# Predicting post-construction settlement of waste material in a superfund site pre-loaded with a surcharge embankment

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ABSTRACT: Thousands of contaminated sites exist nationally in United States of America as a result of waste being buried, or improper management in the past several years. Some of these sites have been selected and monitored as part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), which was passed by US congress in 1980. There have been many successful cases in restoring these superfund sites to productive use in the past. Among those productive uses are ecological enterprises, recreational areas, and commercial buildings. The focus of this study is on preparing a superfund site for commercial use. A surcharge program was adopted as a ground improvement measure to mitigate long-term settlement. There are large number of case studies involving the estimation of soil settlement using a 2D numerical model. However, the models mostly suffer from being limited to the 2D analyses, specifically for structures that are not long in one dimension. The purpose of this project was to develop a 3D numerical model to estimate total settlement of the existing soil at the site. Janbu's approach was used to estimate the primary compression settlements of soil as it provides a better fit to the load-settlement curves at any stress level. The results show that the design settlement can be achieved after 3.5 months of implementing the surcharge program.

RÉSUMÉ : Des milliers de sites contaminés existent à l'échelle nationale aux États-Unis d'Amérique en raison de l'enfouissement des déchets ou d'une mauvaise gestion au cours des dernières années. Certains de ces sites ont été sélectionnés et surveillés dans le cadre de la Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), qui a été adoptée par le Congrès américain en 1980. Il y a eu de nombreux cas de réussite dans la restauration de ces sites de superfonds à une utilisation productive dans le passé. Parmi ces utilisations productives figurent les entreprises écologiques, les aires de loisirs et les bâtiments commerciaux. L'objectif de cette étude est de préparer un site de superfonds à usage commercial. Un programme de surcharge a été adopté comme mesure d'amélioration du sol pour atténuer le tassement à long terme. Il existe un grand nombre d'études de cas impliquant l'estimation du tassement du sol à l'aide d'un modèle numérique 2D. Cependant, les modèles souffrent surtout d'être limités aux analyses 2D, en particulier pour les structures qui ne sont pas longues dans une dimension. Le but de ce projet était de développer un modèle numérique 3D pour estimer le tassement total du sol existant sur le site. L'approche de Janbu a été utilisée pour estimer les tassements primaires de compression du sol car elle offre un meilleur ajustement aux courbes charge-tassement à n'importe quel niveau de contrainte. Les résultats montrent que le règlement de conception peut être atteint après 3,5 mois de mise en œuvre du programme de surtaxe.

*Keywords:* Numerical modeling; deformation; Janbu's method; Site monitoring.

## 1. INTRODUCTION

According to the United State Environmental Protection Agency (EPA), thousands of contaminated sites exist around the US due to hazardous waste being left out in the open, or otherwise improperly managed. These sites include manufacturing facilities, processing plants, landfills and mining sites. In 1980, the United States Congress passed legislation known as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). This became informally known as the superfund program. Well reported events, such as the Love Canal explosion, triggered legislation to monitor and limit the potential threat posed by buried waste that has been mostly forgotten. To return sites that are suspected or known to be contaminated, another initiative was taken by the EPA to establish the Superfund Redevelopment Initiative (SRI). The SRI's mission is to ensure that necessary tools and knowledge are present to return these sites to productive use. As of 2019, there are 1335 superfund sites that have been placed on the National Priorities List. According to the EPA, "The national priorities list is the list of sites of national priority among the known releases or threatened releases of hazardous substances, pollutants, or contaminants throughout the United States and its territories" ("Superfund: National Priorities List (NPL) | US EPA", 2019). Superfund sites that are currently in reuse are presented in Figure 1.

Due to the complexity of the Superfund site, and the several unknow settlement behavior of these sites, in the past they had been usually not selected for construction to avoid complications. However, in more recent years, as the demand for land in highly populated areas has significantly increased, the superfund sites have gained more attention.

