Loading Patterns in Varved Pleistocene Sediment in the NYC Area

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INTRODUCTION

In 1976 James Parsons of Mueser Rutledge Consulting Engineers described the engineering characteristics of the varved silts and clays found in the New York City area. Over the years MRCE has conducted extensive testing of the local soils, including work for numerous NYC housing projects, which was the source for much of Parsons' data. The test programs included consolidation tests. A consolidation test can be used to determine the maximum load to which a given soil has been subjected. In his study, Parsons determined that the varved soils of New York City were highly overconsolidated, meaning that the sediments had settled under weights significantly greater than the present overburden. He concluded that, although there was no known visible geologic evidence of later glacial advances, a younger advance was the only way to explain such high loads over an area.

Four mechanisms can account for a soil preconsolidating to a value greater than the existing overburden could provide. When preconsolidation values are plotted versus sample depth, the distribution of the values can sometimes be used to determine in which manner a soil profile was previously loaded. Parsons' test values came almost entirely from Manhattan, with a majority of the sites to the north, particularly along the Harlem Valley. In an attempt to determine the means responsible for the high preconsolidation values in New York City, and to see if these values were consistent across the region, we here provide test data from other sites in New Jersey and around New York City, including information from projects more recent than the 1960s.

CONSOLIDATION TESTS

In most sedimentary deposits there are interconnecting voids between the individual component grains of soil. Below the water table, the voids are filled with water and the column of water helps to support the weight of the soil grains (Figure 1A). When an additional load is applied, the water flows out of the sediment, the grains of soil shift and deform, and the voids become smaller (Figure 1B). As the voids decrease in size, the sample loses volume as it becomes more compacted. If a sample is saturated with water and the water table drops, the soil may dry out. As water is drawn from the soil through evaporation, the voids will shrink and the desiccated soil will consolidate, just as if an increased load had been placed on it. When groundwater levels drop, the upper layer of newly dry soil no longer has a column of water to help support it. As a result, the soil may become compressed under its own increased weight (Figure 1C).

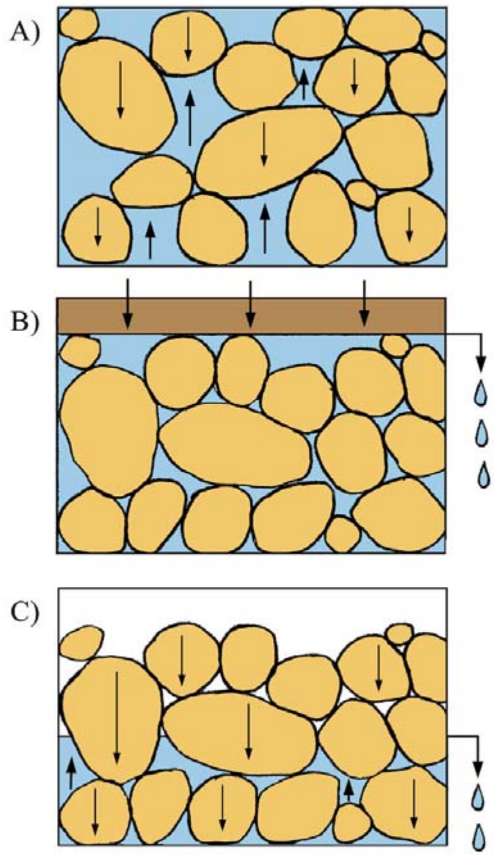

Figure 1 – Sketches illustrating how a soil consolidates. In (A), interconnecting voids fill the spaces between the soil grains. When the soil is saturated the column of water helps to support the weight of the soil. When a load is applied (B), the water flows out of the soil and the voids become smaller and the soil becomes more compact. When the groundwater level drops (C) the soil is no longer partially supported by the water column and the full weight of the soil causes the sediment to compress. Removal of water through evaporation can also cause the soil to consolidate.

A consolidation test is usually conducted on an undisturbed sample of silt or clay. After a sample is set up a small load is applied to it, and the amount of compression that the soil undergoes is measured over time. Initially the sample will compress rapidly as the water flows out of the sample and the grains shift position to decrease the size of the voids (primary consolidation). Eventually the rate of compression will slow, but continue indefinitely, as the sample starts to consolidate mainly as a result of the long-term deformation of the soil grains (secondary consolidation in Figure 2). Once the sample has started secondary consolidation, usually within 24 hours, the load on the sample is increased and compression is again measured. Loads continue to be increased until the sample starts to settle less than it did under the previous load. The weights are then removed, the sample is allowed to swell, and numerous values are calculated (Figure 3). The test results can be used to determine how much and how fast a particular soil will settle under a given load, the permeability of the soil under that load, and the maximum load the soil was previously exposed to (preconsolidation value, Pc).

