Soil Compaction as Indicated by Penetration Resistance: A Comparison of Two Types of Penetrometers

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Introduction

One of the most common ecological changes induced by recreational use is soil compaction, a process in which individual soil particles within the soil matrix are forced to rearrange themselves into closer proximity (Liddle 1997). Some common forces of soil compaction in recreation settings include trampling by foot and vehicular traffic on recreation sites and trails, though soil compaction can also occur from natural causes such as drying and wetting. Soil compaction typically results in reduced amount and size of pore space and total soil volume, which in turn lead to decreased infiltration capacity and increased surface runoff, standing water, and erosion (Brady and Weil 2002). These changes represent site degradation and may have a detrimental effect on vegetation and soil resources.

The objective of this paper was to apply two common types of soil compaction measuring tools in Boston Harbor Islands National Recreation Area to evaluate their utility and data variability.

Measuring Soil Compaction

Four approaches have been developed in agriculture and related disciplines to measure soil compaction: penetrometry, bulk density, conductivity/permeability, and radiation (Freitag 1971). *Penetrometry,* or soil strength, measures the resistance of soil surface to vertical force by poking a rod or penetrometer into the soil. *Bulk density* is determined by the weight of oven-dried solid per unit volume. This approach requires collection of soil samples and oven-drying in a laboratory (Lowery and Morrison 2002). *Conductivity/permeability* evaluates the rate at which water or air permeates through soil. A common technique in this category is infiltration capacity, which requires the availability of field time and distilled water. Finally, *radiation* methods, such as surface nuclear gauges, measure soil density instantly based on penetration of gamma rays or neutrons. This approach requires expensive equipment and licensed users.

Penetrometry and bulk density are the most common compaction measures in visitor impact studies (Liddle 1997). This study adopted penetrometry as the soil compaction measure due to its requiring a minimum of ground disturbance, as mandated by park regulations, and its efficiency in island settings. In a campsite impact study, Marion and Cole (1996) documented a 460% relative change in penetration resistance between the campsites and the control areas as measured by pocket penetrometer. The mean penetration resistance on 29 campsites was 2.8 kg/cm^2, while the undisturbed control sites averaged 0.5 kg/cm^2 (Marion and Cole 1996).

Methods

Study area. This study is part of a larger Visitor Experience and Resource Protection (VERP) research project in Boston Harbor Islands. Soil compaction was evaluated as a potential resource indicator. Boston Harbor Islands consists of 34 islands and peninsulas in Boston Harbor, and is 650 ha in total size. Due to its proximity to population centers, this new park receives an ever-increasing visitation, with 262,000 recreational visits recorded in 2002 (Boston Harbor Islands National Recreation Area 2003). The park is managed by a 13-member partnership that includes the National Park Service, federal, state, and municipal agencies, and non-profit organizations. This paper focuses only on two public-use islands, where soil compaction measurements were performed. Georges Island is a heavily used island with Udorthents (Ud) loamy soil as the dominant soil type. Grape Island possesses a more natural setting with less visitor use. Newport silt loam (NpC) and Pittstown silt loam (PtB) soils dominate Grape Island. They are reported herein as a combined soil type (NpC/PtB).

Penetrometers selected. Two different types of portable penetrometers were chosen to measure penetration resistance as an indicator of soil compaction. The pocket penetrometer (SOILTEST, Inc.) is a spring-loaded instrument 15.2 cm in length and 1.9 cm in diameter. The instrument measures penetration resistance when its 6.4-mm-diameter round tip is pressed 6.4 mm into the soil. When pushed into the ground, a metal ring is pushed up the scale, marking the penetration resistance value in kg/cm^2. The soil compaction tester (DICKEY-john Co.) is a portable cone penetrometer 93 cm in total length with a dial on top to immediately read the soil compaction value (pounds per in^2). An angled cone attachment of 12.7 mm or 19.1 mm is screwed onto the other end of the 70-cm rod that is pushed into the ground. The rod is marked every 7.6 cm to enable measurement of soil compaction at 7.6-cm increments (up to 45.7 cm).

Field procedures. In June 2002, a total of 12 circular plots (6-m radius) were established on Georges and Grape islands. On each island, two plots were randomly located within high-use zones (close to a pier), while another two were randomly located in low-use zones. Within each plot, 12 quadrats (25 cm x 25 cm) were randomly located along six radial transects that are 60° apart. In each quadrat, four penetration resistance (PR) readings were taken using the pocket penetrometer (PP), and four pairs of PR measurements were taken using the soil compaction tester (SCT) at a depth of 7.6 cm and 15.2 cm. Hence, the maximum numbers of PP and SCT readings for each plot were 48 and 96, respectively. Only the SCT readings at the 7.6-cm level are compared with PP readings. Due to rocks, roots, and compaction, not all SCT measurements could be taken at their intended depths, resulting in reduced number of SCT readings in some cases. Eight background PR measurements were taken with two penetrometers, respectively, at adjacent, environmentally similar control areas outside each plot. All measurements of a single plot were completed on the same day.

