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Soil Compaction Thresholds for the M1A1 Abrams Tank:

Field Study at Camp Minden, La.

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Tank exiting plot.

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M1A1 tank traversing through study plot.

Introduction

Training in accordance with accepted standards and under realistic combat conditions is necessary to produce military forces of the highest quality and thus ensure the national defense. In recent years, increased environmental effects on many U.S. military installations can be attributed to a variety of factors including increased mechanization, heavier and faster vehicles, combined arms exercises, testing requirements for advanced weapon systems and more concentrated training because of base realignments and closures. Military training activities frequently result in land degradation that can negatively affect long-term use of the land for training, as well as a broad range of damaging environmental and ecosystem effects.

Military training exercises using heavy tracked vehicles is an intensive land use activity that results in vegetation disturbance and soil compaction, which can have long-lasting environmental effects (Althoff and Thien, 2005; Johnson and Bailey, 2002; Palazzo et al., 2003; 2005; Fehmi et al., 2001; Diersing and Severinghaus, 1984). Continuous long-term or intense short-term traffic by military tanks can cause soil compaction and changes in soil bulk density and soil strength that adversely affect a soil's ability to sustain those functions considered to be indicative of a soil in good condition. Furthermore, these changes may remain virtually invisible until secondary indicators start to appear (Horn et al., 1995). These secondary indicators are most often expressed as reduced soil structure and porosity, altered soil-water relationships, reduced aeration, increased runoff and soil erosion, reduced vigor in plant growth, impaired vegetation regeneration capabilities, altered plant community composition and diversity and altered bird and mammal species diversity and distribution (Palazzo et al., 2003; Brady and Weil, 2002; Ayers, 1994; Diersing and Severinghaus, 1984; Goran et al., 1983).

Soil compaction and the associated negative effects on other soil physical, chemical, biological and hydrologic properties are widely recognized as the primary factors in reduced soil quality and function where tank training activities occur (Prose and Wilshire, 2000). In a review of the relevant military vehicle impact literature, Anderson et al. (2005), suggest that a number of knowledge gaps exist related to the effects of military vehicles on natural resources. They also indicate that the bulk of the research to date had been conducted on military lands in the southwestern United States, while other regional areas like the Southeast and Northeast remain largely understudied. Due to significant regional ecosystem differences, it is unlikely that study results from one region will directly apply to others. As such, the environmental effects of military tank maneuvers on training lands' soils and vegetation are identified as a priority issue at military installations across the country (Althoff and Thien, 2005).

An opportunity to further the study of the effects of military tank traffic in the southeastern United States arose in 2002 when the Louisiana Army National Guard's Camp Minden Training Site was chosen to serve as an M1A1 Abrams battle tank training facility. Approximately 50 M1A1 tanks were scheduled for detailed training and maneuvers at this facility. Camp Minden officials sought to implement a soil and vegetation resilience study to comply with Department of Defense Integrated Training Area Management program's regulations designed to maintain training lands in a condition that accommodates future long-term sustainability.

The purpose of this study was to establish critical soil compaction thresholds for M1A1 Abrams battle tank traffic in an effort to minimize soil physical properties that adversely affect vegetation regeneration. The hypothesis was that management of M1A1 training maneuver timing and intensity levels, as determined by soil moisture conditions and traffic rates, could effectively reduce soil compaction levels and the associated harmful effects on the overall soil quality and vegetation regeneration capabilities. For this purpose, two main treatments were investigated: (1) soil moisture content and (2) tank traffic rates during training maneuvers. The effect of soil moisture content and traffic rate on soil bulk density and soil penetration resistance measured before and after tank traffic were assessed. Furthermore, the influence of the resulting soil compaction on soil moisture retention was investigated.

Material and Methods

Soils of the Study Site

The location selected for the study was the Camp Minden Training Site, which is the Louisiana Army National Guard's second-largest training site. It is located 16 miles east of Bossier City, La., Bossier/Webster parish line and covers approximately 13,682 acres (Figure 1). Camp Minden is located in the Western Coastal Plain Major Land Resource Area (MLRA 133B) and in the Coastal Plain Province physiographic region. Camp Minden is situated on Quaternary geologic sediments derived from braided stream terrace deposits of ancient river systems.

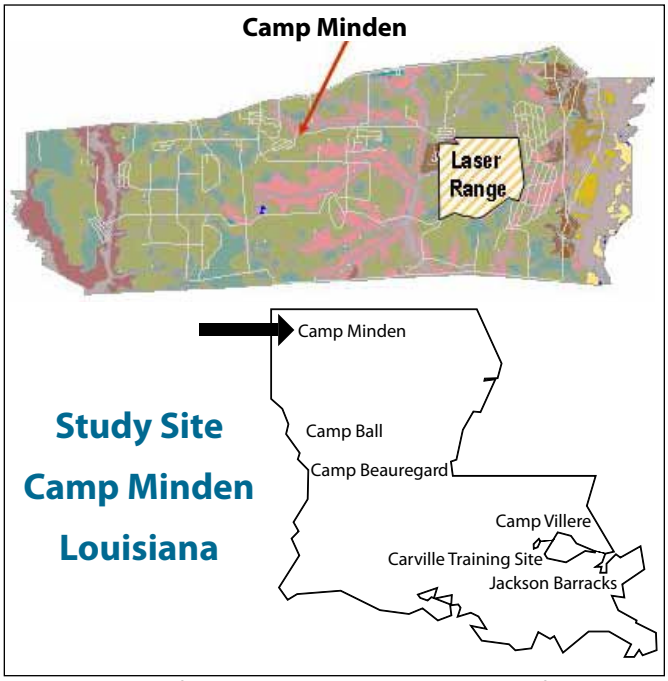


Figure 1. Map of Louisiana Army National Guard facilities and the Camp Minden tank traffic and soil resilience study site, near Bossier City, La.

The training site is situated in an area with nearly level topography dominated by soils mapped as Kolin silt loam. The intermound areas of these soils have been identified as Wrightsville inclusions and typically are level to depressional in nature. The Wrightsville series classifies as fine, mixed, active, thermic Typic Glossaqualfs. It is in land capability subclass IIIw and as such has severe limitations due to wetness that reduce the choice of plants or that require special conservation practices or both. This soil is used mainly as woodland and is moderately well suited as pine woodland. The main concerns in producing and harvesting timber are severe equipment use limitations and severe seedling mortality caused by wetness. When the soil is moist, timber harvesting methods that use standard wheeled and tracked vehicles often cause rutting and soil compaction. Because of this high susceptibility to wetness and the associated negative effects of soil compaction that would result from heavy mechanized maneuvers, our investigation was limited to this soil type.