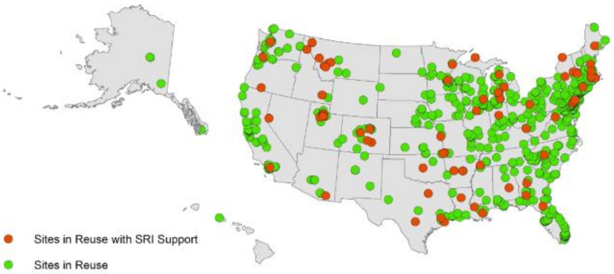


Figure 1: Locations of superfund sites currently in reuse in US

One of the main design challenges that engineers encounter in projects, which involve reuse of these sites, is to estimate the amount of settlement. A significant amount of research has been done to estimate long-term settlement of the subgrade. Most of these methods include either theoretical modelling or settlement monitoring of the site. There are large number of established theoretical methods for predicting settlement, notably Terzaghi's one-dimensional conventional linear model (Terzaghi, 1925). Terzaghi's 1D consolidation theory has been widely used, but it is not always effective due to the uncertainty of coefficient (Li, 2014). Although it can be adopted to predict the ultimate primary consolidation settlement of the foundation, the in-situ consolidation is a three-dimensional problem with varying coefficients of consolidation (Jia et al., 2018). This is especially true for highly interbedded soil profiles on a site where the properties of the soil within one layer can vary significantly.

Since the development of Terzaghi's consolidation theory, the study of soil consolidation has become an important aspect of settlement analysis, especially for soft soil. The coefficients of vertical and horizontal consolidation, $c_v$ and $c_h$, respectively, are among the most significant parameters affecting soil consolidation. These parameters are generally estimated using three major ways: laboratory testing, field testing, and back analysis of field monitoring results. Laboratory testing is a common approach in the industry, mainly due to the relatively low cost and ability to obtain results relatively quickly for multiple samples. However, for a real project, multiple factors affect the coefficient of consolidation; therefore, laboratory and field testing may not simulate the actual behavior of consolidation (Yang et al., 2015).

Yang et al. (2015) conducted a study, which established a back-analysis method for $c_v$ and $c_h$ based on field monitoring results of stratified soil settlement. The method can be used to calculate $c_v$ and $c_h$ of soft soil at different times. This approach overcomes the problems associated with traditional methods, which can only calculate one coefficient at a time. The application of the proposed method can compensate for the drawbacks of laboratory testing, which include consideration of the environmental factors affecting lab testing procedures, and the distortion of experimental results with changes in these factors. The study also found that it is more reasonable to use the coefficients of consolidation, back calculated from the settlement observation data of earlier loading levels (excluding the first level of loading), as parameters for consolidation prediction in later stages. The study concluded that it is necessary to set a certain number of stratified settlement observation points depending on the site specific condition, and use the back-analysis of the field monitoring results of stratified settlement to determine the coefficient of soft soil consolidation.

Another approach was taken by Li (2013) to predict settlement based on the field data. The study was aimed towards providing an alternative approach for predicting settlement that is not dependent on determining the initial time point. The proposed approach is a simplified method that is based on Terzaghi's 1D consolidation equation, irrespective of the initial time point.

Other methods that are dependent on the determination of an initial time point include Asaoka's method (Asaoka, 1978), and the hyperbolic method (Tan et al., 1991). Asaoka's method is based on "observational procedure," and the theory is limited by the need to calculate settlement at the initial time, which will require a selection of the initial time point. Different designers will select different initial time points, which can cause deviation in the settlement calculation.

The hyperbolic method proposed by Tan et al. (1991) is based on the rectangular hyperbolic fitting method proposed by Sridharan and Rao (1981) and Sridharan et al. (1987). Since this method is dependent on the initial slope of settlement, the selection of an initial time point is highly critical in the settlement prediction. The proposed method predicts the final settlement using Asaoka's method, and the potential settlement using the observation data. The concept of potential settlement in this model represents the settlement that will happen in the future.

A study was conducted by Islam et al. (2012) to measure the effectiveness of preloading on the time dependent settlement behavior of an embankment. A bikeway underpass was constructed by modifying the side slope of an existing embankment, which was situated on soft compressible soil. Subsurface investigation for the project included piezocone tests and laboratory consolidation tests. The preloading consisted of instrumenting the surcharge embankment, which was constructed to accelerate the settlement. Field data was obtained from settlement plates, and a finite element analysis (FEA) was performed to predict the settlement. The observational field data collected was then compared with the fully coupled, elasto-plastic, nonlinear FEA prediction. It was observed that the FEA model for the soft soil predicted the field response well during the first 100 days. After day 100, the model underpredicted settlement. The authors noted that the underprediction may have been caused by creep settlement, which was neglected by the settlement analysis. Although, the problem in the field is 3D, the FEA analysis was performed using a 2D plane strain model. This was another limitation of the prediction model, as it was not closely representative of the field condition.

