Abstract: Closed landfills are being used beneficially, either as wildlife habitats, parks and golf courses, or even as sites for retail buildings. This paper will focus on the geotechnical aspects of the construction on closed landfill sites. It will include a comprehensive literature review of the current state of the practice of construction on closed landfill sites, typically municipal solid waste. The paper will address such topics as site improvement that is typically done before construction can begin. In addition it will address design issues that need to account for the compressibility and low bearing capacity of the waste material underlying the construction. To provide sufficient bearing capacity, pile foundations are typically used. Downdrag on the piles due to waste settlement is a major problem. Environmental health is also a major concern in such construction because any breach of the landfill containment system would jeopardize public health. Construction on closed landfill sites therefore requires careful planning, and design to account for the characteristics of the waste as well as health and safety issues. These topics will be addressed in the paper. The future of such construction will also be discussed.

Keywords: Landfill, construction, current practice, geotechnical engineering

1. Introduction

More closed landfills are being used beneficially today as demand for usable land increases. There has been an expansion of the possibilities from wildlife habitats, parks and golf courses to retail buildings, family homes, and office parks. The sites that are being built on are mainly municipal solid waste (MSW) landfills. Landfills can be wonderful sites for real estate development. Often located near major transportation routes, many older landfills are located in growing urban or suburban population centers, where demand for real estate is high.
There are many challenges to reusing a closed landfill site. Liability considerations (Superfund, toxic torts) and technical problems (settlement, gas, health and safety) abound. But just as a growing number of formerly-used industrial sites are being redeveloped for productive uses in what has become known as the "Brownfield" movement, so too have landfill sites been increasingly developed for high-value, productive land uses.

The major considerations when constructing on a landfill are evaluating the site for the appropriate type of structure and end use, the actual design process, the environmental health risks and precautions, and finally site monitoring after construction is complete. Landfills will have varying settlement rates depending on the type of waste and foundation used during construction, so careful monitoring is required after the project construction is completed. In the past, construction on closed landfills has resulted in problems associated with excessive settlement. Projects like this need careful and extensive planning, which will be discussed further in the paper.

2. General Design Process

There are also three goals that should be considered during the general design process. They are to achieve acceptable performance as the site settles, avoid penetration of the low permeability landfill cap (barrier layer), and to minimize future maintenance requirements. Keeping these goals in mind while designing, helps keep the engineers on track. To achieve these goals, Keech (1996) has implemented a four-step design process. The four steps are as follows:

- Analyze historical documents and geotechnical reports;
- Define site characteristics (boundary conditions);
- Design foundation for predicted rates of settlement; and
- Define future inspection and maintenance requirements.

These topics will be discussed in more detail in the following sections.

2.1 Analysis of historical documents and geotechnical reports

This process helps guide both the geotechnical and civil engineers. Some of the major documents that should be analyzed are:

- The original landfill grading plan: The original landfill grading plan will shed light on the boundaries of the landfill, and the bottom elevation of the landfill without having to resort to extensive investigations.
- Sequence of landfill operations: Sequencing of landfill operations is of particular importance in assessing the rate of decomposition of the waste and the expected settlement. This information can be obtained from written logs and operation reports, as well as personal interviews with operators of the facility.
- Existing utilities and landfill gas collection systems: The location of these facilities is important in determining the location of the constructed facility.
• Previous uses and topography: Previous use of the facility before development will alter the settlement to be expected.
• Contour map of depth to the barrier and refuse layer: This information will be used by the designer to make sure that none of the construction operations will cause a breach of the barrier layer.
• Contour map of anticipated settlement: This will provide the designer with information on expected settlement due to consolidation of the waste material within the landfill.
• Contour map of settlement per foot of additional fill: This will provide information on settlement to be expected due to loads produced during and after construction due to the addition of the constructed facility.
• General analysis of surcharge and dynamic compaction options: The feasibility of using surcharge or dynamic compaction during construction to preconsolidate the waste material will be determined.

2.2 Defining boundary conditions

Closed landfills are very different from regular ground sites due to the nature of the material that lies below the ground. Differential settlement is a major problem plaguing landfill sites. Boundary conditions exist when large differential settlements take place over short distances. Keech (1996) differentiated between artificial boundaries such as those created by deep foundations as hard boundaries and those due to site changes as soft edge boundary conditions.