Experimental Design

In March of 2003, 48 plots (5 by 5 meters each) were established in the intermound areas of the selected study site, which was in a managed pine forest stand. The plots were distributed over an area of approximately 2.6 hectares (6.4 acres) and were permanently located by driving 1.5 meter by 1.6 centimeter diameter steel rebar rods into the ground at the plot corners. Subsequently, between March 2003 and July 2003, trees were harvested by chainsaw. Trees were removed from the site by skidder while avoiding traffic on research plots to minimize compaction or other disturbance. The site was not replanted, and it remained undisturbed for four years (until June 2007) to allow natural establishment of early succession vegetation.

The experimental design was a completely randomized factorial design to evaluate the effects of soil moisture content (factor 1) and tank traffic rates (factor 2) on soil compaction and soil strength in the soil profile. Each treatment combination was replicated three times, resulting in a total of 27 experimental plots. Based on soil moisture determinations, three levels of soil moisture content were selected – low, medium and high. The effect of tank passes (factor 2) was split into three levels: (i) three; (ii) six; and (iii) nine passes with the M1A1 battle tank in crisscross configuration to achieve complete coverage of each plot. Treatment combinations were randomly assigned to 27 plots with eight additional plots available as controls for follow-up evaluations. In Table 1, measured soil moisture contents in the top 50 centimeters are presented in three separate groups illustrating the differences in their values. To achieve this, a soil core, 1.9 centimeters in diameter and 50 centimeters long, was collected from the center of each plot prior to tank runs. The bulk sample was oven-dried, and its volumetric moisture content was quantified.

To arrive at different moisture levels in the soil profile, sampling as well as tank passes were carried out at different times during the year from August 2007 through October 2007. From the results in Table 1, three soil moisture levels were delineated for the different experimental plots.

The soil moisture distributions for low moisture level ranged from 0.07 to 0.18 cm^3/cm^3 and 0.14 to 0.21 cm^3/cm^3 in the surface 25 centimeters and the 25-50 centimeter layers, respectively. For the medium moisture level, the respective soil moisture ranged from 0.24 to 0.29 and 0.20 to 30 cm^3/cm^3 in the surface 25 centimeters and the 25-50 centimeter layers, respectively. For the high soil moisture

Table 1. Soil moisture content during 2007 at two depths and during 2009 at one depth for low, medium and high moisture plots.

Plot and Treatment	Number of Tank Passes	Sampling Date	Soil Moisture Content (cm^3/cm^3)		
			2007 Sampling		2009 Sampling
			0 to 25 cm	25 to 50 cm	0 to 50 cm
Low Soil Moisture Plots					
P15-L9	9	11-Oct-07	0.08	0.17	0.49
P46-L9	9	11-Oct-07	0.07	0.14	0.41
P47-L9	9	11-Oct-07	0.13	0.17	0.46
P48-L6	6	20-Sep-07	0.12	0.19	0.45
P23-L6	6	11-Oct-07	0.12	0.18	0.48
P47-L6	6	11-Oct-07	0.13	0.17	NA
P12-L3	3	11-Oct-07	0.11	0.14	0.44
P09-L3	3	11-Oct-07	0.18	0.21	0.49
P47-L3	3	11-Oct-07	0.13	0.17	NA
Average Moisture Content			0.12	0.17	0.46
Medium Soil Moisture Plots					
P08-M9	9	20-Sep-07	0.24	0.28	0.5
P40-M9	9	11-Oct-07	0.28	0.20	0.44
P41-M9	9	19-Sep-07	0.23	0.27	0.45
P35-M6	6	29-Aug-07	0.29	0.25	0.48
P21-M6	6	11-Oct-07	0.24	0.22	0.45
P44-M6	6	11-Oct-07	0.29	0.23	0.52
P06-M3	3	20-Sep-07	0.27	0.3	0.53
P21-M3	3	11-Oct-07	0.24	0.22	NA
P05-M3	3	11-Oct-07	0.29	0.22	0.54
Average Moisture Content			0.26	0.24	0.49
High Soil Moisture Plots					
P14-H9	9	21-Aug-07	0.36	0.41	0.55
P13-H9	9	22-Aug-07	0.38	0.38	0.63
P33-H9	9	22-Aug-07	0.36	0.41	0.51
P07-H6	6	21-Aug-07	0.35	0.37	0.54
P16-H6	6	22-Aug-07	0.38	0.37	0.57
P17-H6	6	22-Aug-07	0.4	0.36	0.52
P01-H3	3	21-Aug-07	0.34	0.35	0.46
P32-H3	3	22-Aug-07	0.37	0.37	0.45
P34-H3	3	22-Aug-07	0.36	0.37	0.46
Average Moisture Content			0.37	0.38	0.52

level, the respective soil moisture ranged from 0.36 to 0.40 cm^3/cm^3 and 0.36 to 41 cm^3/cm^3, respectively. The average soil moisture content for the top 25 centimeter depths were 0.12, 0.26 and 0.37 cm^3/cm^3, for the low, medium and high moisture level plots, respectively. For the 25-50 centimeter depth, the respective soil moisture values were 0.17, 0.24 and 0.48 cm^3/cm^3.

For plots at medium and high moisture levels, uniform moisture contents were realized. Only plots at low moisture levels showed significantly lower moisture content at the top 25 centimeter depth when compared to the 25-50 centimeter soil depth – 0.12 versus 0.17 cm^3/cm^3.

Soil bulk density and penetrometer resistance measurements before and after tank passes were performed on the plots having the different soil moisture levels and tank traffic rates. Penetration resistance measurements were carried out using Field Scout SC-900 cone penetrometer (Spectrum Technologies Inc., Plainfield, Ill.). Therefore, in the subsequent discussion, designations low, medium and high soil moisture levels refer to the soil-

moisture content of the different plots as measured during 2007 and given in Table 1.

We also investigated the influence of the tank traffic more than one year following the tank traffic. Our goal was to ascertain whether issues related to tank traffic manifested themselves over time.

Specifically, we quantified the residual effect of the tank traffic on soil penetrometer measurements on Jan., 13 2009, some 14-16 months following application. The date for these subsequent measurements was selected when the soil moisture across all plots was near saturation and relatively uniform throughout the soil profile. Since moisture saturation in the winter months often is attained, soil-moisture measurements were carried out only for the surface 5 centimeters. The moisture content values corresponding to the low, medium and high soil moisture plots were 0.48, 0.49 and 0.53 cm^3/cm^3, respectively (Table 1). Additional measurements were carried out on eight plots that were not subjected to tank traffic and are referred to here as control plots. The average soil moisture content for the control plots was 0.44 cm^3/cm^3 (data not given).

