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Effect of Vehicle Load, Transducer Depth, and Transducer Type on Soil Pressures

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Abstract. *Measurement of soil pressures caused by vehicle loading is difficult and often subject to extreme variability. Two types of soil transducers were compared in an experiment conducted in a Norfolk sandy loam soil in the USDA-ARS National Soil Dynamics Laboratory's (NSDL) soil bin facilities. Stress state transducers (SST), electronic transducers developed at the NSDL for measuring six directional pressures and determining the stress state, were used for this experiment. Rubber bulbs connected by a rubber hose to a dial pressure guage, which measure hydrostatic pressure, were also used in this experiment. Both transducers were buried at depths of 7.5, 15, or 23 cm and were used to measure soil pressures caused by a 30.5L-32 tire with dynamic loads of 19 or 37 kN. The SST's were buried by inserting them into an excavated hole while the rubber bulbs were inserted by a special tool designed to leave the soil surface and surrounding soil undisturbed. Peak values of mean normal stress (calculated from measurements of pressure) from the SST and hydrostatic pressure measured with the rubber bulbs were found to be affected by both loading and burial depth. Similar magnitudes and variation were observed for each transducer. Residual pressure, defined as the pressure remaining after loading was removed, was found to be affected by both loading and burial depth when measured with the rubber bulbs. Continued development and testing of the rubber bulb transducers could provide a simple method of determining levels of compaction that could damage soils and thus prevent excessive trafficking.*

Keywords. Soil stress, soil compaction, soil pressures, transducer, dynamic load

Introduction

Soil compaction reduces crop yields and causes environmental damage (Alblas et al., 1994; Barber, 1994; Box and Langdale, 1984; Gaultney et al., 1982; Reeder and Wood, 1991; Schuler and Kostichka, 1994; Schuler and Lowery, 1984; Schwab et al., 2002; Tupper et al., 1987). Many studies have documented that soil compaction increases runoff and soil erosion (Voorhees et al., 1979) and reduces rooting volume, plant size, infiltration, water storage (Craul, 1994; Ess et al., 1998; Gayle et al., 1992; Unger and Kaspar, 1994). To understand and potentially reduce the effects of soil compaction, accurate methods of measuring soil compaction must be established.

Measuring soil compaction is especially difficult given soil's natural variability. Two methods have been developed for relatively rapid determination of existing soil compaction in fields. Bulk density has emerged as one of the primary methods that allows researchers to determine if a soil is in a compactable state (Erbach, 1982). Samples of soil of a specific volume are obtained, dried, and then weighed to obtain mass per unit volume. However, this process is extremely time-consuming as many samples must be obtained due to soil's inherent variability.

Cone index is another soil measurement that can be used to determine if a soil is compacted. A cone attached to a rod is inserted into the soil while the force is continuously recorded. The cone index is obtained by dividing the insertion force by the base cross-sectional area of the inserted cone (ASAE Standards, 2004b; ASAE Standards, 2004a). This measurement is superior to bulk density in some ways because it is much simpler and quicker to obtain. Many measurements of cone index can be obtained over a field in a short period of time allowing investigators to produce field maps of measured soil compaction.

The previously mentioned measurements of soil compaction are useful tools to determine existing conditions of compaction. However, methods that can be used to measure soil compaction as it occurs are especially useful to determine the detrimental effects of vehicle traffic. Electronic transducers that can measure soil pressures as vehicles pass over them have been used for many years with varied success.

The development of the stress state transducer (SST) was a milestone that allowed accurate measurements of soil pressures and calculation of principal soil stresses (Nichols et al., 1987). The SST has been used for many experiments and was instrumental in showing that reduced tractor tire inflation pressure also contributed to reduced soil stresses (Bailey et al., 1996). However, the SST requires six electronic pressure cells that also require electronic instrumentation. Many soil compaction problems could potentially be solved with simpler measurement techniques.

One of the simpler technologies that have been developed for the measurement of soil compaction requires a rubber membrane be placed in the soil under agricultural vehicles. Bolling (1985) proposed inserting a balloon at an angle to the soil surface and monitoring a water column for increased soil pressures. Turner and Raper (2001) described a similar technique that required a rubber bulb be inserted and attached via a long, flexible, rubber hose to a pressure gauge. These technologies require no electronic instrumentation and can quickly result in useful measurements.

Another advantage of the flexible membrane measurement technologies is that they also allow measurements of residual pressure, or the pressure remaining after the load has been removed. Residual pressures may be a better indicator than peak pressure of resulting soil compaction due to soils elastic-plastic behavior that allows it to rebound after loading.

