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Densifying a Landfill for Commercial Development

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SYNOPSIS This paper presents a case study of a dynamic compaction ("pounding") project, undertaken in Skokie, Illinois. The purpose was to densify a 50-ft deep former municipal waste landfill for support of a one-story warehouse structure on shallow foundations. The majority of the pounding was performed utilizing a 15-ton weight falling from a height of 60 ft. In some areas, lower energy levels were used for surface compaction. All phases of the project are discussed, beginning with the subsurface exploration program and geotechnical analysis, through the experimental test pounding section, and the final check borings to observe that the "production" pounding was successful. A follow-up of the performance of the pounding, by monitoring foundation settlements, is discussed, as are topics such as depth of improvement, offsite vibrations, and energy input.

INTRODUCTION

In 1980, a detailed subsurface exploration and geotechnical analysis were performed, establishing the proposed building site as a former clay pit filled with municipal waste. A cost/benefit analysis comparing available foundation alternatives was developed, and, as will be discussed, dynamic compaction, hereinafter referred to as "pounding", was considered to be the most cost-effective and acceptable option. Since the degree of improvement that could be attained could not be precisely predicted in advance, a pounding test section was completed. Standard Penetration and pressuremeter tests were performed before and after test pounding. Sufficient energy was applied until the fill was considered adequately densified to support the structure on shallow foundations. Throughout the course of the project, communication and coordination was required between the owner, the consulting and design engineers, and the contractor.

In this paper, all phases of the project are discussed, beginning with the subsurface exploration program and geotechnical analysis, through the final check borings to observe that the production pounding was successful. A follow-up of the performance of the pounding, by monitoring the foundation settlements, is also discussed, as are topics such as depth of improvement, offsite vibrations, and energy input.

PROJECT DESCRIPTION

The structure proposed for construction consisted of a one-story, slab-on-grade, 22-ft high steel frame building, 78,400 square feet in plan. Bay spacing was 40-ft by 40-ft. Interior column loads were on the order of 80 kips. The exterior wall load was approximately 6 kips per lineal foot. Floor slab loads were on the order of 400 to 500 pounds per square foot (psf). Truck loading docks were planned for the southern side of the building and on-grade passenger car parking was planned alongside the western part of the building. It was also the intention of the owners to construct a building which would have the necessary capacity for additional load on the northern and eastern sides. Thus, although one building was planned, the site densification process was to include areas of future expansion, as well as aforementioned parking and driveway areas. The combined project area was 102,400 square feet.

SITE CONDITIONS

A search into the history of the site using air photos and maps revealed that the proposed building area was contained (with the exception of the northeastern corner of the property) within the limits of a former and abandoned clay pit. On the basis of the soil borings performed, it was concluded that the pit depth within the project area ranged from approximately 40 to 50 ft at the deepest portion to 22 to 37 ft along the outer edges. Mining in the clay pit ceased around 1936 and the site was used as a municipal waste landfill until approximately 1950. The site was then used only as an outdoor movie theater parking lot. At one time, the fill heights extended approximately 5 to 15 ft above the surrounding street grade. The excess fill was removed approximately one year prior to initiating the pounding.

The fill consisted of varying amounts of decomposed refuse, cinders, ashes, brick, and occasional pieces of wood and organic matter. Broken concrete, paper, and glass bottles were also encountered. A grain size analysis performed on the fill indicated a material similar to a sandy, fine to coarse gravel with little silt and clay (GP-GC). Based upon the Standard Penetration Test (SPT) and the pressuremeter test results, the fill was observed to be generally in a loose to medium dense condition. In some pockets of extremely loose fill, the SPT values were less than 5 blows per foot. In other instances, no resistance was met by the pressuremeter probe. Generally, water content values in the fill were between 20 and 30%, with occasional organic pockets exhibiting water contents as high as 65 to 95%.

Generally, the fill materials were underlain by medium stiff to stiff, natural silty clay. With depth, the consistency of the clay increased from very stiff to hard. "Hardpan" soils (typical to the Chicago area) which are identified by low water contents and high strengths, were encountered at depths varying from 56 to 60 ft below the existing ground surface.

The ground water table was located at a depth of approximately 5 to 8 ft below the existing ground surface.

FOUNDATION SELECTION

Following identification of the subsurface soil and ground water conditions at the site, the options available for foundation support of the proposed warehouse were identified. Initially, three (3) options were considered. Ultimately, two (2) of the options were ruled out in favor of the third. Prior to eliminating two of the options, a comparison of cost as well as construction feasibility and timing was undertaken.