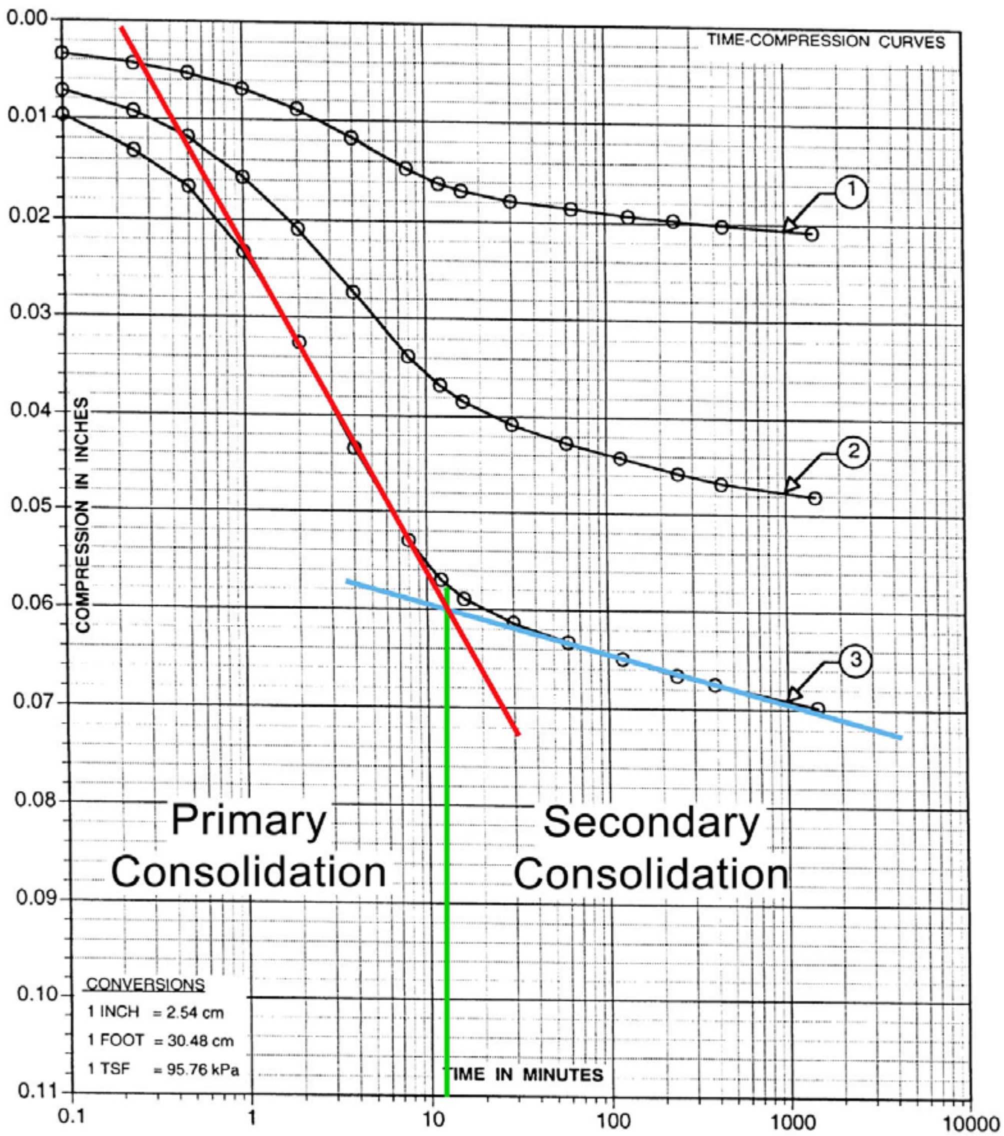

Figure 2 – Typical time-compression curves for a varved silty-clay soil. The three curves represent three increasing loads placed on a single soil sample. When a load is placed on a sample the soil initially compresses rapidly (primary consolidation) as the water flows out and the grains shift and deform to reduce the size of the voids. (See Figure 1.) The rate of compression slows considerably (secondary consolidation) when consolidation takes place primarily due to long term deformation of the grains. Once in secondary consolidation, a soil will continue to compress indefinitely.

When Pc values are plotted against depth in a normally consolidated soil, the points plot along the line (effective overburden stress) that corresponds to the weight of the existing overburden. If the soil was previously subjected to a greater load which is now gone (i.e. glacial ice, eroded sediments, temporarily lowered water table), the points will plot roughly parallel to the overburden line, but at higher values that indicate the higher load. If the groundwater table drops and the soil layers above the water table become desiccated, the Pc values plot along a distinctive curve. Soil closest to the ground surface is the most desiccated and has the highest Pc value. Moving downward closer to the water table, the soil becomes less desiccated and the Pc values approach values normal for the desiccated overburden (Figure 4).

If a soil is left undisturbed and allowed to compress under secondary consolidation for extremely long periods of time, it will consolidate as if it had been exposed to a slightly higher load. Pc values 1.5 times the size of the corresponding overburden values are possible (Terzaghi, Peck, and Mesri 1996). In this situation the Pc values representing the younger soil at the ground surface will plot near the overburden line. With increasing depth and age, the points plot along a curve that gets increasingly larger than the overburden value with depth.

