DYNAMIC COMPACTION:
A Proven Ground Improvement Method for Landfill Sites

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ABSTRACT: During the past 40 years, ground improvement has become a valuable tool for the geotechnical community, as the number of sites with suitable bearing soils become fewer and farther between. Similarly, as time moves on, more sites come into focus for development that have received any number of various landfill materials, be it municipal solid waste (MSW) from households, construction and demolition (C&D) debris from construction activities, or simply soil materials exported from another site. As a result, the challenges to engineers and contractors to design and construct new developments within budget and on time continue to increase.

Dynamic compaction is a ground improvement technique that has been used more frequently to improve in-place landfill materials to a point where vertical construction can proceed without excessive long-term settlements. On sites where dynamic compaction is used, alternative methods of post-improvement evaluation have become more common, given the number of below-grade obstructions at a site that typically prohibit standard drilling approaches. Embankment load testing, plate load testing, and where applicable, post-improvement drilling are all techniques that have been used successfully to evaluate the effectiveness of dynamic compaction programs, as outlined by the three case studies discussed herein.

INTRODUCTION

As time passes, the amount of available, relatively non-complicated development sites decreases. As a result, the need for ground improvement has grown in the past 40 or so years, and the technology used within the industry has improved and advanced at an almost faster pace. In addition to the advances with the capabilities of geotechnical construction equipment, engineers are constantly being asked to push the envelope of existing technologies in terms of where and how they are applied.

Dynamic compaction is a ground improvement method where the technology has not changed significantly over time, except for perhaps the improvements to the cranes doing the work. However, because of its relative economic advantages versus other applicable ground improvement options, it is a method that is consistently used to tackle challenging sites across the world. Primarily, dynamic compaction has been utilized to consolidate uncontrolled granular fill materials and loose sands; it is also used to improve uncontrolled mine spoil materials, karst sites, and sites where liquefaction mitigation is required. More recently, however, dynamic compaction has been used with increasing frequency on landfill sites that do not have excessively thick refuse deposits (greater than about 20 feet) and minimal risk of off-site vibration-related issues, with the specific intent of providing foundation support for vertical structures.

TYPES OF LANDFILLS

Municipal solid waste (MSW) landfills are one type of landfill; however, construction and demolition debris (C&D) landfills, and soil landfills also exist. Regardless of the type of landfill, they all have one thing in common: they are comprised of highly variable materials placed without any sort of engineering controls and are generally unsuitable to provide foundation support for vertical construction as they presently exist. A more detailed description of these common types of landfills that require ground improvement are provided below.

Municipal Solid Waste (MSW) Landfills – Generally speaking, there are two types of MSW landfills. The first would be engineered structures regulated by state/provincial and federal agencies that have traditional liners, leachate collection systems, and caps. These types of structures normally require disruption permits to modify anything and tend not to be penetrated through the cap and waste materials to facilitate surface construction. Conversely, older, unregulated dump sites that were historically filled with MSW are also encountered and require significant improvement to the existing engineering properties to allow for surface construction. Regulated or not, the MSW composition of these landfills generally consists of household waste, trash, and non-hazardous substances. Most notably, unregulated MSW landfills have significant and variable amounts of void space (see Figure 1), leading to significant primary compression, along with elevated secondary compression which derive from the long-term degradation associated with the waste material.

Figure 1 – Unregulated Municipal Solid Waste (MSW) Landfill Material

Construction and Demolition (C&D) Debris Landfills – C&D landfills are unregulated dump sites that contain construction-derived materials such as wood, concrete, and brick mixed with soil; this same mixture of materials is also generated from site demolition activities and clean-up of disaster sites; a typical C&D material is shown in Figure 2. In comparison to MSW material, C&D material is generally comprised of a soil matrix with varying deposits of debris mixed throughout. Depending on the material (i.e., wood, concrete planks, or slab pieces), nestled deposits of unblended or nested materials can occur, leading to the potential for localized voids within the deposit. Overall, the compressibility characteristics of C&D material are less than MSW material, mostly owing to the lack of organic or putrescible material within the matrix.