In cases where surcharge and preloading are used, regardless of the initial method of assessment of settlement, it is common to employ back analysis to match field measurements and refine the geotechnical model. This process was done by Poon et al. (2020) with the objective of assessing time of preload and surcharge removal during the construction of embankments over soft soils. The preload performance assessment involved three main steps, which included the assessment of the degree of consolidation, back-analysis, and review of total and differential post-construction settlement. The degree of consolidation was evaluated using the Asaoka and Hyperbolic methods, then the soil parameters were back calculated through curve fitting settlement and excess pore water pressure versus time curves. The predicted total and differential settlements calculated were validated to meet the design criteria.

Given the presence of soft compressible clay soil on a site, it is impractical to proceed in construction without soil improvement due to the unpredictability of the long-term settlement (Ojekunle et al., 2015). Due to the contaminated subsurface soil on site, options for soil improvement are limited. Removing the contaminated soil and disposing it at another site is not practical given the degree and extent of contamination and the significant financial burden associated with the activity. The option that seemed the most pertinent for this project's goals was to reduce or avoid long-term settlement through a soil surcharge program. The heavier the surcharge load, the quicker the design settlement is achieved. Accordingly, increasing the height of the surcharge embankment above ground would lead to quicker consolidation/compression of the soil. The surcharge program is intended to minimize post-construction settlement under the design loads by temporarily preloading the soil with loads greater than the proposed design loads. After the target settlement is achieved, the temporary surcharge load can then be removed, and construction of the building may begin. Monitoring of subgrade settlement is of great significance to ensure the safety and stability of the subgrade (Jia, et al., 2018). Surcharge preloading has been used extensively and is one of the most common techniques used for transportation projects (Li, et al., 2014). However, this concept does not seem to be well documented for projects of a similar scope and site conditions.

The objectives of this investigation was to discuss a strategy to mitigate the effect of long-term post-construction settlement caused by contaminated waste material buried under the proposed building and to predict the total settlement of the waste material. The superfund site investigated in this research was located in a highly developed urban area surrounded by schools, shops, and other businesses. Extensive subsurface investigation has been done at the site including exploratory borings directly under and around the proposed building. Standard Penetration Test (SPT) and California Ring Samples were collected during the investigation and tested in the geotechnical laboratory. The extent of the waste material and thickness of the waste zone were identified through the subsurface investigation. The properties of the waste layer, which is primarily composed of fine-grained materials contaminated with petroleum products, were determined by laboratory testing. Using the available information relevant to the site, predicting settlement was done through numerical modeling by considering a continuous profile. The presence of the waste material beneath some areas of the proposed building is shown in Figure 2, which raises concerns about the differential settlement given the high compressibility of the waste material relative to the other fill/native material on site. Those concerns, however, can be addressed through a surcharge program, which consists of preloading the soil with imported fill and forcing the settlement to take place prior to construction. The settlement prediction was performed using commercially available software, *Settle3D*. The final products of this study was to provide a prediction of the amount of settlement that would occur after placing the surcharge load as well as the rate at which the settlement will take place.