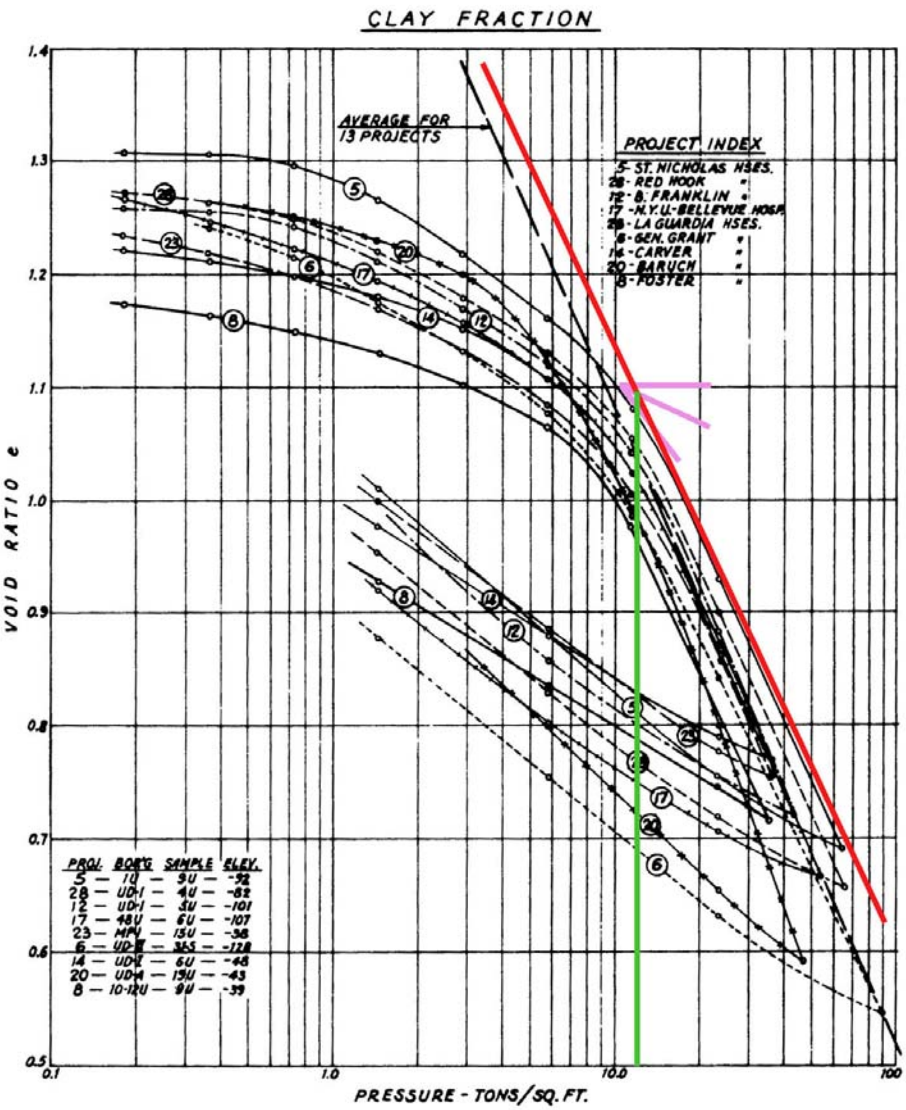

Figure 3 – Typical pressure versus void ratio curves of the clay portion of the varved soils investigated by Parsons (1976). When a consolidation test is completed, the void ratio (= volume of voids/volume of soil) is plotted against the corresponding pressure on the sample. From this graph the maximum load the soil sample was previously subjected to can be determined. Construction using the Casagrande method is shown for sample #5.