Soil Landfills – Soil landfills are just that; sites where heterogenous mixes of soil and rock generated from other locations are placed in a non-engineered fashion to raise grades at a given site. In some instances, the material could be granular soil which could be sufficient for foundation support if its engineering properties are properly improved. Alternatively, an urban fill material could be laden with bricks, concrete, and foundation and slab remnants, which requires a significant effort to improve. There are also strip-mining sites where upwards of 100 feet of uncontrolled mine spoil materials have been dumped back into place to abandon a site following the completion of mining activities (Woods, 2015). Regardless of the case, all these sites have one thing in common – they are uncontrolled materials that by definition in the International Building Code (IBC) (ICC, 2000), have zero allowable bearing capacity in their present state.

Figure 2 – Typical Construction and Demolition (C&D) Landfill Material

DYNAMIC COMPACTION DESIGN FOR LANDFILLS

The degree and depth of soil improvement achieved with dynamic compaction depends upon the total amount of energy applied to the soil; i.e., the more energy imparted to the soil, the greater the degree and depth of improvement. However, given the soil type, the same energy application on two different sites could result in significantly various levels of improvement. A discussion of the three main design components to a successful dynamic compaction program on a landfill site is provided below.

Depth of Improvement – The first design consideration, depth of improvement, is a function of the amount of weight being dropped and the drop height, as well as the type of material being improved; see Eq. 1. The conventional depth of influence formula for dynamic compaction given in Geotechnical Engineering Circular No. 1 DYNAMIC COMPACTION, FHWA-SA-95-037 (Lukas, 1995) is as follows:

(1) $D = n*(WH)^{1/2}$ where: D = depth of influence (m)
n = empirical coefficient based on soil
W = weight of tamper (Megagrams)
H = drop height (m)

The empirical coefficient "n" is based on the soil type being improved; when it comes to landfill sites, this is the most significant parameter in successful design. For overall comparison, the general ranges that are used in practice today for a given soil type are provided in Table 1. As can be seen, pervious granular soils have a higher n-value, meaning that for a given weight/drop height combo, the depth of influence in sandy material is considerably more than in landfill material. This is a result of particle structure of sand being more densely packed, which allows energy transfer to happen more efficiently. Alternatively, in a landfill matrix, with significant amounts of voids, energy is dissipated while traveling through the matrix, reducing the depth of effective improvement.

Table 1 – Typical "n" Values Used for Depth of Improvement (Lukas, 1995)

Soil Type	Range of "n" Values
Pervious Soils	0.5 to 0.6
Semi-Pervious Soils	0.35 to 0.5
Impervious Materials / Mine Spoils	0.35 to 0.4
Landfill Deposits (Newer to Older Deposits)	0.35 to 0.65

Applied Energy – The second design consideration of a successful dynamic compaction program is the amount of energy to be applied to soil, or simply, the applied energy. Applied energy is the energy per unit volume (kJ/m^3), calculated as shown below (Lukas, 1995).

(2) $$\text{Applied Energy} = \frac{(Pounder\ Weight)*(Pounder\ Height)*(\#\ of\ Drops)*(\#\ of\ Passes)}{(Grid\ Spacing)*(Grid\ Spacing)*(Depth\ of\ Improvement)}$$

The amount of applied energy is a function of the drop height, drop weight, number of drops, grid spacing, and the anticipated depth of improvement noted in Eq. 2. The applied energy required of a program can vary significantly depending on the soil type being targeted for improvement and is generally a function of the grain-size distribution. Table 2 provides the industry standard ranges for targeted applied energy based on these soil types (Lukas (1995), Zekkos et al (2012), and Woods et al (2016)). As can be seen, for landfill deposits, the amount of energy required could be four to five times that which is required for granular deposits to achieve the same level of improvement.

Table 2 – Typical Applied Energy Ranges for a Given Soil Type (Lukas, 1995)

Soil Type	**Range of Applied Energy (kJ/m^3)**
Pervious Soils	200 to 250
Semi-Pervious Soils	250 to 350
Landfill Material	600 to 1,100
Coal Mine Spoil Material	150 to 350

Pounder Specifications – A third main component in designing a successful dynamic compaction program, based on the authors' experience, is the dimensioning, and more importantly, contact pressure of the pounder(s) to be used. Although none of the formulas outlined above contain a mechanism accounting for this explicitly, experience shows that the choice of pounder can be vitally important to the success of a program. On sites where deep penetration is required to affect improvement, such as sandy sites or MSW sites, high contact-pressure pounders that will punch into the subgrade are ideal. Generally, a good target pressure for this application would be on the order of 1,000 to 1,500 psf.