Option 1 -- Dynamic Compaction

Because of the erratic thickness and composition of the fill, it was imperative that if any new construction was to be supported directly on the fill, site densification would be required. Fortunately, the fill had been in place a sufficient amount of time, and the majority of the organic material appeared to have decomposed. No gas was detected as the bore holes were advanced. Thus, concern over significant future decomposition and resulting settlement was not a consideration.

It was recommended that a suitable solution for densifying the soils would be by means of pounding to a point where spread footings and a slab-on-grade system could be utilized. Based upon the Menard (1975) formula modified by Leonard, et al (1980) and Lukas (1980), a 15-ton weight dropping a distance of approximately 60 ft was determined necessary to achieve proper densification. Once the area had been densified, the footings could be placed within the fill and designed for a maximum net allowable soil bearing pressure of 3,000 psf. Previous experience with densification of landfill deposits by pounding indicated that a pressuremeter modulus of 50 tsf within 10 ft of ground surface and 30 to 40 tsf at lower levels would be achieved. For the magnitude of the loads, this would result in a predicted settlement of approximately 1 inch.

Option 2 -- Deep Foundation Alternative

The second option consisted of extended foundations and a structural floor slab. The most suitable foundation, given the possible corrosion potential of the fill, as well as the proximity of existing structures, was caissons (drilled piers) extending to the "hardpan" soils at a depth of approximately 56 ft below existing grade. At this depth, the caissons could be designed for a maximum net allowable soil bearing pressure of 20,000 psf.

Several drawbacks to the caisson foundation alternative were anticipated. These included the need for permanent steel casing through the fill materials and soft clay layers to prevent sloughing, caving in, or squeezing of these materials into the shaft excavation. The casing would increase the cost of the project and the construction time. It was also anticipated that the contractor may encounter obstructions from large concrete chunks in the fill which would add further to construction costs and delays.

Option 3 -- Combined System

The combined system involved dropping a lighter weight, such as an 8-ton weight, and densifying the upper portion of the fill for support of the floor slab. Deep foundations would still be used to support the structure. This option would reduce the building settlement which would be encountered in Option 1, while at the same time alleviating the necessity of a structural slab which would be required for Option 2. However, the high cost of caissons was still present, as was the possibility of construction delays.

Cost Analysis

A cost analysis of the first two options was performed. A price for the third option was not prepared, since the anticipated delays with the combined system were not tolerable. The client was very concerned that the occupancy date be met. The anticipated costs were as follows:

1. Pounding to densify area, stone necessary to raise site to design subgrade, and cost of slab and footings	$500,000
2. Caissons/structural slab	$1.0 - $1.3 million

On the basis of cost, construction feasibility, as well as construction timing, Option 1 was selected, with the understanding that an experimental test pounding section would precede production pounding.

MONITORING PROGRAM

Depending upon the soil type encountered, representative soil samples in the check borings were obtained by means of the split-barrel and shelby tube sampling procedures. However, settlement and bearing capacity evaluations were based on the pressuremeter tests performed at selected test depths. Due to the larger test area in the pressuremeter device, a more representative evaluation of the compression characteristics of fill can be obtained. This is particularly important in erratic fills, since the pressuremeter test averages out inconsistencies to obtain representative values.

In addition to the aforementioned testing, three field monitoring methods were employed. These were: full-time field inspection by a qualified soil engineer familiar with the pounding process; continual checks of crater depths; and monitoring of overall ground settlement after each leveling pass. Through experience, Lukas has found that the overall ground settlement following pounding and leveling can be expected to be on the order of 10% of the total depth of improvement in the fill. Thus, continual monitoring of the site settlement is an indication of the effectiveness of the pounding. The purpose of monitoring crater depths is to isolate inconsistencies for further evaluation. Hard spots can be an indication of a crust forming, and soft spots can either be an indication of unsuitable soils which should be removed or of an area where additional pounding is required. Both services require inspection by full-time field personnel who are familiar with the pounding process and have the experience and authority to alter procedures when necessary.

Ground velocities developed during pounding were monitored at increasing distances from the drop location. These results indicated that the surface vibrations in the fill rapidly dampened with increasing distance from the point of impact. An analysis was also made as to how the monitored vibrations compared with vibrations measured in other soil types. A graph depicting this comparison is shown on Figure 1. The vibration monitoring was also used as a guide in determining the effect of the pounding on adjacent live utilities. The pounding came within 15 ft of buried utility lines with no damage occurring. In addition, no damage was observed to adjacent structures. The vibration monitoring was performed utilizing a VME seistector which measured resultant peak velocities.