Soil Texture and Liquid and Plastic Limits

The soil particle size distribution, particle densities and USDA textural classes were determined for each plot. Soil particle size distribution was determined using the hydrometer method (Gee and Bauder, 1986, and particle density was determined using the pycnometer method (ASTM D854-00 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, 2000). The Unified Soil Classification System classes and Atterberg liquid and plastic limits for the less than 2 millimeter particle size fraction were determined using ASTM 4318-00 Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils (2000).

Bulk Density

Three soil bulk density core sample replicates were taken from each experimental plot at the 20 centimeter and 50 centimeter depths prior to tank traffic. Soil depths of 20 centimeters and 50 centimeters were chosen to yield information on the epipedon (A and EBg horizons) and the argillic subsoil (Btg/E horizons), respectively. Soil core samples were facilitated by excavating a 30 centimeter diameter hole to a depth of approximately 60 centimeters deep at the center of each plot. The cores were taken by driving a 68.7 cm^3 (3 centimeters long by 5.4 centimeters diameter) brass cylinder horizontally into the bore hole's wall. These cores were used to establish the pre-traffic soil bulk densities of the individual plots in June-August 2007. Post-traffic soil bulk densities were determined subsequent to tank passes by excavating the original bore hole and taking an additional three cores within 30 centimeters of the original core samples during August-December 2007. In total, 12 bulk density cores were extracted from each plot.

Penetration Resistance

Initial cone penetration resistance measurements were taken at 5 centimeter depth intervals to a depth of 45 centimeters using a Spectrum Technologies Inc. (Plainfield, Ill.) Field Scout SC-900 cone penetrometer. The penetration resistance measurements were taken in August, September and October 2007, when tank traffic was applied to individual plots. A total of 18 penetration resistance measurements were taken in each of the 27 experimental treatment plots. Nine measurements were taken immediately preceding and nine were taken immediately after tank passage to minimize possible temporal effects related to soil moisture change and possible disturbances. The measurements before and after tank traffic were taken along a diagonal transect in predetermined 1 meter grid sections within each plot. Cone penetration rate of 2 centimeters per second, as specified in the ASAE standards, was followed. The measurements were taken under variable soil moisture levels as previously outlined in Table 1.

In addition, follow-up penetration resistance was measured at 1 centimeter depth intervals to a total depth of 60 centimeters using a Penetrologger cone penetrometer (Eijkelkamp Agrisearch Equipment, Giesbeek, Netherlands). This was carried out in January 2009 when all plots were at relatively uniform soil moisture and near saturation (0.40 ± 0.05 cm^3/cm^3). The programmed penetration rate of 2 centimeters per second, as specified in the ASAE standards, was followed. Seven penetration resistance measurements were taken from each plot. An additional eight randomly selected control plots were used to compare residual soil compaction effects on plots that had tank traffic and the undisturbed control plots. The penetration resistance measurements were taken along two diagonal transects in predetermined 1 meter grid sections within each plot. A total of 224 penetration resistance measurements were taken for a total of 13,440 data points.

Soil Moisture Retention

Soil moisture retention curves were developed for a subset of field extracted soil cores using the pressure plate method. The moisture retention curves were used to evaluate changes in pore size distribution of the soils resulting from tank traffic induced soil compaction. Twelve soil cores (2 centimeters long by 5.08 centimeters diameter) were extracted from the 20 and 50 centimeter depth intervals of two high moisture, nine pass treatment plots and adjacent nontrafficked control areas on Sept. 15-16, 2009.

The extracted cores were wrapped in cellophane to prevent moisture loss during transport to the laboratory. Prior to placement on the ceramic pressure plates, the cores were shaved at both ends to ensure maximum surface contact and were allowed to saturate for five to seven days. The moisture retention or characteristic curves were developed using the following pressures 0.1, 0.3, 0.5, 1.0, 3.0, 5.0, 10.0, and 12.5 bars.

Results and Discussion

Soil Texture and Liquid and Plastic Limits

Soil texture results were grouped and averaged in four groups referred to here as site areas S1 to S4. Those areas correspond to centralized data loggers around which individual plots were distributed (Table 2). The soils of the study site are considered fine-grained soils and consist of various percentages of silt and clay with smaller percentages of sand.

Of potential relevance to this study was the identification of soil textures in the A, EBg, and Btg/E horizons. Generalized USDA soil textures were as follows: (i) A horizon – silt loam; (ii) EBg horizon – silt loam and silty clay loam; and (iii) Btg/E horizon – silty clay loam and silt loam.

Furthermore, classification of soils under the Unified Soil Classification System uses a combination of letters to describe soil properties that primarily affect engineering properties. The soils at the Camp Minden study site are thus classified as ML, CL and CL-ML. The study area is dominated by CL and to a lesser degree ML soils, where C equals fine-grained soils with plastic characteristics; M equals fine-grained soils with nonplastic to slightly plastic characteristics; and L equals fine-grained soils with low liquid limit values less than 50. The Unified Soil Classification System designations and Atterberg limits of the Camp Minden soils are given in Table 3.

Bulk Density

Analysis of variance and Tukey-Kramer HSD (honest significant differences) statistical analysis were used for treatment means comparisons. Data analysis after tank disturbance indicated no significant treatment effects ($P \leq 0.05$) for changes in bulk density at the 20 centimeter or the 50 centimeter depth. Table 4 shows the average post-tank bulk density values as grouped by moisture level and traffic rate. The table illustrates the average trends of the treatment levels without consideration of treatment interactions and is presented as a simplified overview of the tank traffic experiment results.

At the 20 centimeter depth, moisture treatment effect followed the trend high > medium > low moisture levels with average bulk densities of 1.65, 1.61 and 1.57 g/cm^3, respectively (Table 4). At the same depth interval, the traffic rate treatment effect followed the trend 6 >3 = 9 passes with average bulk densities of 1.63, 1.60 and 1.60 g/cm^3, respectively. At the 50 centimeter depth interval, the moisture treatment effect followed the trend medium

Table 2. Mean particle size fractions, particle density and USDA textural class.

Site Area† and Soil Depth	Clay (< 2µm)‡	Silt (2-50µm)‡	Sand (>50µm)‡	Particle Density	USDA Texture
	---------- % ----------			g cm^{-3}	
S1-20cm	28±3	66±5	6±2	2.69	SiL, SiCL
S2-20cm	24±3	68±3	8±2	2.69	SiL
S3-20cm	23±2	62±3	15±3	2.69	SiL
S4-20cm	24±3	61±4	15±4	2.69	SiL
S1-50cm	28±7	62±2	10±8	2.69	SiCL, SiL
S2-50cm	26±3	66±4	8±5	2.69	SiL, SiCL
S3-50cm	27±4	57±4	16±6	2.69	SiCL, SiL
S4-50cm	27±6	56±2	17±6	2.69	SiCL, SiL

† Site area denotes plots associated with data loggers S1 to S4 and depth (cm).
‡ Values following ± represent standard deviation.