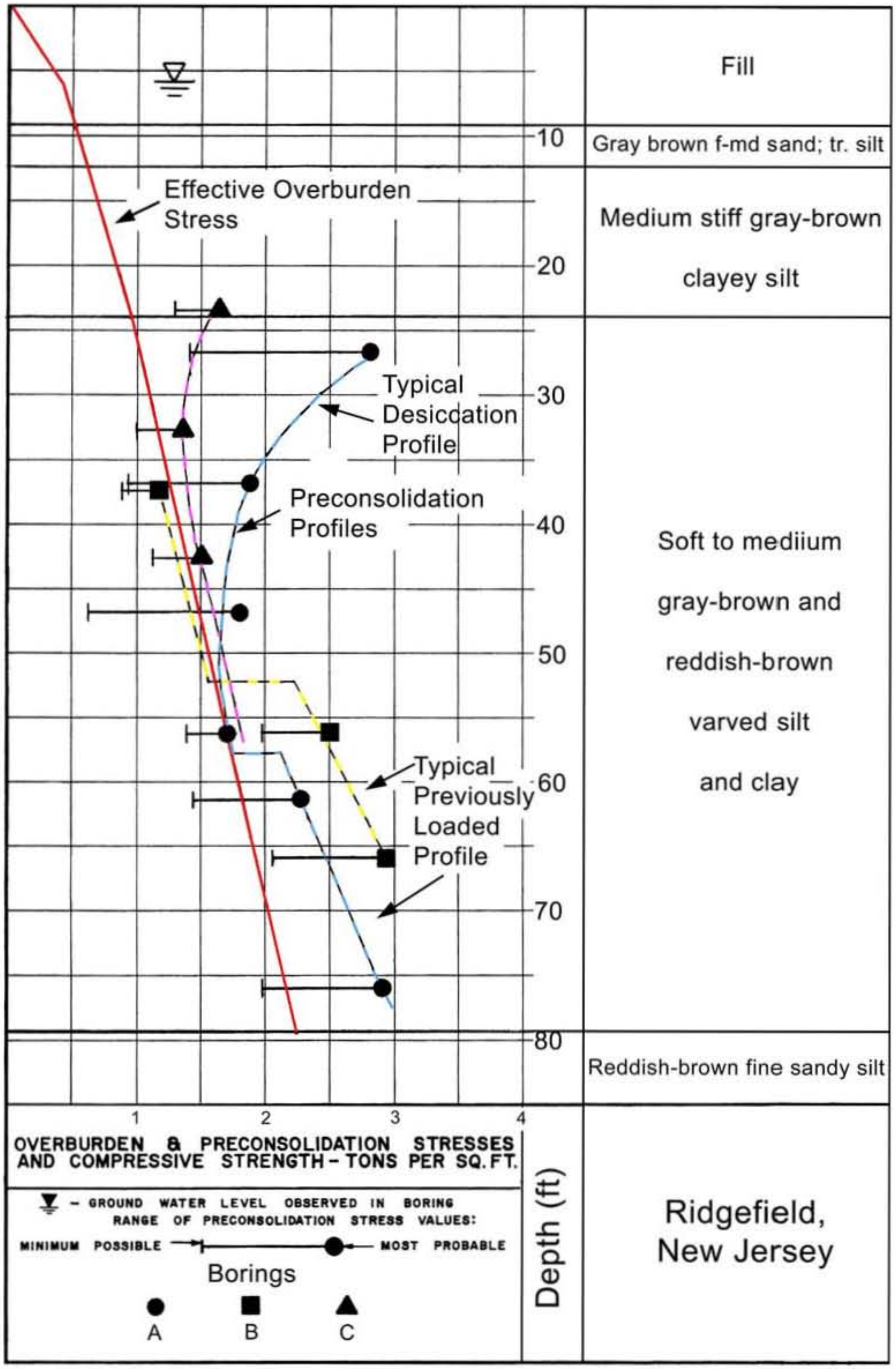

Figure 4 – From a site in Ridgefield, NJ, loading history of a soil based on patterns in Pc values plotted against elevation. Samples plotted along the overburden line are normally consolidated. Samples overconsolidated at the ground surface becoming normally consolidated with depth are desiccated. Samples that plot parallel to, but greater than, the overburden line have been previously loaded to the higher pressures.

RECENT GLACIAL LAKE HISTORY

According to many experts, the last major glacial advance across the New York City area left behind the "pre-Woodfordian" Harbor Hill terminal moraine, which stretches across Long Island, Queens, Brooklyn, the Narrows, Staten Island, and into New Jersey (Figure 5). Sanders and Merguerian (1994, 1998) envision a younger glacial advance, their "Woodfordian" glacier, from a NNE flow direction. As the "pre-Woodfordian" glacier started to melt and retreat, glacial Lake Bayonne formed between the moraine and the ice front. The lake initially had a spillway across the moraine at Richmond Valley. This outlet lies at the current elevation of +30 feet when corrected for regional isostatic rebound. Regionally the earth's crust was depressed after thousands of years under the massive weight of glacial ice. As the ice melted away, the ground surface slowly rose back up to a stable level.

When a new spillway eroded down at Perth Amboy, the lake level dropped to El. -30 feet (Stanford and Harper 1991 and Stone et al 2002). Once ice had retreated north of Hell Gate, a new spillway draining into the Long Island Sound area opened up for the region at El. -30. Lake Bayonne dropped to the level of Lake Hackensack west of the Palisades intrusive sheet, and to the level of Lake Hudson east of the Palisades. A spillway through Kill Van Kull (currently El. -20 feet) once connected the two lakes, allowing Lake Hackensack to drain eastward into Lake Hudson. When a new outlet opened up at the Sparkill Gap, Lake Hackensack started to drain northward and then eastward into Lake Hudson. With continued ice retreat, Lake Hudson extended northward up the Hudson Valley, possibly coinciding with Lake Albany. Over time the glacial lakes were filled with lake bottom varved sediments and outwash sands. When the terminal moraine was ultimately breached at the Narrows (Merguerian 2003), the lakes started to drain. Near the Narrows roughly 200' of the glacial strata were scoured away.