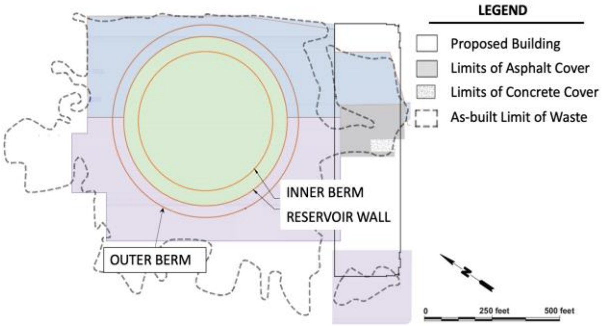


Figure 2: Site plan with limit of waste materials

## 2. MODELING AND ANALYSIS

### *2. 1. Site-specific characterization*

The historical investigation showed that in the 1920s, the site was located near a prolific oilfield in the country that was used for disposal and storage of petroleum and its byproducts. Waste disposed at the site included petroleum-related products, such as sludges, solvents, construction debris, drilling mud, and other waste materials. Historical aerial photographs further confirmed the presence of potentially hazardous materials in the form of liquids that were depleted on site. The site was also contaminated with heavy metals, polynuclear aromatic hydrocarbons (PAHs), and volatile organic compounds/semi-volatile organic compounds (VOCs/SVOC). The site was covered by approximately 2 to 9 m (6 to 29 ft) of engineered and undocumented fill, including inert waste materials. The fill material consists of silt and lean clay with some interspersed layers of silty sands. In certain areas of the site, impacted waste consisting of hydrocarbon laden sump material underlies the fill. The hydrocarbon laden sump material was classified as silt or clay with low density and high moisture content. Beneath the fill material is an older alluvium native soil. The native material up to the explored depth of 15.5 m (51 ft) consists of older surficial deposits of Pleistocene age consisting of interbedded clay, silt, and poorly graded sand. Groundwater was not encountered during field explorations to a depth 15.5 m (51 ft) below the ground surface. However, according to the State of California Seismic Hazard Zone Report, the historic high groundwater level near the site was mapped between 6 and 9 m (20 and 30 ft) below the ground surface (CGS Web App, 2019).

### *2.2. Surcharge program*

The design load causing settlement includes the weight of the new fill above the existing grade, which ranges from 2 to 5 m (6 to 15 ft), and the floor load of 48 kPa (1000 psf). The floor load of 48 kPa (1000 psf) is equivalent to approximately 2.5 m (8 ft) of fill. This estimate assumes that the unit weight of the fill is 19.6 kN/m$^3$ (125 pcf). Therefore, the design load will range from 90 to 140 kPa (1900 to 2900 psf), which is equivalent to an embankment fill of 4.5 to 7 m (15 to 23 ft) above the existing grade. An outline of the proposed building with the fill load and boring locations are presented in Figure 3.

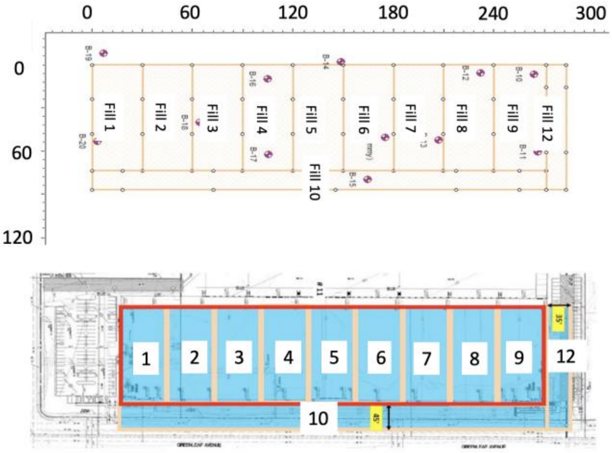


Figure 3: Building model with surcharge loads and borings layout (numbers in the figure are associated to each Fill)

The larger the surcharge load placed, the faster the design settlement is achieved. At that point, the surcharge load can then be removed, and construction of the proposed building may begin. Figure 4 displays the location of the embankment configuration while, the cross sections relative to the proposed building and the over-excavation limits are illustrated in Figure 5.

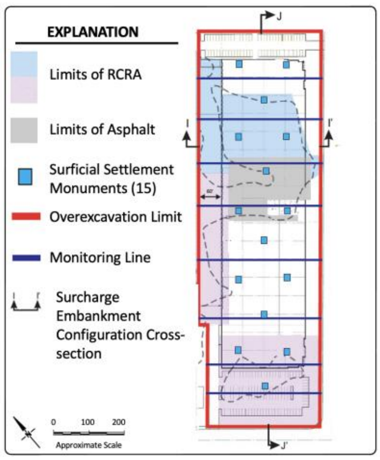


Figure 4: Structure over-excavation limits and proposed monitoring lines

The total settlement and the rate of the settlement depends on the rheological and consolidation properties of the surcharged soil. These properties are estimated from laboratory and field testing and because they vary greatly, especially for the soft drilling waste, it must be recognized that the properties represent engineering judgement. Therefore, the actual duration of the surcharge program should ultimately be determined by the field monitoring program that would be implemented in the future. The surcharge program is deemed completed when a specified level of settlement is achieved or when the rate of settlement decreases below a pre-determined threshold.