POST-IMPROVEMENT TESTING/EVALUATION

One of the biggest challenges in geotechnical engineering is ensuring that a sufficient amount of data has been collected before, during, and after construction, so that all parties involved can agree that project objectives have been met. Most sites will have pre-improvement data, obtained during the design phase. However, these data are usually limited to discrete boring or test pit locations across a site and represent a relatively small portion of the overall site area. During execution of the dynamic compaction program, greater quantities of visual data on crater depth and drop penetration are collected in the field, which helps assess whether soft areas or voids were encountered and subsequently remediated.

For most dynamic compaction programs, visual observation of ground response is a simple, qualitative method of providing a first-pass evaluation of the effectiveness of the dynamic compaction program. One of the main benefits of such a program is that the tamper is essentially probing the site at each of the drop points. At each location, the response of the ground can be evaluated. This information can then be combined with further intrusive testing methods such as borings, cone penetrometers, or other regionally used methods to provide a strong overall picture of the improved subgrade conditions. The type of post-improvement program to be implemented is generally specified by the Geotechnical Engineer, based on the conditions expected to be encountered, as well as the regional preference (Woods, 2017).

On landfill sites, however, discrete sampling approaches such as this can be highly problematic, particularly on MSW or C&D sites where buried obstructions can significantly skew testing results or prevent advancement of drilling equipment. In these instances, alternative approaches to data collection become extremely important to providing the level of confidence needed for assessing the effectiveness of the ground improvement work. Embankment load testing with settlement plates and large-scale plate load testing to mimic foundation loading conditions have become more common, and to a lesser degree, geophysical testing has been used on landfill sites where obstructions impacting post-improvement testing has been a concern. In the case studies highlighted below, the soil types, program design, and most importantly, post-improvement evaluation techniques will be highlighted.

CASE STUDY NO. 1 – MIXED-USE DEVELOPMENT, TEMPE, AZ

The first case study is a mixed-use commercial development in Tempe, Arizona that spans a footprint of 2.5 million square feet. The subsurface conditions at the site generally consisted of 40 to 45 feet of predominantly granular C&D material encountered from the ground surface down. Based on the requirements of the Geotechnical Engineer, a depth of improvement of 25 to 26 feet was specified. Ultimately, a four-pass improvement program was developed; two passes over the entirety of the site, and then an additional two passes within building locations. A breakdown of the applied energy at the site is as follows:

> Entire Site – 20-ton drop weight, 60-foot drop height, n = 0.45, two passes on a 15-foot grid spacing, six drops per point. This resulted in an Applied Energy of 228 kJ/m^3 for the site, with a depth of influence of 27-feet.
>
> Building Areas – 20-ton drop weight, 60-foot drop height, n=0.45, two passes on a 12-foot grid spacing, six drops per point. This resulted in an Applied Energy of 356 kJ/m^3, also with a depth of influence of 27 feet.

Combining the four passes, a total applied energy of 584 kJ/m^3 was imparted withing the building footprints at the site. This energy is near the lower-end boundary recommendation of 600 kJ/m^3 for landfill material (Lukas, 1995). However, given the highly granular nature of this material, this was deemed to be a reasonable amount of energy to improve the soils at hand. Additionally, it should be noted that the craters from the two initial site passes were filled with crushed rock material prior to completion of the two additional building passes.

Despite the granular nature of the soils at the Tempe site, obstructions existed from buried debris and the rockfill material driven into the subgrade during the second two passes. Consequently, discrete SPT or CPT testing was not considered viable to assess the dynamic compaction program. Instead, plate load testing was conducted for each of the two parcels at the site, to replicate what could be expected under foundation loading conditions; for this project, the design allowable bearing pressure was to be 2,500 psf.

A 4-foot by 4-foot steel plate was loaded incrementally to a maximum pressure of 7,500 psf; in both load tests (see Figure 3), observed settlements were on the order of ¼-inch or less. Extrapolating to a 10-foot by 10-foot sized footing, and applying aging factors, the anticipated settlement at the site was calculated to be on the order of one-inch over 30 years, which was less than the required maximum of 1.5-inches of long-term settlement. Significant amounts of long-term degradation-related settlement was not considered to be an issue, given the mostly granular nature of landfill matrix and the fact that the material had been in place for over 30-years at the time of construction.