TYPICAL NEW YORK CITY SOIL PROFILE

In New York City north of the Harbor Hill terminal moraine the soil profile typically consists of bedrock often overlain by a layer of basal till. Above the till, the soil tends to be more coarse grained towards the present ground surface and more fine grained with depth. Varved silts and clays are often just above the basal till. The deposits coarsen upward into varved silts, then silty fine sands, and eventually into clean fine to coarse grained outwash sands. Locally, there may be areas with discontinuous, often thin till above the outwash, quite possibly the result of post-Harbor Hill "Woodfordian" glaciation. In the river valleys the glacial deposits are overlain by river sands and organic silty clays and occasionally by marsh-related peat (Figure 6).

PRECONSOLIDATION VALUES IN NEW YORK CITY

In his study, Parsons determined that the varved soils of New York City, particularly those in northern Manhattan, were highly overconsolidated (Figures 7 and 8). The varved lake deposits had generally been subjected to loads 5 to 10 tsf (tons/ft^2) greater than the currently

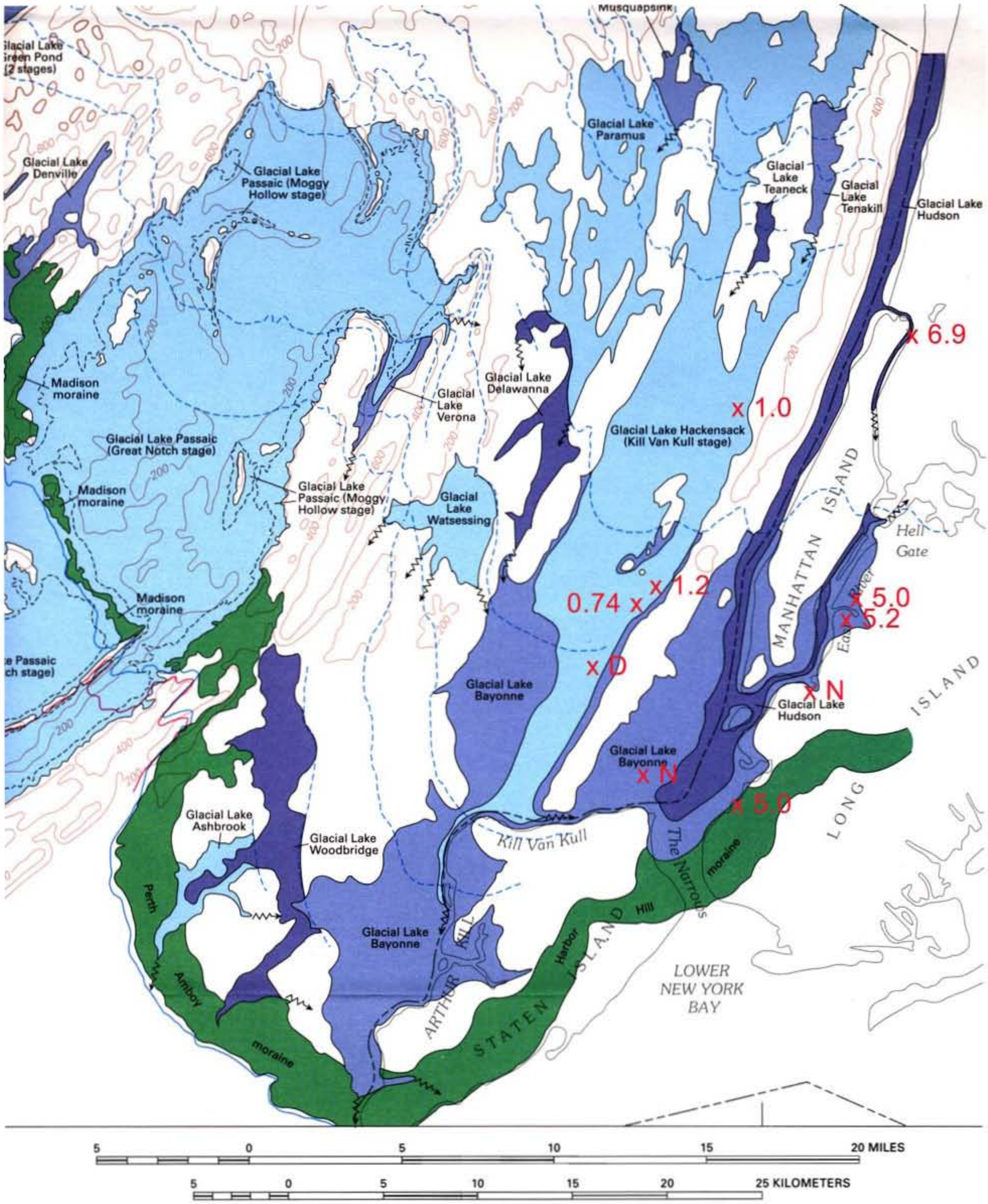

Figure 5 – Surficial geological map of northern New Jersey with locations of additional sites studied in the New York and New Jersey area. The numbers indicate the average amount of overconsolidation (in tsf) for non-desiccated soils at each of the locations (x). D indicates only desiccated samples were tested; N indicates the soil is normally consolidated under the existing overburden. (Adapted from Stone et al 2002.)