Table 3. Atterberg limits expressed as gravimetric soil moisture content (g/100g soil) and Unified Soil Classification System class for shallow (20 centimeter) and deep (50 centimeter) horizons for the different plots.

Site Area† and Soil Depth	Liquid Limit (g/100g)	Plastic Limit (g/100g)	Plasticity Index (g/100g)	USCS Class
S1-20cm	28	17.4	10.6	CL
S2-20cm	26.1	20.5	5.6	CL-ML
S3-20cm	24.2	19.9	4.3	CL-ML
S4-20cm	25.9	18.6	7.3	CL, CL-ML
S1-50cm	29.1	18.5	10.6	CL
S2-50cm	30.7	17.7	13.0	CL
S3-50cm	29.6	18.4	11.2	CL
S4-50cm	29.5	18.7	10.8	CL

† Site Area denotes plots associated with data loggers S1 to S4

Table 4. Average soil bulk density at 20 and 50 centimeter depths after tank passes for the different moisture plots. Values in parenthesis are the standard deviation.

Mean Soil Bulk Density (g/cm3) by Moisture Level and Number of Tank Passes				
Moisture Plots	Number Tank Passes			Means by *Moisture Level*
	3	6	9	
		20 cm Depth		
Low	1.58 (0.08)	1.59 (0.11)	1.55 (0.10)	*1.57 (0.09)*
Medium	1.58 (0.11)	1.68 (0.07)	1.58 (0.09)	*1.61 (0.09)*
High	1.64 (0.07)	1.63 (0.06)	1.67 (0.08)	*1.65 (0.07)*
Means by Tank Passes	*1.60 (0.08)*	*1.63 (0.08)*	*1.60 (0.08)*	
		50 cm Depth		
Low	1.58 (0.06)	1.61 (0.05)	1.48 (0.08)	*1.56 (0.06)*
Medium	1.61 (0.05)	1.60 (0.05)	1.62 (0.05)	*1.61 (0.05)*
High	1.64 (0.07)	1.61 (0.04)	1.57 (0.05)	*1.60 (0.05)*
Means by Tank Passes	*1.61 (0.06)*	*1.61 (0.05)*	*1.56 (0.06)*	

> high > low, with bulk densities of 1.61, 1.60 and 1.56 g/cm^3, respectively (Table 4). The traffic rate treatment effect in the 50 centimeter interval was 3 = 6 > 9 with bulk densities 1.61, 1.61 and 1.56 g/cm^3, respectively.

Increases in soil bulk density as a result of tank traffic was observed for all experimental plots regardless of the number of tank passes (see Figures 2 and 3). Overall soil bulk density increases throughout the soil profile were 0.04, 0.07 and 0.04 g/cm^3 for the low, medium and high moisture plots, respectively. Such increases in bulk density appear similar for all moisture levels. Nevertheless, the largest increase due to compaction from tank passes was measured for the medium moisture plot after six passes. In contrast, lowest increase in bulk density was observed for the low moisture plots after nine tank passes. We recognize the extensive heterogeneity of the soil profile across the landscape as a contributor to the variability in the observed bulk density. Nevertheless, such increases indicate soil moisture is a significant soil parameter in changes of bulk density resulting from tank traffic.

The lack of statistical significance observed among treatment combinations using analysis of variance and Tukey's HSD tests at $P = 0.05$ can be attributed to low sample replicate numbers and high soil heterogeneity at

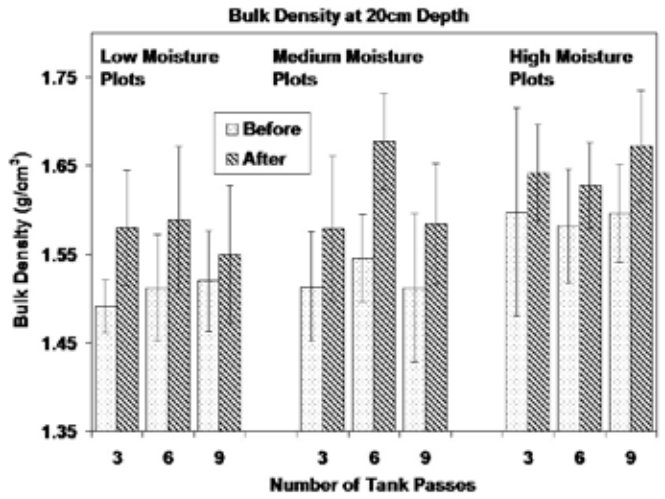


Figure 2. Mean bulk densities before and after tank traffic and ± 95 percent confidence intervals at 20 centimeters depth.

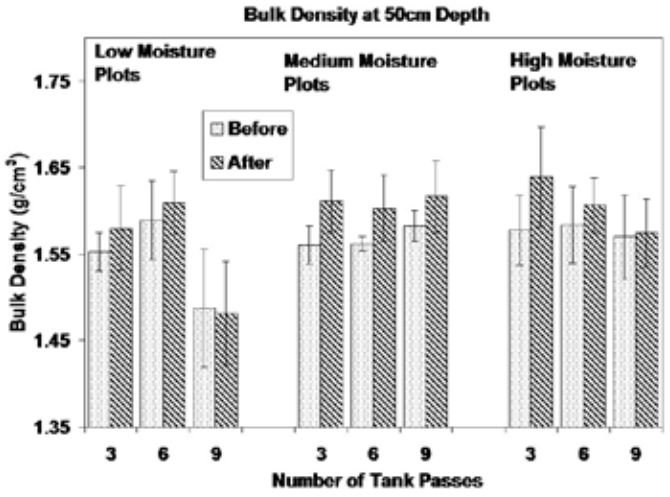


Figure 3. Mean bulk densities before and after tank traffic and ± 95 percent confidence intervals at 50 centimeters depth.

the site. Trends in the data strongly suggested a moisture treatment effect, however. Considering individual treatment factor only, "moisture" was a stronger determinant of final bulk density than was "traffic rate" at both the 20 centimeter and the 50 centimeter depths. The Leverage plots indicated that, at the 20 centimeter depth interval, moisture treatment was significant ($\alpha = 0.05$) but that neither traffic rate level or the interaction between moisture treatment and traffic rate were significant ($P = 0.05$). At the 50 centimeter depth interval, Leverage plots indicated that moisture treatment, traffic rate and their interactions all were borderline significant at a confidence level of 0.05, as indicated by confidence interval curves.