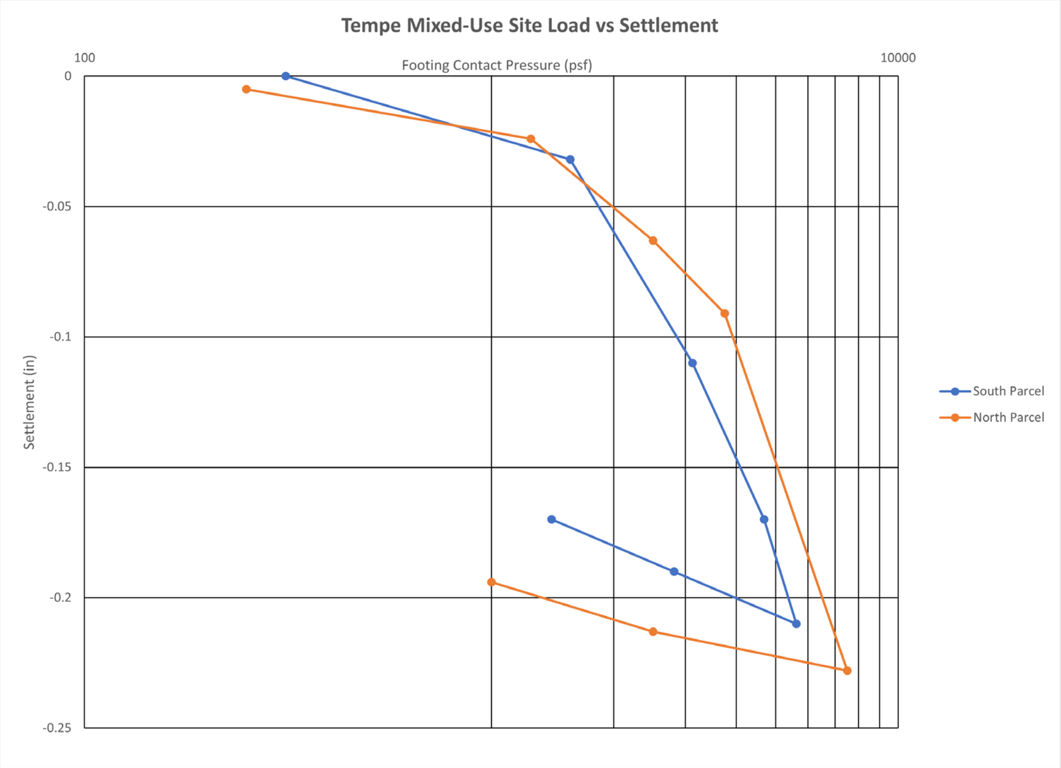

Figure 3 – Summary of Plate Load Test Results, Tempe Site

CASE STUDY NO. 2 – INDUSTRIAL FACILITY, HIALEAH, FL

Over the past several years, dynamic compaction has been implemented on about 15 million square feet of site area at an industrial facility in Hialeah, Florida. The end-use of the vertical construction at the site consists of several one-story distribution centers that serve the booming e-commerce industry. The subsurface conditions at the Hialeah site generally consist of about 12 to 13 feet of MSW material overlying limestone bedrock. Per the recommendations of the Geotechnical Engineer, the dynamic compaction program at the site was to consist of two passes over the entire site. A breakdown of the applied energy at the site is as follows:

> Entire Site – 16-ton drop weight, 60-foot drop height, n = 0.35, two passes on a 12-foot grid spacing, ten drops per point. This resulted in an Applied Energy of 982 kJ/m^3 for the site, over the landfill depth of 13 feet.

The total applied energy of 982 kJ/m^3 is closer to higher-end recommendation of 1,100 kJ/m^3 for landfill material (Lukas, 1995), which was appropriate, given the amount of refuse material in the overall landfill matrix. A three-foot cap of clean, compacted fill materials was to be placed across the site following the completion of the dynamic compaction work.

Similar to the Tempe site, the amount of refuse at the site impeded the use of drilling and discrete testing for assessing the dynamic compaction work. In this instance, embankment load tests were conducted to assess the long-term performance of the site. For this project, the design allowable bearing pressure was to be 3,000 psf.

At eight locations throughout the first four building footprints, embankment load tests were constructed to assess the settlement of the improved subgrade under load. The tests consisted of constructing a 20-foot high by 120-foot diameter stockpiles of existing soils at the exposed subgrade elevations following dynamic compaction; a settlement plate was installed at the center of the embankment load and monitored over time. Based on the calculated unit weight and geometry of the embankment soils, the resultant stress on the landfill soils was 1,800 psf, which exceeded the stresses which were to be felt at the surface elevation of the landfill materials under the design foundation loads. As can be seen in Figures 4 and 5, settlement under the embankments was generally on the order of ¾-inch or less, which met the stated project settlement criteria of 1-inch.