TEST POUNDING

For the test pounding, a 60-ft by 60-ft area was selected. The section was located in the vicinity of a boring which indicated the thickest (50 ft) and potentially loosest deposit of fill. A 15-ton weight, manufactured by the contractor, consisted of a series of horizontal steel plates bolted together to form a cylindrical shape. A 6-inch thick bottom plate was attached to the weight to facilitate extraction from the fill and reduce suction forces. The diameter of the bottom plate, slightly larger than the remaining portions of the weight, was 5 ft. The design contact pressure was 1,530 psf. The remaining dimensions were 4'7" high and 4'6" in diameter. In order to lift the weight 60 ft in the air, a 100-ton capacity crane was required.

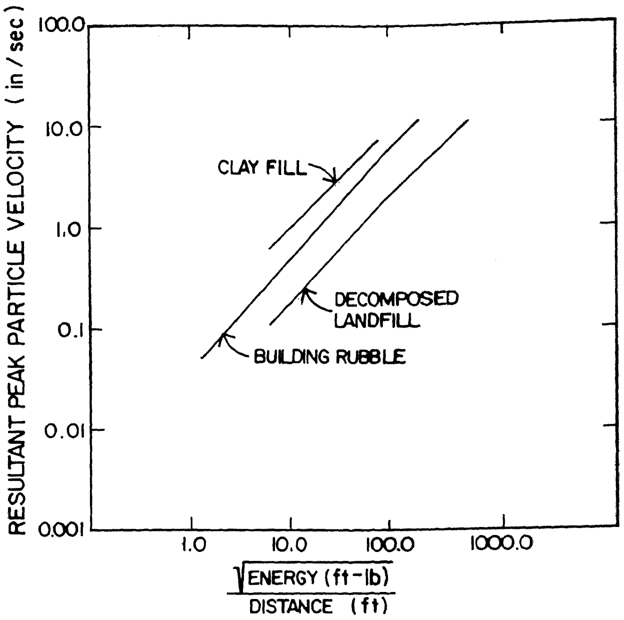

Fig. 1. Resultant Peak Particle Velocity vs. Energy Input and Distance from Weight

Eight-foot crater spacings were selected and a total of 93 individual craters were created in the test section. The pounding was actually completed in two phases, with the first phase consisting of 54 craters across the entire site on the 8-ft grid, followed by an additional 39 craters superimposed over pounded and regraded surface area. Each crater received an average of two to three tamps per location per pass. Crater depths averaged approximately 6 ft, and an attempt was made to keep the weight penetration above the water table. Originally, three passes were planned in the test section, but difficulties with the crane equipment prevented this within the time budget for the test pounding. Both crater depths and adjacent ground heave were carefully monitored throughout the test pounding process. The average energy input was approximately 56 tons-ft/ft^2 (184 ton-m/m^2). Average ground reduction following the test pounding was 3'6", amounting to approximately 11% of the total depth of improvement (30 ft).

A soil boring was performed in the test section following the pounding and SPT and pressuremeter test results were obtained. These results were compared to tests performed prior to pounding and a graph comparing the results is shown on Figure 2. It was interesting to note that an increase in density was observed immediately above the natural clay.

