can trigger explosive combustion of the gas.

Methane Control

From analysis of the processes involved in methane generation, there are two clearly defined approaches for dealing with methane accumulating beneath buildings or in service trenches. The first is the more aggressive – or active – approach and involves preventing methane generation at the source. This can be accomplished by altering anaerobic conditions to marginal aerobic conditions. Introduced oxygen is toxic to the methane generating microbial population. The consequent side-effect is that aerobic conditions result in composting of the organic matter, which occurs at greatly accelerated rates unless a very fine balance can be realized between oxygen and methane. This is described in detail in the 1995 report by CH2M Hill.

The approach to achieve the required balance has been to install air injection wells into the organic waste, to inject air and to observe the rate of methane generation in an attempt to eliminate methane production while avoiding aerobic composting. Since flow rates and pathways for gas migration within landfills are highly erratic, it is almost impossible to deliver air uniformly throughout the methane-generating layer. Zones of aerobic and anaerobic conditions exist in close proximity, where rates of decomposition can vary by orders of magnitude. Monitoring at the surface may detect low to negligible methane concentrations, but this may be attributable to dilution at low concentrations rather than to a perfect balancing of anaerobic and aerobic conditions. As a result, the associated subsidence of the landfill causes extreme differential settlement over very short horizontal distances as has occurred at several sites within the Cape Horn Industrial Park.

The second approach to methane control is passive and involves letting the methane-generating processes proceed while preventing methane accumulating under buildings or sealed surfaces to concentrations that are within the explosive range. As discussed by McQueen et al (1998), commonly used procedures include:

1. Vapor barriers consisting of plastic sheeting beneath the building slab;
2. Air-tight construction of all service conduits through slabs;
3. Use of the building ventilation system to either maintain aggressive venting of the building atmosphere or to build up a positive pressure in the building to prevent methane entry to the building;
4. Construction of methane collection trenches beneath the floor slab connected to ventilation stacks to exhaust collected gases at roof level; and,
5. In the case of lateral migration of methane from offsite through utility trenches or through permeable soil, construction of collection trenches or impermeable curtains around the perimeter of the building.

Each of these measures has been used in the Cape Horn Industrial Park with success.

Foundation Design Options

The problems associated with foundation design in the business park include variability in thickness of the landfill, compressibility of the landfill and methane control. There are four options for foundation design; each reflects a different level of risk to long-term performance of the structure.

Construction of Building without Further Ground Improvement - Analysis of the settlement data for the initial general preload indicates that for the effective preload height and structural loads for a typical warehouse building, the original general site preload did not remain in place for a sufficient length of time to reduce long-term settlements to tolerable values. For buildings designed with conventional spread footings and an anticipated live load on the floor slab of about 15 kPa, without additional ground improvement beneath the building footprint, it was estimated that the structure could undergo total settlements in the range of 200 to 400 mm, including both consolidation and subsidence due to biodegradation. The corresponding differential settlement was predicted to be up to 200 mm over a distance of 30 m over a service life of 30 years.

At least three buildings have been constructed with conventional spread footings without further ground improvement. Of the three, two experienced slab cracking and shifting of tilt-up concrete panels. For both of these buildings, differential settlement was exacerbated by an air injection methane control system. Actual settlements without the air injection system would have been well below the estimated long-term values.

Foundation Improvement with Additional Preload - Additional preloading is a mechanism to deal with post-construction consolidation of the landfill materials. However, preloading has less effect on the magnitude of biodegradation. The net effect of additional preload is therefore to reduce post-construction total settlement and to smooth out potentially abrupt differential movements. To be effective within a reasonable time frame, the preload height for typical warehouse structures was determined to be between 3.5 and 4.5 m above slab grade. Figure 2b shows the settlement response of a lot underlain by landfill under a 4.5 m preload. Figure 2c shows the preload settlement response of a nearby site that is not underlain by landfill. While total settlement at the end of 4 months varied between 230 and 430 mm, the rate of settlement from extrapolation of the curves for a net preload of about 4 m would be 70 to 100 mm per log cycle or 150 to 200 mm over the next 30 years. Since average building loads are substantially less than the equivalent of 4 m of fill, the post-construction settlement of a typical warehouse would be significantly less than 100 to 200 mm over 30 years.

At least three buildings have been constructed on the principle of additional preloading and conventional spread footings. Two of the buildings have performed within the range of predicted settlements, but the third experienced abrupt differential settlement along the lines of air injection wells installed for methane control.

Weight Compensation – Because the original general site preload was not left in place for a sufficient length of time, or, conversely, was not high enough for the shorter preload duration, the full preload impact was not adequate for reasonable building performance. As an alternative to placing a second, higher preload, weight compensation can be used to reduce long-term differential settlements. One method involves replacement of subgrade soil beneath loading bearing walls and column pads with Lightweight Cellular Concrete (LCC). LCC has approximately one-third the unit weight of sand fill, and therefore by sizing a wall footing trench appropriately, a load compensation effect can be achieved, which is equivalent to the load of the walls. The applied structural loads are attenuated through the LCC trench fill resulting in a combined soil and structural applied stress at the base of the trench, which is less than the overburden pressure prior to construction. In effect, the foundation of the walls is designed to float. This effect, combined with the past preloading, reduces the total long-term settlement. By offsetting much of the effect of consolidation, the post-construction settlement is then essentially due to biodegradation. The beam effect that the LCC provides further reduces the impact of biodegradation-induced differential settlement on building performance. The predicted long-term total settlement is expected to be in the range of 100 to 250 mm, with differential settlements in the order of 75 to 125 mm over the width of the building.

The LCC method has been used for construction on at least 6 of the lots in the business park. Where data are available, all of the buildings but two are performing within the predicted range of settlement. For the two buildings that have experienced larger than predicted differential settlement, the building footprint extended beyond the limit of previous site grading fill and preloading, and some of the LCC was placed directly on landfill material.

Pile Foundations – Pile foundations offer the least risk of damaging settlement occurring to the building. For this option, piles are driven through the landfill and soft native silt into the underlying sand. Because of potential obstacles to pile driving, timber piles are provided with driving shoes to assist penetrating the landfill. Typical embedment lengths for timber piles in this area are about 15 to 20 m. Steel piles may be driven deeper to achieve set, but would have an increased capacity. Site services entering the building require flexible connections as the yard area would settle relative to the rigidly supported building.

At least four buildings in the business park have been constructed on piles. To date the general performance has been satisfactory, except for one building where an air injection methane system was installed. In this case, up to 600 mm of settlement of the pavement adjacent to the building occurred, requiring several repairs to the pavement.

Conclusions

The Leeder Landfill has unique settlement problems that must be considered when preparing foundation designs for structures built over organic waste. Because of unpredictability in determining the distribution of settlement, the degree of risk for projects on this site is greater than on conventional mineral soil sites. Several foundation treatments are conventionally available to address the settlement issues that can reduce the risk factor to acceptable levels for warehouse-type structures. In conjunction with the foundation design issue, methane generation due to biodegradation of the organic waste must also be addressed. It has been found that, where air injection has been used to control methane generation, unplanned, and significant, settlements have resulted in unacceptable damage to the buildings.

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