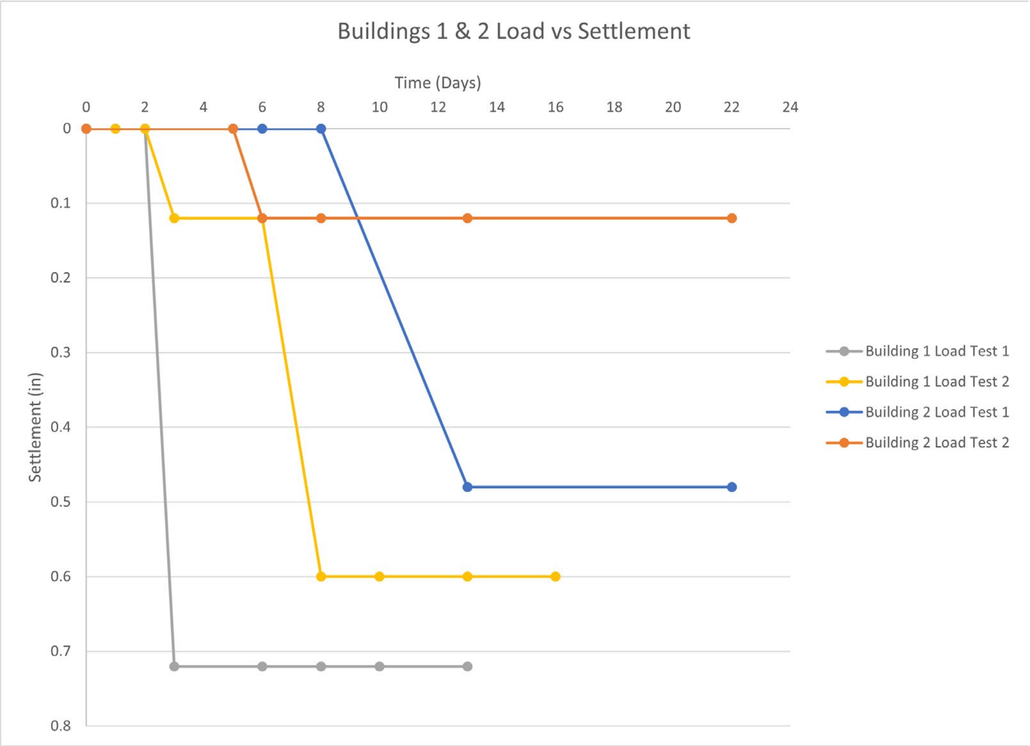

Figure 4 – Summary of Embankment Load Tests for Buildings 1 and 2

Figure 5 – Summary of Embankment Load Tests for Buildings 3 and 4

CASE STUDY NO. 3 – PRUDENTIAL CENTER, NEWARK, NJ

Prior to construction of the Prudential Center in Newark, New Jersey, the site had previously been occupied by low-rise residential and commercial structures, rail facilities, and historic grave sites (which had to be properly exhumed and relocated prior to construction). Following the demolition of the vertical structures, a dynamic compaction program (along with limited removal and replacement zones at the perimeters to help mitigate vibration concerns in the urban setting) was implemented over a footprint of about 300,000 square feet. The subsurface conditions at the site consisted of about 15-feet of miscellaneous urban fill material underlain by native glacial outwash sands; the upper 5 to 10 feet of which was loose in nature (Woods et al, 2005).

Initially, a dynamic compaction program was to be implemented with the goal of achieving an allowable bearing pressure of 4,000 psf. However, based on conversations with the Structural Engineer that concluded that an increase to 6,000 psf would reduce foundation concrete costs by over 30%, a test program was implemented at the site to assess what design bearing pressure was achievable (Woods, (2005), Woods (2013)). Based on the work conducted as part of the test program, the dynamic compaction parameters used for production were as follows:

> <u>Entire Site</u> – 15-ton drop weight, 55-foot drop height, $n = 0.5$, two passes on a 10-foot grid spacing, four drops per point. This resulted in an Applied Energy of 255 kJ/m^3 for the site, with a depth of influence of 25-feet. In addition to the two area passes, a third high-energy pass using the same parameters was conducted over the footprint of all foundation locations.