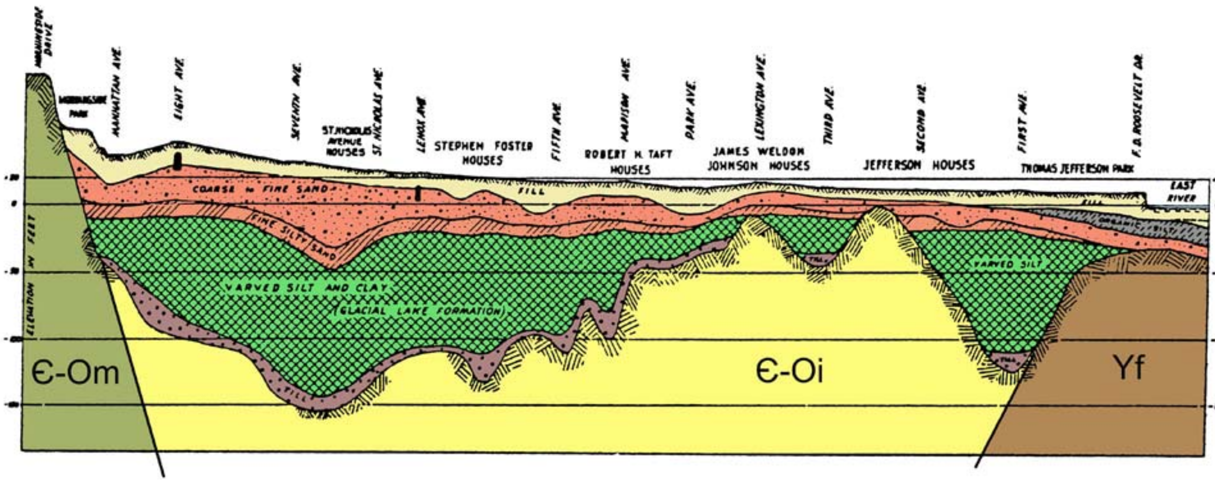

Figure 6 – Geological section across 113th Street in Manhattan. The section shows the general fining downward trend present across Manhattan; note that the upper glacial layer (orange) consists of coarse and fine sand overlying fine silty sand. Varved silt deposits tend to be especially thick in upper Manhattan compared to the rest of the island. Units Є-Om = Manhattan Schist, Є-Oi = Inwood Marble, Yf = Fordham Gneiss. Line of section shown in Figure 7. (Annotated, colorized version adapted from Parsons 1976.)

existing overburden. This is equivalent to placing roughly an additional 175 to 350 feet of dry soil, or 80 to 165 feet of saturated soil on top of the existing ground surface. The existing varved deposits generally have no more than 125 feet of granular sediments above them, and often significantly less. If the groundwater table dropped completely below the overlying sediments to the level of the deepest varved soil, the overburden pressure would only increase by about 3.5 tsf. Thus, another mechanism is needed to explain the distribution of excessive loading.

No evidence suggests that the amount of soil above these varved deposits was significantly greater than what currently exists. None of the sample locations are in an area likely to have undergone anomalous erosion. This includes areas that would have been scoured by a flood resulting from a breach of the dammed up end moraine. Such a breach would cause the water table to drop, but lowering it over 100 feet to just above the bedrock would still not increase the overburden enough to account for the difference. (See Figure 8.) In addition, the trend of the Pc values parallels the existing overburden line, not the gentler slope of the drained soil overburden line. Study of soil samples and a plot of Pc values vs. depth shows that the soil does not appear to be desiccated. The Pc values also do not follow the curved plot expected for soil that has been settling under secondary consolidation for an extensive period of time. A preliminary analysis of the Parsons data suggests that the soil follows the pattern typical of an increased overburden.

PRECONSOLIDATION VALUES IN GLACIAL LAKE HACKENSACK

Preliminary analysis of additional data shows that the pattern of Pc values in the area of glacial Lakes Bayonne/Hackensack in New Jersey are distinctly different from the values of Lakes Bayonne/Hudson in New York. Most experts are in agreement that in glacial Lake

Hackensack the water originally flowed to the south. As glacial ice retreated and isostatic rebound took over, the southern end of the lake rose relative to the northern end and drainage patterns reversed (Stanford and Harper 1991). For a period of time before drainage reversed again, the lake drained to the north through Sparkill Gap and the sediments south of Moonachie became subaerially exposed. As a result of this exposure the upper varved lake sediments became desiccated. Pc values from sites in the Lake Hackensack area display the pattern typical of desiccation in the surface soils. In projects where tested samples went below the level of desiccation, the values for the lower strata rise and follow a pattern typical of a soil that has been loaded to roughly 0.75 to 1.0 tsf greater than the existing overburden. (See Figure 4.)