Soil Penetration Resistance

A primary goal of this study was to assess the influence of different levels of soil moisture on changes in penetration resistance and soil bulk density as a result of traffic by the A1M1 Abraham tank. Penetration resistance before and after tank passes are shown in Figures 4-6. These penetration resistance measurements were carried out during 2007 on plots having low, medium and high moisture levels as discussed under the Methods section (Table 1).

For plots with low soil moisture content profiles, prior to tank passes, high penetration resistance values were measured for all plots as shown in Figure 4. The penetration resistance values ranged from 3 to 4 MPa throughout the soil profile. Such penetration resistance results were not unexpected, particularly near the soil surface where low moisture contents in the range of 0.07 to 0.18 cm^3/cm^3 were encountered.

Following three, six and nine tank passes, consistent increases in penetration resistance measurements were observed compared to penetration resistance measurements before tank passes. Such an observation was consistent throughout the soil profile. After six and nine tank passes, penetration resistance values exceeded 5 MPa near the surface compared to plots after three tank passes where lower values were observed (< 5MPa). Nevertheless, the effects of the number of passes appear somewhat inconsistent when low moisture contents were dominant in the soil profile.

For plots with medium moisture levels, initial penetration resistance distributions before tank passes were about 3 MPa throughout the soil profile as shown in Figure 5. The only exception was for soil depths below 20 centimeters where a maximum occurred. An increased penetration resistance was measured for all plots following tank passes. Such a penetration resistance increase was about 2 MPa and was observed throughout the soil profile regardless of the number of tank passes. Moreover, regardless of the number of tank passes, penetration resistance distributions followed the overall trend of the initial penetration resistance distributions – those prior to tank trafficking. Such trends in penetration resistance prior to and following tank passes may be somewhat unique and were not found in the other experimental plots of high or low soil moisture levels.

For plots with the highest moisture level, initial (prior to traffic) penetration resistance values versus soil depth were lowest among all measured plots as shown in Figure 6. Penetration resistance values did not exceed 3 MPa throughout the soil profile. The effect of tank traffic was largely concentrated in the surface 15 centimeters with an average increase of 1 MPa regardless of the number of tank

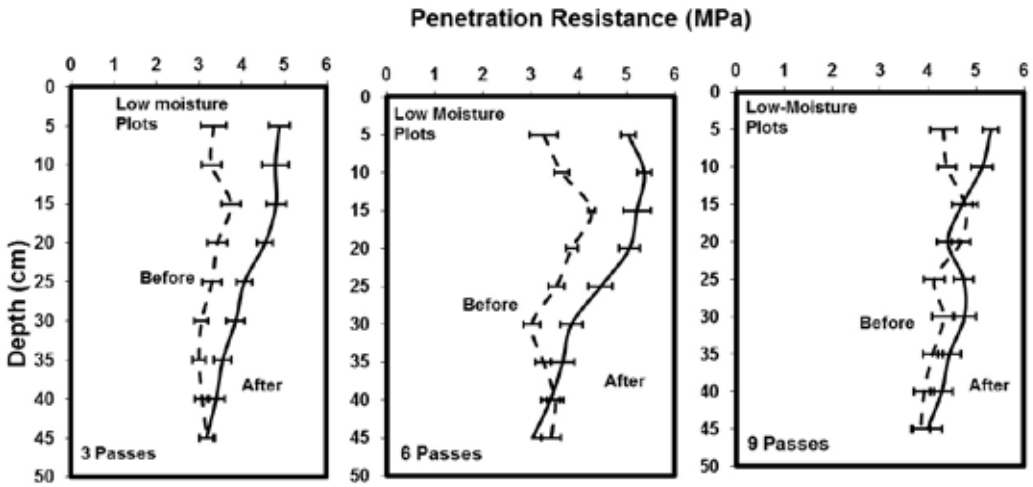


Figure 4. Penetration resistance versus soil depth as measured during 2007 on the low moisture plots before and after three, six and nine tank passes.

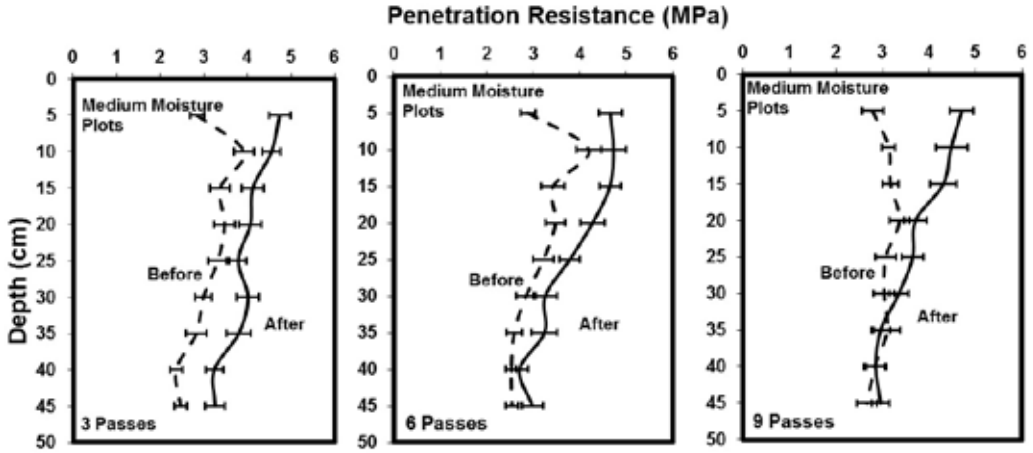


Figure 5. Penetration resistance versus soil depth as measured during 2007 on the medium moisture plots before and after three, six and nine tank passes.