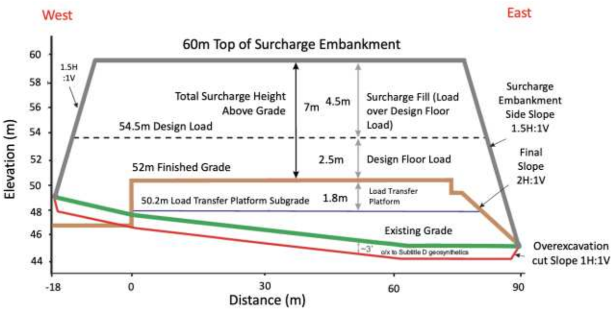


Figure 5: The surcharge embankment configuration, section I-I'

The height of the surcharge embankment and the expected duration of the surcharge program can be optimized to the construction logistics (e.g., material availability, construction sequencing, and schedule). As an initial proposal, the surcharge program presented herein was based on a duration of three to four months. Surcharge embankment sizing for a different duration may be developed once the planning for the project reaches the final stages. For the three to four-month duration, a surcharge fill thickness of 4.5 m (15 ft) above the design load is required over the Subtitle D (blue and pink areas in Figure 4) cover area. This represents a fill thickness of 9 to 11.5 m (30 to 38 ft) over the existing grade (i.e., 7 m (23 ft) over the floor slab subgrade). For illustrative purposes, the surcharge embankment height over the existing grade could likely be reduced to 3 m (10 ft) if surcharge program duration over six months were acceptable.

## 3 SUBSURFACE INVESTIGATION

The subsurface investigation of the site was executed by a professional consultant, who made the data was made available as part of a collaborative arrangement. A total of 11 borings were performed beneath the proposed building area in addition to the 15 nearby borings on site. The 11 borings were advanced using a telescoping hollow stem auger and limited access track rig. Standard Penetration Testing (SPT) was performed using a 63.5kg (140lb) automatic trip hammer with a drop of 75cm (30 inches) in general accordance with ASTM D1586. Bulk, small grab bag samples, and driven ring-type samples were collected at an interval of every 1.5 m (5 ft) beginning at a depth of 3 m (10 ft) below the ground surface. The samples were collected using an SPT and California-type samplers that are driven by the same equipment mentioned above. The four telescoping hollow stem augers, which include B-12, B-13, B-14, and B-20, were advanced to depths ranging from 9.1 to 11.7 m (30 to 38.5 ft). The telescoping hollow stem auger borings were drilled using a CME-95 drill rig. To avoid dragging the waste material to native soil, two different diameter augers were employed: a 380 mm (14.75-inch) diameter auger was advanced through the waste material until it reached the fill/native interface, and a 200 mm (8-inch) diameter auger was then advanced through the larger diameter auger to reach target depth within the native zone.

### *3.1. Laboratory Testing*

Some of the samples collected during the subsurface investigation were tested in the laboratory to obtain design parameters regarding the specific nature of the underlying soil. Various laboratory procedures were performed on the samples, including but not limited to the following:

- In-situ moisture content and dry density (ASTM D2937)
- Percent passing sieve 200 (ASTM D1140)
- Grain size distribution (ASTM D6913 and D7928)
- Direct shear testing (ASTM D3080)
- Consolidation testing (ASTM 2435)
- Expansion index (ASTM D4829)

The soil in the site was mainly classified as CH, CL-ML, ML, and SM at different locations of the site, with SPT values ranging between 3 and 30. Other soil characteristics were also found through above mentioned lab tests and used in the numerical model.

## 4 SETTLEMENT ANALYSIS AND METHODOLOGY

Given the presence of weak soil beneath the existing grade and dispersed waste material in certain areas, it was expected that the total and differential settlement would be significant. The SPT blow counts represent the extent to which some of those layers are soft/loose. An evaluation of the potential total and differential settlement was required to provide design recommendations. The final design considerations would ultimately be governed by the predicted settlement. The design of the surcharge embankment, which includes the height and staging, would also depend on the predicted settlement.

The settlements were calculated beneath the building and surcharge embankment footprint using input design parameters developed based on the data from the field observations, SPT values, converted California-type driven sampler blow counts, laboratory testing results, and published correlations. The settlement analyses were performed using *Settle3D*, which incorporated non-horizontal soil stratigraphy determined by interpolating equivalent layers between adjacent borings. Variable magnitudes of surcharge, geometrical loading configurations, and time dependent consolidation were all considered and implemented into the model. The analyses were performed in three dimensions beneath the surcharge by utilizing the principle of superposition (i.e., by calculating the settlements at any given point based on compounding the stress contributions from all considered surcharges). The 3D model provides a better representation of the field conditions at the site.