Soft edge boundaries can develop because refuse depths vary and the actual bottom of the landfill is not level. Composition of the landfill also varies throughout, which means the rate at which it decomposes will vary. The age of the landfill also causes soft boundaries. The type and thickness of the landfill cover can cause changes in the loading of the landfill mass as well as if the site was ever used for anything else such as recycling or storage. Many of the variables for soft edge boundaries conditions are hard to define. Therefore, observation over long periods of time and empirical data will provide accurate enough information to go ahead with construction.

Hard edge boundary conditions occur mainly where the site meets the structure and vertical shear occurs. Utility connections that cross hard edge boundaries are of concern. Isolated pile caps and grade beams may sometimes protrude from the site as the area settles. With many sites, retaining walls may be required near the edge of the site; these spots should be given much attention. As with the soft edge boundaries, hard edge boundaries need to be looked at carefully so that nothing is overlooked.

2.3 Design foundation for predicted rates of settlement

Foundation design for buildings on closed landfills requires special consideration. Suitable foundation design requires an evaluation of the total and differential settlement,
the effect of the foundation on air and water quality due to possible puncturing through the liner system, and impact of the landfill environment on foundations.

Settlements of solid MSW are not as well understood as those for soils. Sowers (1968, 1973), Sheurs and Khera (1980), and Edil et al. (1990) have proposed models for prediction of landfill settlement. Data compiled by Fassett et al. (1994) showed that published data and formulas can be used to develop conservative initial settlements, but site-specific measurements are required. In most cases settlement can exceed 4 inches. To reduce settlements after construction, site improvement techniques can be employed. Some methods suggested by Dunn (1993) are:

- Delaying construction so that decomposition can take place
- Compaction of the surficial deposits of the MSW
- Surcharging
- Dynamic compaction
- Grouting or fly ash injection

2.3.1 Shallow Foundations

Most structures constructed on closed MSW landfill require deep foundations unless it is a very lightly loaded building when shallow foundations can be used. Shallow foundations used include conventional spread footings, reinforced concrete mats, and grid foundations (Dunn 1993). Additional reinforcement is used in these shallow foundations to be able to tolerate the stresses developed due to differential settlement. In most cases, an engineered fill is provided which provides the bearing capacity. In cases where this cannot be provided, bearing capacity calculations are difficult because the strength properties of MSW are difficult to determine. It is advisable to use a range of published values of strength of MSW from Jessberger and Kockel (1991), Mitchell and Mitchell (1992) or Fassett et al. (1994). High factors of safety are also required to account for the uncertainties in the strength properties of MSW.

2.3.2 Deep Foundations

Pile foundations are the deep foundation system of choice for larger buildings constructed on closed MSW. Design of pile foundations require an analysis of the vertical and lateral pile capacity, downdrag loads, the impact of the construction on the landfill environment including the likelihood of punching through the landfill liner, and corrosion resistance of the pile (Dunn 1993). Downdrag loads on piles can be significant. Downdrag develops when the surrounding material settles more than the downward movement of the pile shaft. To calculate the negative skin friction values developed on the piles, shear strength properties cited by Fassett et al. (1994) can be used. If it is found to be significant, field pull out tests can be done to determine the downdrag effect. To reduce downdrag on piles in MSW, techniques that will reduce the downdrag on piles can be used including coating the piles with bitumen, installing an outer casing, or pre-drilling the pile.
Corrosion of piles is a serious issue as decaying MSW generates acids, chlorides, and sulfates. To reduce the effect of corrosion on piles, Rinne (1994) suggested some of the following approaches:

- Use of Type II or V cement.
- Increasing the thickness of concrete cover over the reinforcement.
- Designing a strong concrete mix.
- Using epoxy coated steel reinforcement.
- Using cased piles, with the casing backfilled with concrete or bentonite.
- Cathodic protection of steel piles.

Design of foundations also requires careful consideration of the site plan and constant vigilance being exercised to determine if there is any leachate or landfill gas migration due to construction. Pile foundations cannot be driven through geomembranes or thin clay liners without breaching the landfill. Pile foundations can be installed more easily in natural sealing layers. It will be required by the construction company to demonstrate to the regulatory agency that there will be no migration of leachate into the groundwater or gases into the atmosphere as a result of the construction.

Planning for differential settlement has also to be done. There are three main areas that need to be designed for differential settlement. They are finish slopes, site utilities, and pedestrian/utility connections to the structure.