The same plots and quadrats were relocated and remeasured in August and October 2002 to evaluate temporal changes. The August data were collected during a severe drought, resulting in extremely high PR readings under unusual soil moisture regimes. For comparability purposes, only data from June and October 2002, representing the beginning and end of the visitor-use season, are presented. PR readings from two plots representing the same use level were combined. Relative PR change of each plot was calculated by the difference between mean plot and control PR values divided by the control mean PR value. Relative changes are valid for comparison among sites with varied background PR levels. Data variability was evaluated by the coefficient of variation (CV; standard deviation as the percentage of the mean). The percentage of successful SCT penetration to each depth level in each plot was reported as penetration depth. All SCT and PR readings were converted to kg/cm^2 for analysis and reporting.

Results

Beginning of visitor-use season. High-use plots started with higher PR values on both islands in June. On Georges Island (Ud soil), the mean PP–PR was 3.0 kg/cm^2 for high-use plots and 2.1 kg/cm^2 for low-use plots (Table 1). The relative PR change based on PP was 54.3% for high-use plots and 53.0% for low-use plots (Table 2). On the other hand, the mean SCT–PR was 31.6 kg/cm^2 for high-use plots and 18.8 kg/cm^2 for low-use plots. The relative PR change based on SCT readings was 66.4% for the high-use area and –0.05% for the low-use area, indicating essentially the same PR level between use and control sites in the latter case (Table 2).

PR values as measured by both penetrometers were lower on Grape Island (NpC/PtB

Table 1. Penetration resistance measurements on Georges Island (Ud soil) using two types of penetrometer.

Penetrometer/ Use Level		June 2002				October 2002			
		Mean (kg/cm^2)	Std. Dev. (kg/cm^2)	Coeff. of Var. (%)	n	Mean (kg/cm^2)	Std. Dev. (kg/cm^2)	Coeff. of Var. (%)	n
Pocket Penetrometer									
	High Use	3.0	0.8	25.8	96	2.3	0.9	37.9	96
	Low Use	2.1	0.8	37.1	96	1.5	0.8	51.7	96
Soil Compaction Tester (7.6 cm)									
	High Use	31.6	7.3	23.1	80*	23.7	6.2	26.0	47*
	Low Use	18.8	5.2	27.8	92*	24.5	7.2	29.5	60*

* Some readings were unable to be obtained due to failure of the equipment to penetrate to the required depth.

Table 2. Relative percentage changes in penetration resistance on George Island (Ud soil).

Penetrometer/ Use Level		June 2002	October 2002
Pocket Penetrometer			
	High Use	54.3*	35.4
	Low Use	53.0	60.9
Soil Compaction Tester (7.6 cm)			
	High Use	66.4	21.3
	Low Use	-0.1	25.9

soil). For example, the mean PP–PR was 2.0 kg/cm^2 for high-use plots and 1.5 kg/cm^2 for low-use plots. According to the relative PR difference, use sites on Grape Island actually had more substantial compaction change as compared with their off-site controls. For example, relative PR changes for PP were 85.9% and 143.5% for high- and low-use plots respectively, while those for SCT were 111.7% and 53.5% (Table 4).

With respect to variability of PR measurements, results were comparable between the two soil types, with CV values ranging from 23.1% to 37.1% on Georges Island (Ud) and 31.2% to 42.1% on Grape Island (NpC/PtB) (Tables 1 and 3). The measurements on high-use Ud plots showed less variability, while the NpC/PtB plots exhibited a reverse pattern. Pocket penetrometer readings appeared to have a higher variability than SCT readings in

Table 3. Penetration resistance measures on Grape Island (NpC/PtB soil) using two types of penetrometer.

Penetrometer/ Use Level		June 2002				October 2002			
		Mean (kg/cm^2)	Std. Dev. (kg/cm^2)	Coeff. of Var. (%)	N	Mean (kg/cm^2)	Std. Dev. (kg/cm^2)	Coeff. of Var. (%)	n
Pocket Penetrometer									
	High Use	2.0	0.9	42.1	96	2.4	0.8	35.9	46*
	Low Use	1.5	0.6	37.2	96	1.8	0.4	22.2	48*
Soil Compaction Tester (7.6 cm)									
	High Use	16.6	5.9	35.2	96	22.5	4.6	20.6	38*
	Low Use	10.4	3.2	31.2	96	12.9	2.3	17.5	47*

* Only one plot was measured for each use level in October due to logistical constraints. Some readings were unable to be obtained due to failure of the equipment to penetrate to the required depth.

Table 4. Relative percentage changes in penetration resistance on Grape Island (NpC/PtB soil).

Penetrometer/ Use Level		June 2002	October 2002
Pocket Penetrometer			
	High Use	85.9*	34.8
	Low Use	143.5	42.7
Soil Compaction Tester (7.6 cm)			
	High Use	111.7	37.8
	Low Use	53.5	25.7

most cases, particularly on Grape Island (Tables 1 and 3).