In contrast to the prior to case studies, the urban fill at the Prudential Center site was generally granular in nature with a minimal number of obstructions. Consequently, discrete pre- and post-improvement testing consisting of SPT borings and CPTs were conducted both before and after the work in the test area, and SPTs were conducted following the production dynamic compaction work throughout the site to verify the effectiveness of the program. As can be seen in Figure 6, average N-values increased from about 24 bl/ft to 31 bl/ft from pre- to post-improvement, but more importantly, the minimum N-values increased from 7 to 14 bl/ft, which indicated that the loose zones within the treatment zone were densified considerably.

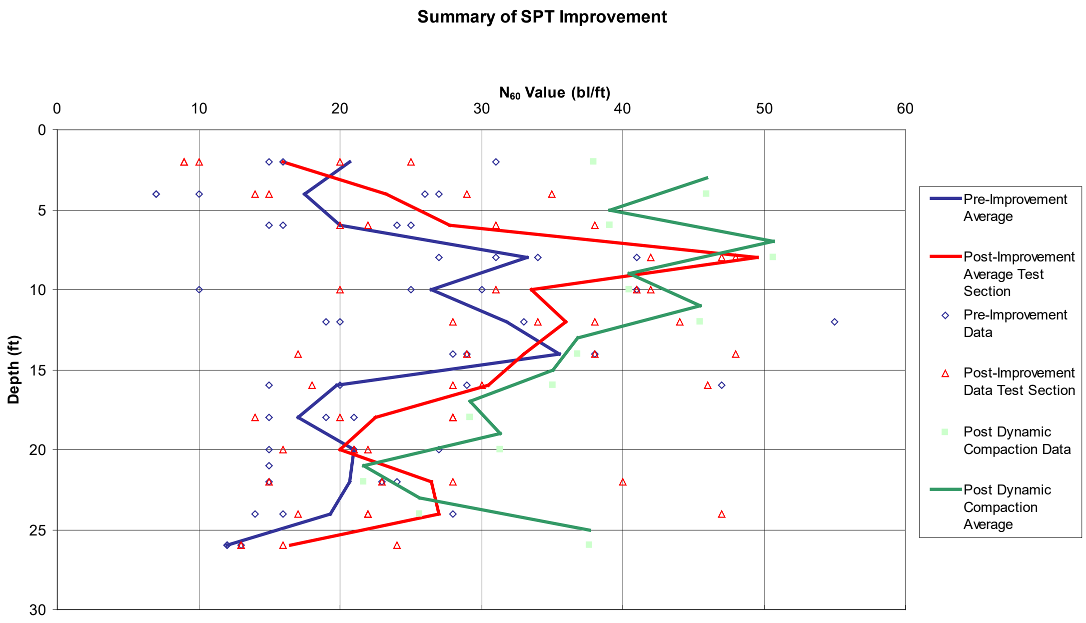

Figure 6 – Summary of Post-Improvement SPT Testing at Prudential Center

As a result of the thorough testing that occurred as part of the test program, settlement analyses for the proposed foundation loadings indicated that an allowable bearing pressure of 6,000 psf could be utilized for design, while keeping post-construction settlements to the design maximum of 2-inches.

CONCLUSIONS

Ground improvement has many varying forms, just as construction sites have many varying subsurface conditions. Sometimes, a given ground improvement solution may simply not be the correct choice if the soil conditions are not compatible. In the instance of constructing on landfills, there are several ground improvement options to choose from, but recently, dynamic compaction has solidified itself as an option for ground improvement on landfill sites, as long as the following considerations are addressed as part of the design and implementation of the program:

- Understanding the thickness, makeup, and age of the landfill deposits is critical in assessing the effectiveness of the program and developing design criteria.
- Loading requirements and the nature of the surface construction must be clearly understood and considered to ensure that estimated post-construction settlements are in line with what is needed. Achieving this means that effective communication between the Geotechnical Engineer, Structural Engineer, and Specialty Subcontractor is paramount.
- Having a game-plan for post-improvement evaluation plan that fits the site characteristics and still demonstrates that the required design parameters have been achieved is critical to establish up front to avoid issues during the

execution of the project. The evaluation could include observations during production, discrete testing post-improvement, or embankment or plate load tests.

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