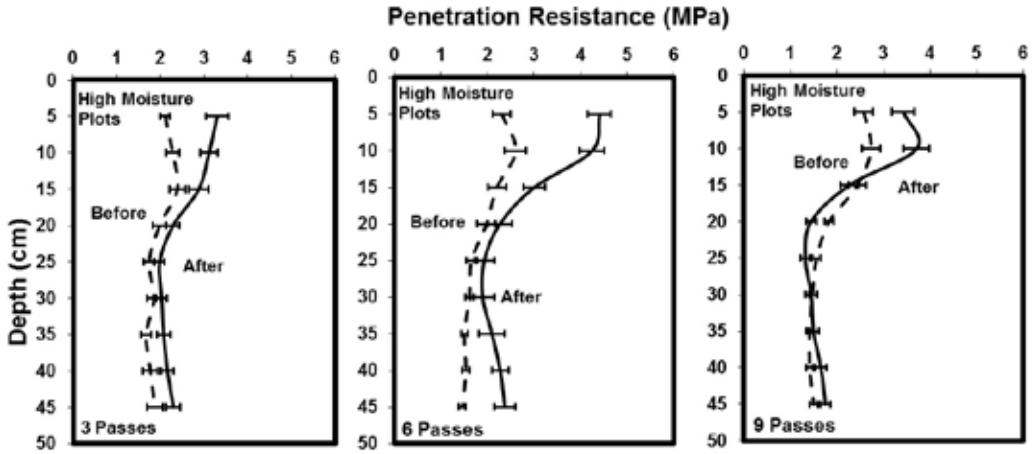


Figure 6. Penetration resistance versus soil depth as measured during 2007 on the high moisture plots before and after three, six and nine tank passes.

passes. The effect of the number of passes on penetration resistance distribution was unclear. A highly compacted soil was observed after six passes where highest penetration resistance values were encountered. Smaller increases in penetration resistance were realized in the soil profiles after three and nine tank passes. Thus, the effect of different tank passes on soil compaction did not follow a clear trend.

Residual Effect

Results of follow-up penetration resistance measurements, which were made on Jan. 13, 2009, are shown in Figure 7. These measurements were made more than one year after the different tank passes were carried out in 2007. These 2009 penetration resistance measurements were performed to investigate the residual effects of tank traffic on compaction of the soil profile for the plots having low, medium and high levels. Additional measurements were carried out on eight randomly selected control plots that were not subjected to tank traffic in 2007 or any time thereafter. These measurements were performed on Jan. 13, 2009, and are referred to here as control plots since they were not subjected to any tank passes.

The 2009 penetration resistance results show the lowest compaction through the profile for low moisture plots, which showed slightly higher penetration resistance values than the control plots. This finding was consistent regardless of the number of tank passes, as exhibited in Figure 8 where averages for all tank passes were made and penetration resistance measurements were grouped by the different moisture levels. The penetration resistance results show the highest residual compaction was encountered for the high moisture plots where penetration values exceeded 1 MPa. For the medium moisture level; the residual penetration resistance was significantly higher than that for the low moisture plots as well as the control plots. These results indicate that the residual effects of tank traffic were strongest for plots with highest soil moisture at the time of tank traffic. Therefore, based on the penetration resistance data of the residual effects, tank traffic should be avoided when high soil moisture levels are encountered.

The 2009 penetration resistance measurements were taken when the soils were at average moisture content of 0.44 cm^3/cm^3 or greater, which is at or near saturation in these compacted soils. As such, these values were less than would be expected at moisture content near field capacity, and care should be taken not to underestimate root limiting potentials based upon these penetration resistance values. Numerous researchers have attempted to make moisture corrections for penetration resistance values with varying degrees of success (Busscher et al., 1997; Christensen et al., 1989). Such data can be used to make inferences, however, regarding the relative degrees of compaction and increase in soil strength among treatment levels and to provide an overall indication of the effect of tank traffic on soil compaction levels throughout the soil profile. Our results indicated that the effect of the number of passes on penetration resistance values was inconsistent regardless of the soil moisture level of the profile. This finding is similar to results from other researchers who indicate that as much as 80 percent of potential soil compaction occurs during the first pass with subsequent passes causing additional,

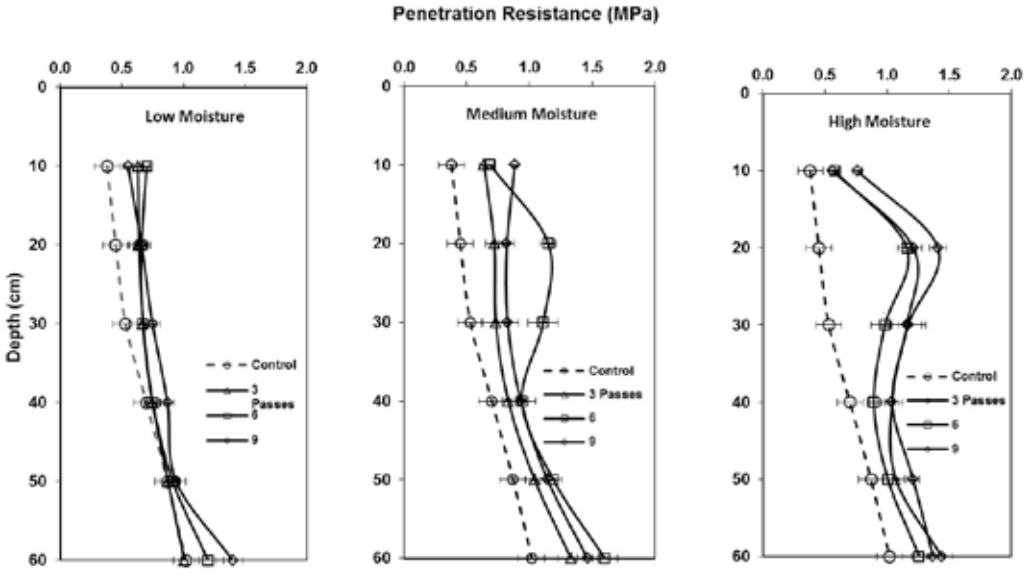


Figure 7. Penetration resistance versus soil depth as measured on Jan. 13, 2009, on plots subjected to three, six and nine tank passes during 2007. The plots were initially under low, medium and high moisture levels. The control plots did not receive tank traffic at any time.

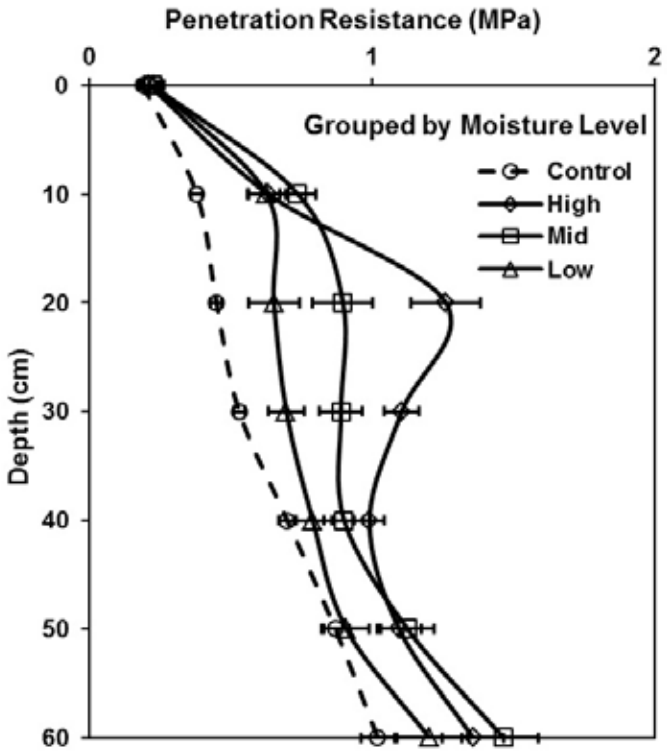


Figure 8. Penetration resistance versus soil depth as measured on Jan. 13, 2009. The plots were grouped by moisture level as low, medium and high. The control plots did not receive tank traffic at any time.