End of visitor-use season. All Georges Island plots were reassessed in October 2002. Due to inclement weather conditions, only one high-use plot and one low-use plot were remeasured on Grape Island, resulting in fewer readings. Consistent with June data, high PR values were recorded on high-use sites using both penetrometers. On Georges Island (Ud), the PP mean was 2.3 kg/cm^2 for high-use plots and 1.6 kg/cm^2 for low-use plots, both of which were lower than at the beginning of the visitor-use season (Table 1).

The relative PR changes based on PP were 35.4% and 60.9% for high- and low-use plots, respectively (Table 2). The SCT–PR mean for the high-use plot was 23.7 kg/cm^2 and 24.5 kg/cm^2 for the low-use plot. The relative PR changes were 21.3% and 25.9% for high- and low-use plots (Table 2).

On Grape Island (NpC/PtB), the PP–PR mean was 2.4 kg/cm^2 for the high-use plot and 1.8 kg/cm^2 for the low-use plot. These values were higher than the June values (Table 3). The relative PR changes based on PP were 34.8% and 42.7% for the high- and low-use plots, respectively; these were lower than the June values (Table 4). The SCT results showed similar patterns on this island.

Both soil types exhibited a higher variability of PR measurements at the end of the visitor-use season, with CV values ranging from 26% to 51.7% for George Island (Ud) and 17.5% to 35.9% for Grape Island (NpC/PtB) (Tables 1 and 3). In the Ud soil type there was the same pattern in which high-use sites exhibited less variability, while in the NpC/PtB soil type there was less variability on low-use sites. Quite consistently, PP showed a higher degree of variability than SCT in both soil types.

Penetration depths. These measurements were applicable to only SCT. The results suggest that soil was generally less penetrable on high-use sites and on Georges Island (Ud), on which most of the SCT measurements were not able to reach the depth of 15.6 cm. At the 7.6-cm level, there was a decreasing trend in penetration depth from the beginning of the visitor-use season (83.3–95.8%) to its end (68.8–79.2%). Soil was more penetrable on Grape Island (NpC/PtB soil). Twenty-four percent to 46% of SCT measurements reached the penetration depth of 15.6 cm. The soil was less penetrable at the 7.6-cm level in October, with the percentage penetrated decreasing from 100% to 85% on the high-use site.

Discussion and Implications

It should be noted that the PR values of two penetrometers cannot be directly compared due to differences in their measurement depth and mechanism. However, they may be evaluated based on their utility and data variability. The PP is less expensive (about $60) and is very efficient to operate with one person. The ring attached to the penetrometer holds the PR reading until it is reset. Pocket penetrometer measurements also create less ground disturbance. In contrast, the SCT is more expensive (about $250), is harder to carry, and requires two persons to operate effectively. One person must be dedicated to taking the dial reading, as it changes constantly. Another person must keep track of rod markings to ensure that a reading is taken at each desirable penetration depth. As a result, the inter-rater variability could be higher. This aspect of measurement error, however, was not assessed in this study. Furthermore, the two sizes of cone tip and corresponding scales on the dial gauge could create confusion.

On the other hand, the PP readings contain a higher degree of variability based on CV. This may be due to the short penetration depth of this equipment. Irregularities of soil surface, such as rocks, stones, plant litter, and tree or grass roots, are more likely to interfere with the PP readings. Since SCT measures compaction at a deeper level, it is less influenced by surface conditions. The SCT is also capable of measuring compaction at various depths.

There are several other observations from this study. First, the relative PR changes in this study were much lower than those reported in Marion and Cole (1996). This may be related to generally higher PR levels on both use and control areas in Boston Harbor Islands as compared with campsites in Delaware Water Gap National Recreation Area (Marion and Cole 1996). Second, the PR level of Georges Island was generally higher than that of Grape Island. A number of factors, such as soil type and amount of use (higher visitation on Georges Island), may have contributed to this variation. Third, the high-use plots on Georges Island (Ud soil) showed less data variability for both penetrometers, whereas less data variability were found on the low-use areas on Grape Island (NpC/PtB soil). In other words, data variability of PR readings appeared to increase with decreasing PR level. A possible explanation is that soil strength could become more uniform in compacted soil. Finally, the relative PR changes were found to decrease in most cases from June to October, indicating the closing gap of PR between use and control areas. Both decreasing on-site PR values and/or increasing control PR values may have caused this effect.

Concluding Remarks

There are a number of limitations in this study. Only two islands and two penetrometer types were involved. Bulk density and soil moisture were unavailable to provide a more comprehensive comparison. The control areas are not entirely free of human influence and may be subject to limited foot traffic. This data set is being further examined to understand spatial and temporal patterns and to correlate with vegetative ground cover.

While soil compaction has been excluded from the final list of resource indicators for implementation of VERP at Boston Harbor Islands, this study has provided the park with baseline PR data on three different islands (data on Peddocks Island were not presented here). It seems useful to conduct similar measurements on selected sites that show signs of growing degradation. The PR data can inform management of the need for visitor and/or site management actions to reduce soil compaction and increase soil quality of recreation sites.

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