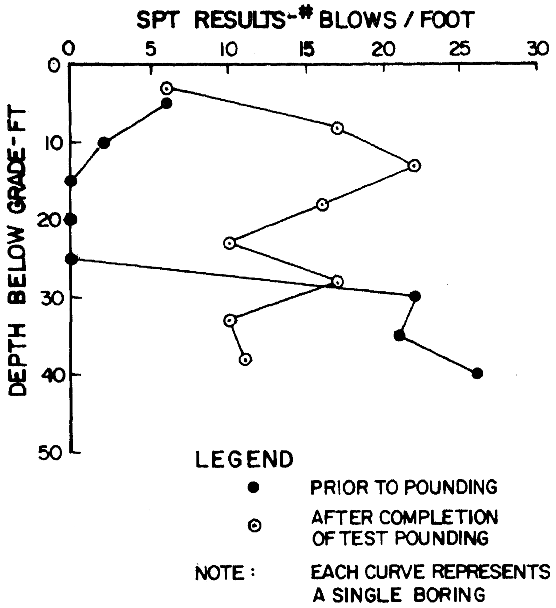

Fig. 2A. Standard Penetration Test Results Before and After Test Pounding

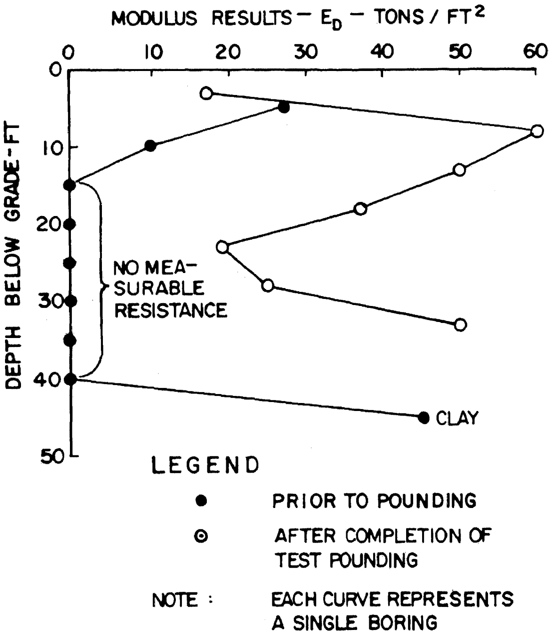

Fig. 2B. Pressuremeter Test Results Before and After Test Pounding

On the basis of the test pounding results, it was concluded that a 15-ton weight dropping from a height of approximately 60 ft would be utilized. Crater spacings would be on the order of 8 ft (center to center). Three to five passes, with each pass involving a minimum of two tamps, or that number necessary to achieve a maximum crater depth of 6 ft, was specified. Following each pass, the craters were to be leveled. Following the final pass, the craters were to be releveled and the surface compacted. With regard to minimum density criteria, it was suggested that an average minimum of 15 blows per foot be achieved with the SPT test and an average minimum modulus of 50 tsf be achieved with the pressuremeter test within 10 ft below the footing and 30 tsf below this level.

PRODUCTION POUNDING

Construction Difficulties

Despite the success of the procedure as indicate by the test section, several construction-related difficulties were encountered during the production pounding phase. One of the most significant problems was related to the consistency of the fill. Although the material noted by the soil borings appeared to consist primarily of miscellaneous rubbish and building materials, isolated pockets of organic and clayey soils were encountered. These areas were so soft that crater depths oftentimes averaged 7 to 10 ft on a single drop. At these depths, the weight became very difficult to extract, due to suction forces which developed. Some deep craters were also encountered in the more granular portions of the site, but suction was not as dramatic in these soils and extraction of the weight was typically a routine process. To deal with the suction problems in the more cohesive soils, the following procedure was established:

> On the first pass across a new area, the weight was dropped one or more times per crater, depending upon the resistance offere The object was to produce a crater less than 7 ft deep. Typically, five or six passes were necessary to achieve the require density. If the soft and wet areas containe predominantly cohesive soils, the materials were removed to a depth of about 7 ft and backfilled with granular soil. Large stone was recommended for deep undercut areas, while smaller size stone was recommended for the upper 3 ft of new fill placed.

A second problem which appeared was the loose, fluffy material which collected at the ground surface. Even with the second and third passes of the weight, it was difficult to compact these surface materials to a point where they were suitable for a floor slab subgrade. Thus, the procedure developed was that once the final pass had been completed crushed rock was used to fill the craters and to bring the area to approximate floor slab subgrade. The stone was compacted either using the 15-ton weight dropping a distance of 20 ft, or a lighter weight (5 to 6 tons) dropping a distance of 30 to 40 ft. It was found that the lighter weight was the preferable solution since a secondary crane was brought out to do the surface tamping and production with the larger crane was not slowed.

Water created a problem with the deeper crater depths, and also became a problem when the pounding approached the pit edges. This problem occurred as a result of the change in material type from the fill to the natural clay soils. In effect, the pounding forced the water towards the pit edges, but the lower permeability of the clay slowed the water passage. The consequent build-up of water in the craters reduced the pounding effectiveness. The solution to this problem was to cut isolated drainage trenches into the sides of the pit, thus providing an exit point for the water. Water was continually pumped out of these trenches and the ground water was subsequently lowered in the immediate pit area.

Another unusual problem which occurred was associated with the longevity of the cables used to lift the 15-ton weight. At first, the contractor utilized a 7/8-inch diameter cable. However, the cable broke on the average of once every two days. Thicker cable could not be utilized due to the mechanical restrictions of the crane. Finally, it was decided to use a 1-1/8-inch diameter cable reduced during fabrication to 7/8-inch. This was a relatively successful solution, although mechanical breakdowns still did occur.

Summary of Results

Soil borings with pressuremeter and SPT tests were performed following completion of the production pounding. An averaged comparison of before and after data is presented on Figure 3. From the data, as well as our full-time observation during the production pounding, it was concluded that sufficient compaction was achieved.