but progressively less, compaction (Daum, 1996; Horn et al., 1995; Lenhard, 1986; Taylor et al, 1982). The penetration resistance data suggested that the soil moisture level has a significant effect on soil penetration resistance and was the dominant variable of concern with respect to compaction potential in the soils of this study at Camp Minden, La.

Based on the data shown in Figure 8, the general trend was such that penetration resistance values throughout the profile below 10 centimeters followed the trend high moisture > medium moisture > low moisture > control plots. In addition, because the high and medium soil moisture treatment levels consistently produced penetration resistance values significantly greater than the controls, efforts should be made to avoid tank exercises when soil moisture contents are greater than or equal to 0.26 cm^3/cm^3 and should be greatly restricted when conditions are similar to the high moisture plots with soil moisture in the 0.40-0.46 cm^3/cm^3 range. As such, it is anticipated that these soils readily deform and compact as the moisture contents approached the liquid limit (19 percent on a gravimetric bases ≈ 0.29 cm^3/cm^3 on a volumetric bases). Moreover, significant deformation and compaction is expected at moisture contents greater than the liquid limit under compaction energy of the M1A1 tank. This conclusion is in agreement with other research showing that optimal conditions for soil compaction often occur at water content above field capacity, particularly as water content approaches the soil's liquid limit (Porsinsky etal., 2006; Akram and Kemper, 1979; Soane et al, 1981; Gent and Morris, 1986; Startsev and McNabb, 2001).

Soil Moisture Retention

Soil moisture retention results for Camp Minden soils that received tank traffic are shown in Figures 9 and 10. The moisture retention curves represent average moisture contents at different applied pressures and are presented for two soil depths; 20 and 50 centimeters. These retention curves were developed to assess changes in total porosity and pore size distribution of soils resulting from induced compaction due to tank traffic. Furthermore, we carried out similar retention measurements on cores obtained from an adjacent "control" area that was not subjected to tank passes. Since the cores from the control areas were not immediately adjacent to plots that received tank passes, such results provide only overall, rather than specific, comparisons for the same soil and not for specific plots.

Tank traffic resulted in a decrease in total soil porosity as manifested by the decreased moisture content at low suctions (< 0.5 bar). This decrease is a direct result of compaction due to tank passes and a decrease in corresponding soil bulk density. Compaction results in decreased large intra-aggregate pores accompanied by an increase in intermediate size pores (Hillel, 1998).

An average bulk density from 1.65 g/cm^3 at 20 centimeters as well as 50 centimeter depths was observed in the control plots. In contrast, bulk density values for the plots that received tank passes were 1.76 and 1.66 g/cm^3

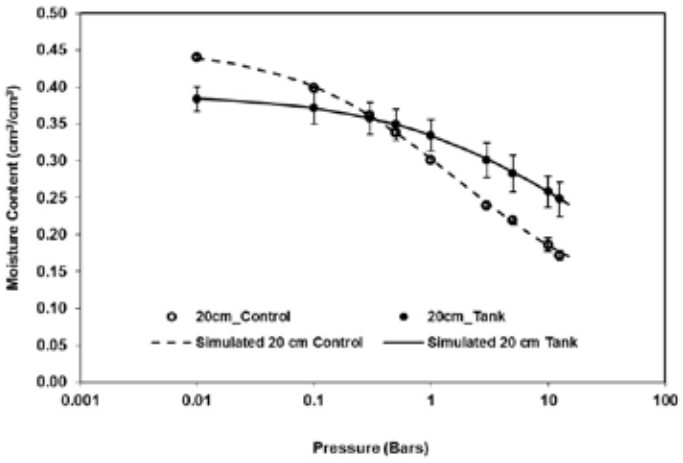


Figure 9. Measured retention results for soil cores at 20 centimeter depths from a control plot that received no tank passes and from a high moisture level plot after nine tank passes. The dashed and solid curves are simulations using the van Genuchten model.

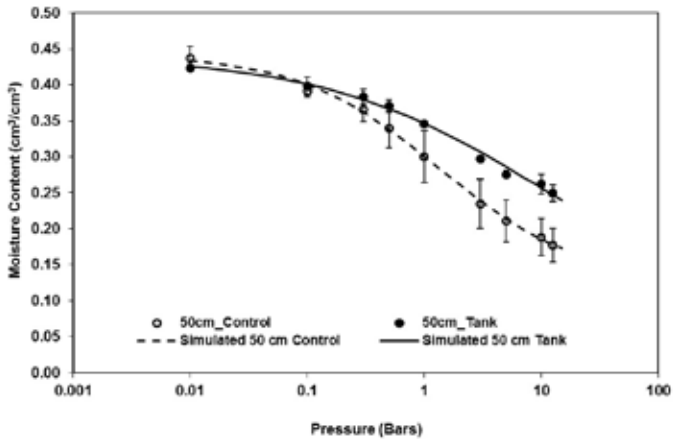


Figure 10. Measured retention results for soil cores at 50 centimeter depths from a control plot that received no tank passes and from a high moisture level plot after nine tank passes. The dashed and solid curves are simulations using the van Genuchten model.