The finish slope and grading design is a soft edge boundary. Design for this is usually for the ultimate finish slope desired after differential settlement. This is a long and iterative process, which includes testing the design by applying the expected settlement from the contour map. Settlement from the additional fill also needs to be considered. Paving materials on the site should be flexible and the use of Portland concrete cement should be limited. Many times an additional fill is needed, but it is smart to minimize it since more fill adds to the settlement of the site.

When designing for site utilities, settlement and fill settlement need to be considered. Utilities should try to be condensed into one area. With gravity utilities, it has to be noted that no reversal in flow direction takes place due to settlement. Sometimes utilities can be placed above grade without affecting the aesthetics of the building. With all of the utilities more problems arise, so factors of safety are incorporated to ensure the quality of the structure.

The pedestrian and utility connections to the building are especially important for buildings on pile foundations. Where walkways and utilities enter and exit the building, there is a great amount of vertical shear where the building meets the ground. The amount of dislocation at these points is greater for pile-supported buildings. Some of the methods used to fix this problem are placing hinged slabs at the building entrances and making sure grade beams/footings are formed to provide a smooth slip surface for site settlements. Again, designing for these considerations incorporates factors of safety into the project.

2.4 Inspection and maintenance requirements
While planning the final design, the future has to be considered. After the structure is finished, it needs to be monitored to ensure safety. During construction, settlement monitors should have been placed so that the actual settlement can be tracked and compared to the anticipated settlement. The condition of the pavement needs to be checked on. Slopes and small cracks or voids have to be filled/sealed in order to keep water infiltration minimal. If hinged slabs are used, the leading and tailing ends where the angular rotation occurs, have to be inspected. Utility connections have also to be checked where they connect to the building or run off site.

3. Environmental health considerations

Environmental health is also a concern that needs to be factored into the final design. The major hazards of landfill gas are flammability, asphyxiation and toxicity, and the odor (Card, 1991). The flammability of landfill gas is due to the presence of methane, which is explosive when mixed with air at certain ratios. Asphyxiation (suffocation) and toxicity can occur due to the minimal amount of oxygen in the gas. The landfill gas also has adverse effects on the vegetation of the surrounding area. The gas also gives off a strong, unpleasant odor. All of these risks have a direct effect on the end use of design and the surrounding community of the site. The risks are life threatening and need to be given great concern when designing the site.

The level of risk from the landfill gas depends on the composition, the rate of generation and emission, the rate of dispersion and diffusion, and the potential migration route. There are many solutions to these problems. To decide on a solution, one has to do extensive research and observation of the site and then put one of the most effective solutions to use. A few of the design solutions are encapsulation, passive venting, gas-detection and alarm systems, and gas management systems.

3.1 Encapsulation

Encapsulation refers to placing a low permeability cap, like clay over the site to control gas emissions. The requirements for a material that will serve as an effective cap is given in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Design Criteria</th>
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<tbody>
<tr>
<td>Plasticity Index</td>
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<tr>
<td>Moisture Content</td>
<td>(&lt; 1.2 \times \text{optimum moisture content})</td>
</tr>
<tr>
<td>Compaction</td>
<td>(&lt;5% \text{ air voids})</td>
</tr>
</tbody>
</table>

3.2 Passive venting
The main purpose of passive venting is to remove or reduce gases that are produced prior to construction and to control migration of gases. Typical venting systems can comprise of trenches or gas wells. Beneath buildings, a void space, which is ventilated by air vents through the cavity wall, may be provided between ground slabs and the building structure.

3.3 Gas detection and alarm systems

In residential and retail buildings on a closed landfill, gas detection and alarm systems will be installed to monitor and protect against any build-up of dangerous levels of gases. The alarm system is usually a two-stage alarm, with a low-level alarm indicating that gas levels have increased and ventilation and investigation is required, and a high-level alarm to indicate elevated gas levels in excess of permitted values requiring evacuation of people.

3.4 Gas management systems

Gas management systems include regular monitoring of landfill gas concentrations at specific monitoring points, which could be at under-floor voids in buildings as well as regular servicing and maintenance of existing landfill gas collection systems.

4. Conclusions

The steps of the design process on a closed landfill site contain more requirements than on a regular site. The developing on a closed landfill can run smoothly as long as the site is analyzed properly and the characteristics of the ground are considered along with the environmental health risks and post construction monitoring is planned for. Some examples that this can be done are the Key Largo Landfill, which was talked about before, the SanLando Landfill, which was turned into a softball complex, and the Dyer Boulevard Landfill closure. All of these sites were successful projects that followed the proper steps for construction on a closed landfill.

5. References