The settlement was then calculated assuming that the existing soils within the building area were overexcavated and recompacted. In addition, it was assumed that only materials below the extent of overexcavation were subject to settlement (i.e., the overexcavated and recompacted soils used to reach the design grades will not compress) - because the soil is compacted to 95 percent relative compaction and because granular soils were used, which result in immediate settlement from imposed loading. The settlement model was based on the 11 borings beneath or near the proposed building footprint. The design loads ranged from 90 to 140 kPa (1900 to 2900 psf), which includes the weight of the new fill to finished grade as well as the design floor load of 48 kPa (1,000 psf). To model the effect of the varying loads over the building footprint and the surcharge embankment areas, the respective footprints were divided into rectangular areas with varying magnitudes of surcharge.

The settlement analyses included calculation of the settlement due to primary consolidation/compression, total settlement due to a particular loading condition, and the time-dependent consolidation to achieve a given amount of settlement. It should be noted that the term consolidation used herein does not necessarily refer to the load transfer in saturated soils from the pore water to the soil skeleton due to pore pressure dissipation, but also includes the process of time-dependent compression of unsaturated soils that may behave in a similar fashion to saturated soils in terms of total settlement, but which undergo time-dependent compression due to their rheological properties.

Janbu's method was used to compute primary compression settlement. This method was selected specifically due to the complexity of the soil at this project and because Janbu's method is able to better fit the load-settlement curve from consolidation testing at any stress level than the more commonly used approach based on a linear fit of the logarithm of the applied stress versus settlement (i.e., coefficient of compression method). The primary compression settlement was then calculated from the strain induced in a soil layer (Eq. 1) due to the increase in effective stress.

$$\varepsilon = \frac{1}{mj}\left[\left(\frac{\sigma'_f}{\sigma_r}\right)^j - \left(\frac{\sigma'_0}{\sigma_r}\right)^j\right] \qquad (1)$$

where:

$\sigma'_f$ = final effective stress
$\sigma'_0$ = initial effective stress (usually at the middle of the considered soil layer)
$\sigma'_r$ = reference stress (i.e., atmospheric pressure, 100 kPa (2,089 psf))
$m$ = Janbu's modulus number
$j$ = Janbu's stress exponent

Total settlement for each layer is the product of the strain multiplied by the soil layer thickness. The values of the modulus number and stress exponent were determined from consolidation tests performed on relatively undisturbed samples that were inundated during testing. Time-dependent consolidation parameters were then developed based on consolidation tests where deformations with time were measured at a specific stress increment. The average value of the coefficient of consolidation, $C_v$, (Eq. 2) was calculated from laboratory consolidation tests based on the Log-Time Method ($t_{50}$) and the Square Root of Time Method ($t_{90}$).

$$C_v = \frac{TH_{dr}^2}{t} \qquad (2)$$

where:
$T$ = Dimensionless factor; $T$ = 0.197 for log-time method for 50 percent consolidation, and $T$ = 0.848 for square root method for 90 percent consolidation.
$t$ = Time corresponding to a particular degree of consolidation (i.e., $t_{50}$ for 50 percent consolidation and $t_{90}$ for 90 percent consolidation).
$H_{dr}$ = Length of the longest drainage path at 50 percent consolidation.

It should be noted that the coefficient of pore pressure, *B-bar*, was estimated from published data and existing correlations based on the degree of saturation. Because of the relatively large impact on the result and the known variability of the mud/Impacted Waste material, values of the upper and lower bound were estimated and used in the analyses. Also, the $C_v$ values for the native alluvium and the recompacted fill were not developed from laboratory results but were estimated based on published correlations and engineering judgement.

## 5 RESULTS OF SETTLEMENT ANALYSES

The results of the primary compression analyses indicated that the average settlement of the most compressible part of the impacted waste under the Subtitle D cover would be about 44 cm (17.3 inches) with a maximum settlement of about 58 cm (23 inches). The average settlement of the areas outside the Subtitle D cover would be about 15 cm (6.0 inches). To expedite and reduce construction settlement and to reduce post-construction settlement, a surcharge load was added to the design loads. It was estimated that an applied surcharge lasting about three to four months would be acceptable. Using the time-dependent compression feature in *Settle3D* and by assuming partially saturated conditions encountered in the field, the load equivalent to 4.6 m (15 ft) of surcharge fill was required to achieve the average settlement of about 58 cm (23 inches). The results of analyses showing the settlement distribution under the surcharge embankment at different stages are shown in Figure 6.