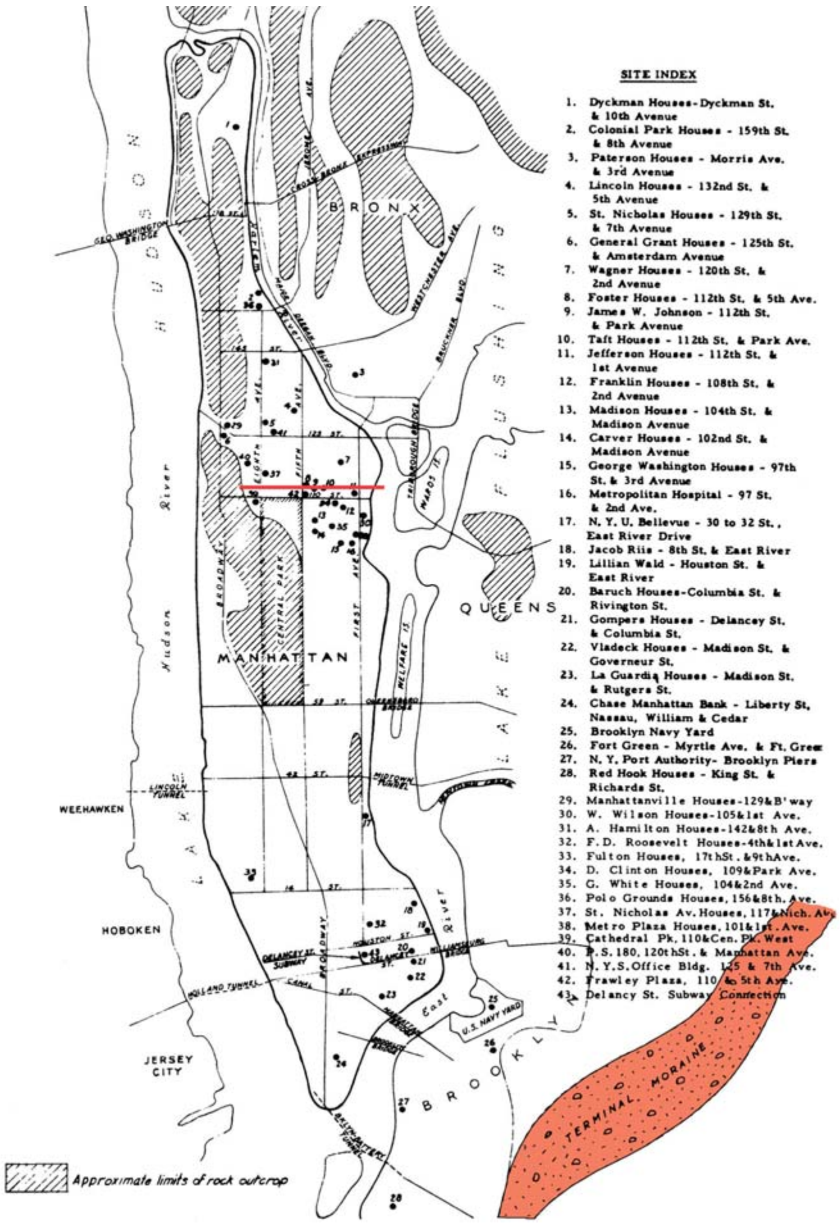

Figure 7 – Varved soil site locations investigated in Parsons (1976). Not all of the sites listed had consolidation tests performed as part of the testing program. The red line across 113th Street shows the line of section of Figure 6.