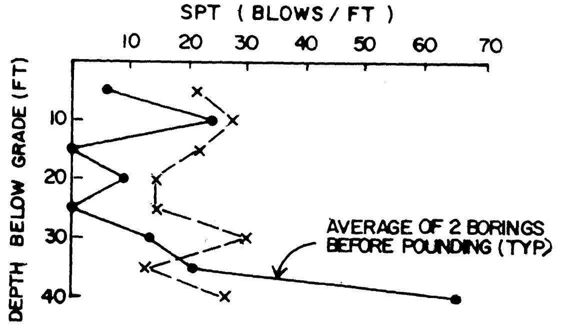

Fig. 3A. SPT Results Before and After Pounding

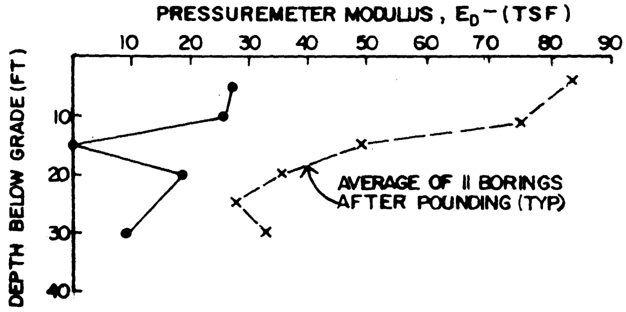

Fig. 3B. Pressuremeter Results Before and After Pounding

As with the test pounding phase, the depth of improvement was observed to be on the order of 30 ft. This depth of improvement (in equivalent meters) computes to be approximately $0.58\sqrt{WH}$; where W = 15-ton weight and H = 18-meter drop. A comparison was also made between areas where pounding was performed on stone and no stone surfaces. The density improvement appeared slightly greater where stone was placed in the craters and on the surface prior to the final phases of tamping. Stone thicknesses were on the order of 3 to 4 ft. On the basis of an average of twelve tamps at each location, the average energy input with the 15-ton weight was 170 ton-ft/ft^2 (560 ton-m/m^2). Ground subsidence after pounding, and releveling and compacting, averaged 3.5 to 4.0 ft, which was approximately 12 to 13% of the total depth of improvement of approximately 30 ft.

Long-Term Performance

In order to evaluate the long-term performance of the structure, settlement markers were established on the building and were monitored for a period of six months from footing construction through completion of the superstructure. A summary record of the results is shown on Figure 4. Readings of initial settlement were only slightly higher than the predicted range of an inch. Long-term settlement was less than 1/4 inch. To date, no known signs of distress have occurred to the building.

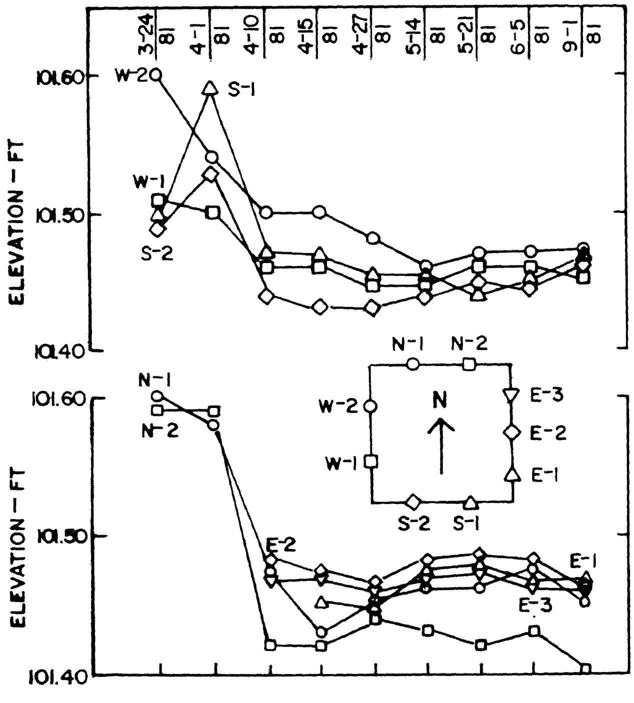

Fig. 4. Settlement Record

CONCLUSIONS

Given the site conditions, the age of the fill, and the extent and density of the fill, the pounding alternative was considered the most cost-effective solution for the site. On the basis of the long-term performance of the building, indicating maximum settlements within the predicted ranges, the pounding process was considered a successful alternative. In the process, several new construction techniques were learned. These were associated with winter weather difficulties, cable problems, water removal, the importance of the pounding and grid sequence, as well as the use of stone stabilization to facilitate surface tamping. Coordination between all parties became a critical factor, as did full-time inspection during construction. In summary, marginal sites such as former landfills can be successfully and economically developed if properly evaluated and carefully monitored during construction.

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