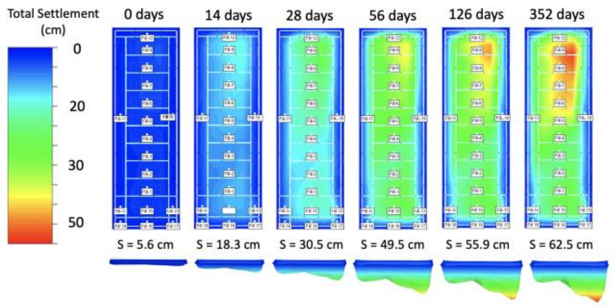


Figure 6: Predicted settlement distribution under the surcharge embankment at different stages, plan view (on the top) and elevation view (on the bottom)

It can be seen that the highest rate of settlement would occur directly after the application of the surcharge load, after which the rate at which settlement would occur decreases with time. The average total settlement at 4 months is approximately 58 cm (23 inches). At that point, the settlement rate would have been dropped significantly, below 0.2 mm/d (0.01 inch/d), as shown in Figure 7.

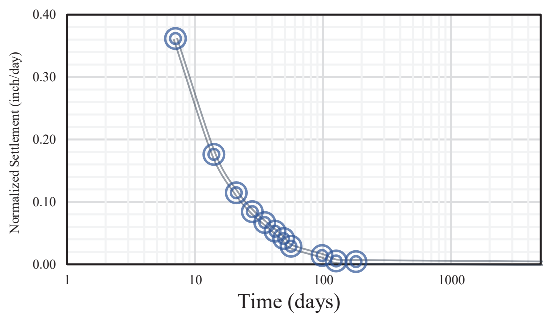


Figure 7: Normalized Settlement (in/day) vs Time (days)

Based on these results, the surcharge program could be terminated after four months, when construction of the proposed building could begin. As previously stated, the surcharge embankments are among the commonly used ground improvement techniques for sites with soft compressible soil. These temporary loads are meant to force the soil to consolidate quicker and allow the design settlement to be completed prior to construction. This project considers a site composed of a soft compressible soil layer that is contaminated with drilling waste materials. Consequently, the site requires a form of ground improvement that is suitable for the current conditions. Given the limitations imposed by environmental regulations pertaining to the contaminated soil on site, a surcharge program consisting of a pre-load embankment ranging from 2.1m (7 ft) to 4.6m (15 ft) above the design grade is recommended. The height of the surcharge embankment above existing grade was designed depending on the presence of waste material underneath the proposed building. The area to the north of the proposed building is heavily impacted by the presence of a thick waste layer in the subgrade, and as such the surcharge embankment is higher over that area.

It should also be noted that the above calculated total settlement mostly encompasses the effects of primary consolidation. It is assumed that the effects of secondary compression settlement would have not yet been fully achieved after the four months suggested time period and would likely require a much longer period for the secondary compression settlement to be achieved. Although the authors believe that the secondary compression for this soil would not be significant, but the results of this investigation should be used with caution.

## 6 CONCLUSIONS

The purpose of this project was to analyze the total settlement resulting from an imposed surcharge embankment and to estimate the length of time required to achieve the design settlement. The surcharge embankment was modeled using *Settle3D* software, and soil properties were obtained from the subsurface investigation and lab testing. Janbu's approach was used to calculate primary compression settlements, as this method provided a better fit to the load-settlement curves obtained from consolidation tests. Time-dependent consolidation parameters were obtained from consolidation tests, and an average coefficient of consolidation was calculated using the Log-Time Method ($t_{50}$) and the Square Root of Time Method ($t_{90}$). Specific conclusions can be drawn from the results of the analyses, as detailed below:

1. The average total settlement after four months of applied surcharge loading was approximately 58 cm (23 inches). The rate of settlement decreased significantly after 100 days to less than 0.5 mm/d (0.02 inch/d).
2. After approximately four months, the settlement rate dropped to less than 0.2 mm/d (0.01 inch/d). At that point, the design settlement was achieved and the surcharge could be removed.
3. The settlement was most severe beneath the Subtitle D cover area, north of the building. This was expected given the presence of a soft waste layer with variable thickness.
4. The total settlement after four months mostly encompassed the effects of primary consolidation. However, it was assumed that the effects of secondary settlement were not fully achieved by this point.
5. For the secondary settlements, a much longer period than four months would have been needed to realize this settlement.
6. Since the surcharge load was much larger than the design loads, much of the settlement would have taken place and the soil would have been overconsolidated prior to the construction phase.

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