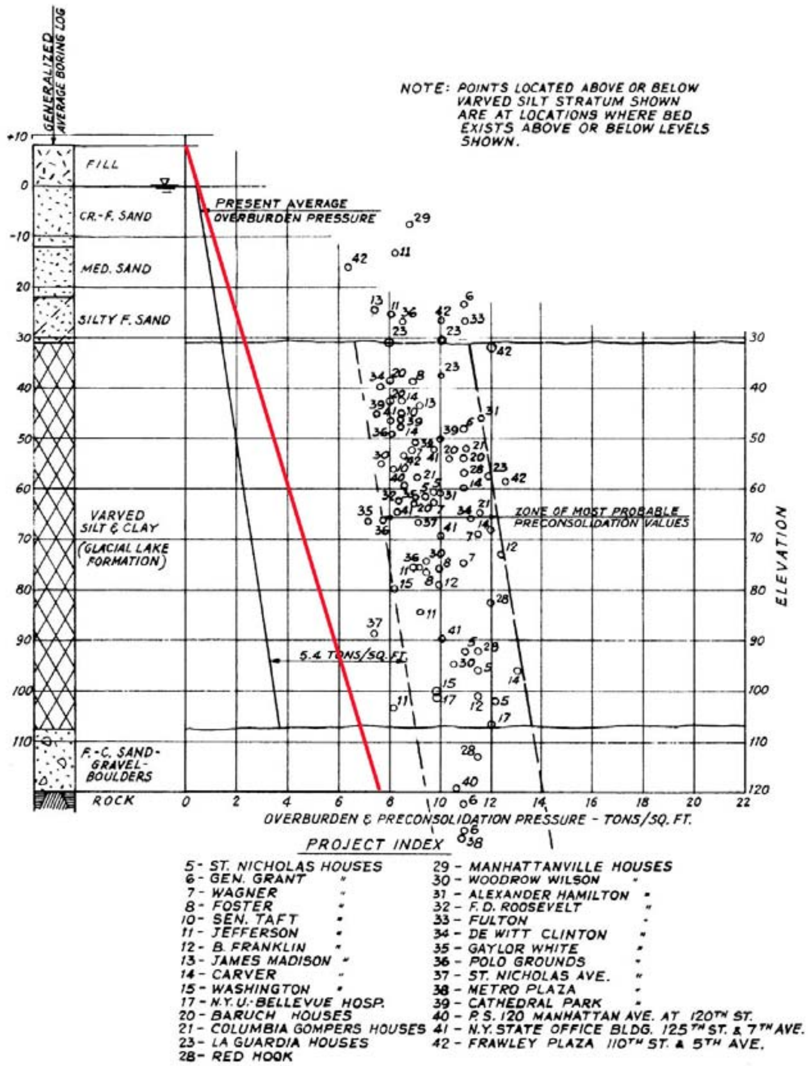

Figure 8 – Summary of Pc values versus elevation from the consolidation tests analyzed by Parsons (1976). The Pc values plot at values significantly higher than the existing overburden. If the water table lowered to bedrock the increased load shown by the new overburden (red line) would still not rise to the level of the measured Pc values.

Lowering the water table by 25 feet will increase the load on this type of soil by 0.78 tsf. If a water table drop was responsible for the change in load, then all of the Pc values below the original water table level would increase by the same amount. The data points from New Jersey tend to show a pattern of more desiccated soil at the top, decreasing to normal or near normal consolidation values with depth, then a sudden increase in values towards the bottom of the soil profile. In some cases the normally consolidated soils in the middle of the profile do not have values high enough to have been loaded to the same extent as the underlying sediments. Presumably the lower strata were subjected to increased loads, possibly through glacial loading. Later deposition took place above the previously loaded strata and the upper portion of the newer sediments became desiccated.

VALUES FROM ADDITIONAL NEW YORK CITY LOCATIONS

For comparison, we conducted a preliminary review of other sites in New York City, particularly along the east side of the East River (Figure 5). In general, these samples show no indication of desiccation. Tests run near the northern tip of Manhattan were overconsolidated by 5 to 8.5 tsf which are comparable to the values Parsons (1976) measured from northern Manhattan. Samples from several sites in Queens and Brooklyn tended to be overconsolidated by 4 to 5.5 tsf rather than the higher values found in northern Manhattan. There were a few locations along the very edges of the current Hudson and East Rivers where the varved soils are not overconsolidated. A site in Bayonne, New Jersey and a site in Fort Greene, Brooklyn are reported to be normally consolidated under the existing overburden. A report for the Brooklyn Naval Yard indicates that samples in deeper open water are overconsolidated by up to 2.3 tsf, although samples landward are normally consolidated.

If glacial loading is responsible for the observed differences in Pc values, then presumably the ice was thicker to the north and thinner to the south and may have been confined to the center of the river channels rather than reaching the edges. If the glacial Lake Bayonne/Hackensack area was subjected to additional loading, it was not to the greater extent that occurred in the Lake Bayonne/Hudson region.

DISCUSSION

A key point of Parsons was that the Pc values indicated excess loading had occurred, presumably by glaciers, even though there was no visible physical evidence of a younger glaciation. In the interim, new field data has identified features of glacial erosion and deposition from such an event (Sanders and Merguerian 1991a, 1991b, 1994; Sanders et al 1997). These new data support the multi-glacier hypothesis of Sanders and Merguerian (1998) and also support their interpretation that the youngest “Woodfordian” glacier was not an extensive ice sheet but was a thinner glacier that was locally channelized into valleys. In soil samples from several locations across the city, we have seen thin and discontinuous deposits of glacial till above the varved and/or outwash soils. Some are found in the general vicinity of sites that are preconsolidated. In some locations the upper glacial till has a composition and presumably a source different from the underlying sediment. There are also locations where the varved soils are clearly a different color from the basal till, the result of a facies contrast promoted by contrasting NNW and NNE glacial flow directions (Merguerian and Sanders 1996).

The New Jersey glacial geologic map of Stone et al (2002) states that the glaciers receded first in the western part of the state and lastly in eastern NJ. This suggests that the ice flow shifted from a northwestern direction to a north or northeastern source area. This supports the Sanders and Merguerian (1998) contention that Pleistocene history of the NYC area is complex and that the youngest advance came from the northeast. The map also states that there were minor readvances during the general recession. The text does not define what constitutes a “minor readvance”, but local Pc values appear to support the concept that some form of readvance occurred. It was more significant east of the Palisades than to the west, and it may have been primarily localized along the northern fringe of NYC, with more southern flow confined to the river valleys. We adopt the tantalizing view that the youngest "Woodfordian" glacier may not have reached the position of the Harbor Hill moraine at all. The glacial lakes behind the Harbor Hill moraine may have been dammed by the moraine until breaching of the dam took place at the present site of the Narrows channel.

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