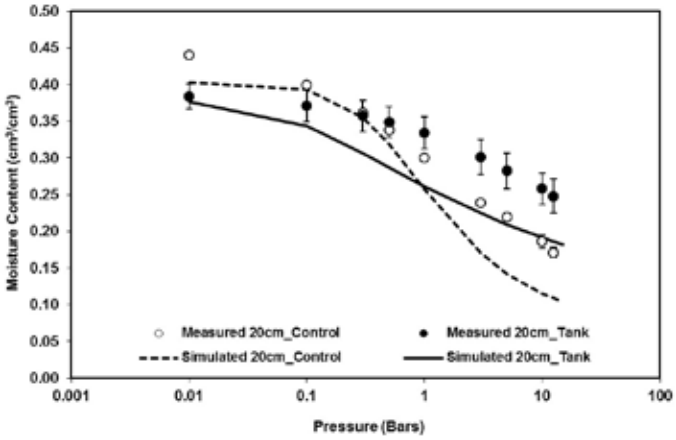


Figure 11. Measured retention results for soil cores at 20 centimeter depths from a control plot that received no tank passes and from a high moisture level plot after nine tank passes. The dashed and solid curves are simulations using the Rosetta model.

for the 20 and 50 centimeter depths, respectively. At large suction values (>1 bar), large differences in soil moisture contents were observed between the control and plots that received tank passes. The influence of compaction at large tensions was not expected and is not completely understood. Nevertheless, Assouline (2006) states that bulk density change, due to compaction, is an integrative variable that reflects the total change in the voids volume of the soil. Lenhard (1986) states that subtle changes in the voids volume, distribution, tortuosity or connectivity could still occur during compaction, especially during elastic deformation, while no corresponding changes in bulk density are noticed.

Several models have been proposed to describe moisture retention results such as those shown in Figures 9 and 10 (Hillel, 1998). The solid and dashed curves shown in these figures were obtained by nonlinear least-squared optimization for the van Genuchten (1980) model given by:

$$\Theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{\left(1 + (\alpha h)^n\right)^m}$$

where θ_r and θ_s (cm^3/cm^3), which represent residual and saturated water contents, respectively, and α (1/cm) and n, which represent curve shape parameters and $m = 1 - 1/n$ is assumed. Excellent descriptions of the measured retention data were obtained for all plots at the two soil depths. Model details and best-fit parameter estimates from the nonlinear optimization are available in Lindsey (2009).

The second retention model used was the Rosetta model, which is capable of estimating water retention and unsaturated hydraulic conductivity parameters of the van Genuchten (1980) equation given above based on surrogate soil data (Schapp, 2001). Known sand, silt and clay percentages, bulk density, soil moisture at 0.3 bar (field capacity) and at 15 bar (wilting point) of the soil cores were used as input data for the Rosetta model. Moisture retention curves such as those given here are not routinely measured. Under such conditions, the second model provides an estimated or an approximate soil moisture retention curve based on soil texture and limited retention data at the field capacity and wilting point (measured or estimated). This model resulted in poor overall predictions of the retention results in our samples as shown in Figures 11 and 12. Nevertheless, this model can be a useful tool in predicting moisture contents at low tensions and should be avoided for the high tension values (> 1 bar). We should emphasize here that moisture retention results are prerequisite for describing water flow in the soil profile under water-unsaturated conditions.

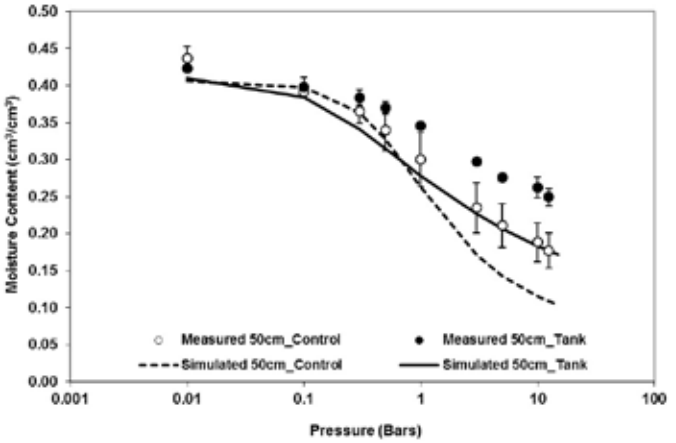


Figure 12. Measured retention results for soil cores at 50 centimeter depths from a control plot that received no tank passes and from a high moisture level plot after nine tank passes. The dashed and solid curves are simulations using the Rosetta model.

The relative shift of pores size distribution toward the predominance of smaller pores at the 50 centimeter depth interval, as indicated by the higher moisture retention values at the higher pressures, suggests a significant degree of compaction could be expected. However, there appears to be a shift in pore size distribution without a corresponding increase in bulk density at that depth interval. Other researchers made similar observations, and Horn et al. (1995) argued that retarded water fluxes at high water content, in conjunction with loading at high dynamic forces, can result in a homogenized soil, characterized by a low bulk density and a predominance of fine pores. Shroff and Shah (2003) suggested that, at high water content at or near saturation, with additional compaction effort, soil particles may simply be realigned with a more orderly arrangement of particles and no substantial increase in bulk density. Assouline (2006) stated that bulk density change due to compaction reflects changes in the volume of voids in the soil.

Summary and Conclusions

In this study, soil compaction thresholds from traffic by M1A1 Abrams battle tanks were established in an effort to minimize changes in soil physical properties that adversely affect vegetation regeneration. For this purpose, two main treatments were investigated: (1) tank traffic rates at the time of tank training maneuvers and (2) moisture content of the soil profile. The influence of Abrams tank traffic on soil bulk density and penetration resistance was measured immediately after tank passes on plots having different soil moisture levels. Major findings include:

- Increases in soil bulk density as a result of tank traffic were observed for all experimental plots regardless of the number of tank passes. Overall soil bulk density increases throughout the soil profile were 0.04, 0.07 and 0.04 g/cm^3 for the low, medium and high moisture plots, respectively. Such increases in bulk density appear similar for all moisture levels.
- Following three, six and nine tank passes, increases in penetration resistance measurements were observed. The effects of the number of passes appear somewhat inconsistent, however, when low moisture contents were dominant in the soil profile (0.12-0.17 cm^3/cm^3).
- For plots having medium soil moisture levels (0.24-0.26 cm^3/cm^3), penetration resistance distributions followed the overall trend of the initial penetration resistance distributions – those prior to tank trafficking. Such trends were not found in the other experimental plots of high or low soil moisture levels and were consistent regardless of the number of tank passes.
- For plots with the highest moisture level (0.37-0.38 cm^3/cm^3), the effects of tank traffic were concentrated in the surface 15 centimeters with an average increase of 1 MPa regardless of the number of tank passes. The effects of the number of passes on penetration resistance distribution were unclear.
- The effects of different tank passes on soil compaction did not follow a clear trend.
- Based on the residual effects of tank traffic, efforts should be made to avoid tank exercises when moisture contents in the soil profile are 0.26 cm^3/cm^3.
- Tank traffic should be restricted, when possible, at soil moisture contents in the 0.40-0.46 cm^3/cm^3 range.

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Van Genuchten, M. Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898. received no tank passes and from a high moisture level plot after nine tank passes. The dashed and solid curves are simulations using the Rosetta model.



Typical plot after tank traffic.

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