The objectives of this experiment were, therefore:

1) to compare the sensitivity and variability of the SST and a rubber pressure bulb for measuring peak soil pressures, and
2) to compare peak and residual soil pressures as measures of soil compaction.

Methods and Materials

An experiment was conducted in the soil bins at the USDA-ARS National Soil Dynamics Laboratory to determine the effects of dynamic load on soil pressures as measured by two different transducers and on soil compaction as measured by bulk density and cone index. This experiment was conducted in an indoor soil bin containing Norfolk sandy loam soil (*fine loamy, kaolinitic, thermic Kandiudults*). Norfolk sandy loam soil is a Coastal Plain soil commonly found in the southeastern U.S. and along the Atlantic Coast.

The soil condition used for the experiment was created by using a rotary tiller to till the soil down to a depth of 60 cm and then leaving it relatively loose. The surface was then bladed and rolled smooth to create a uniform surface.

The tractor tire used in the experiment was a Firestone 30.5L-32 R-1 agricultural tractor tire that had the lugs filled with rubber (fig. 1). The Traction Research Vehicle (TRV) was used to conduct the experiment. This machine is capable of operating and controlling a single tire for use in the soil bins, as described by Burt et al. (1980) and Lyne et al. (1983).

Figure 1. Tire mounted on TRV.

The tire was operated in the following manner: two load levels of 19 kN and 37 kN, inflation pressure of 110 kPa, 0% slip, speed of 0.08 m/s, with four replications.

SST's (fig. 2) were buried in the center of the path of the tire. These transducers measured the soil pressures in six directions and provided values that allowed the calculations of principal stresses. Instrumentation was used that enabled all six channels of pressure to be measured over the entire period that the tire was moving across the transducers. The burial procedure for these transducers consisted of placing a piece of plywood on the soil surface adjacent to where the transducer was to be located. A large hole was then excavated with post-hole diggers and the loose soil placed on the plywood. After the SST transducer was placed in the bottom of the hole at the appropriate depth, the loosened soil was carefully placed back in the hole. Any remaining soil was uniformly distributed across the soil surface.

Figure 2. Rubber bulb with pressure gauge (left), rubber bulb with electronic sensor (center, data not reported), and SST (right).

The pressure bulbs were similar to those described and used by Turner and Raper (2001) which were hydraulically filled rubber lines and bulbs attached to a dial pressure gauge (fig. 2). No instrumentation was used to monitor the pressures measured by the bulbs. Each dial gauge had a peak measurement needle that stayed at the maximum value that was measured by the bulb. The burial procedure for the bulbs consisted of using a screw-type auger to remove a column of soil angling downward to the desired location of the bulb transducer. Approximately a 45° angle was used perpendicular to the direction of travel of the tire to allow the dial pressure gauge to be located outside of the tire track.

The transducers were buried in the center of the tire track at three depths: 7.5, 15, and 23 cm. Values measured with the SST's were compared against the measurements by the bulbs at similar depths.

Mean normal stresses calculated from pressures measured by the SST were used to compare to pressures measured by the pressure bulb. The mean normal stress was calculated as the average of the vertical and perpendicular side pressures measured by the SST. This value was thought to be similar to the hydrostatic pressure measured by the pressure bulb.

Ten measurements of cone index were obtained per replication prior to the test to determine the original soil condition. The Rimik manual penetrometer (Toowoomba, Australia) was used to acquire the cone index data. At the conclusion of the experiment, three replications per plot were obtained to determine the resulting soil condition from the load application.

Prior to the experiment, one measurement of bulk density was obtained per replication at each of the three depths at which transducers were placed (7.5, 15, and 23 cm). At the conclusion of the experiment, one measurement of bulk density was obtained per plot at each of the three different final burial depths of the transducers (5.1, 8.8, and 14.2 cm).

The randomized complete block experiment was analyzed with an appropriate ANOVA model using SAS (Cary, NC). Treatment effects were separated using single degree of freedom contrasts. A predetermined significance level of $P \leq 0.1$ was chosen to separate treatment effects.

Results and Discussion

Tire Loading

Increased tire loading resulted in increased bulk density (fig. 3). A correlation coefficient of 0.45 was calculated for the linear regression equation between dynamic load and bulk density. The scatter in the data indicates the amount of variability that was found for dynamic load as well as for bulk density measurements.

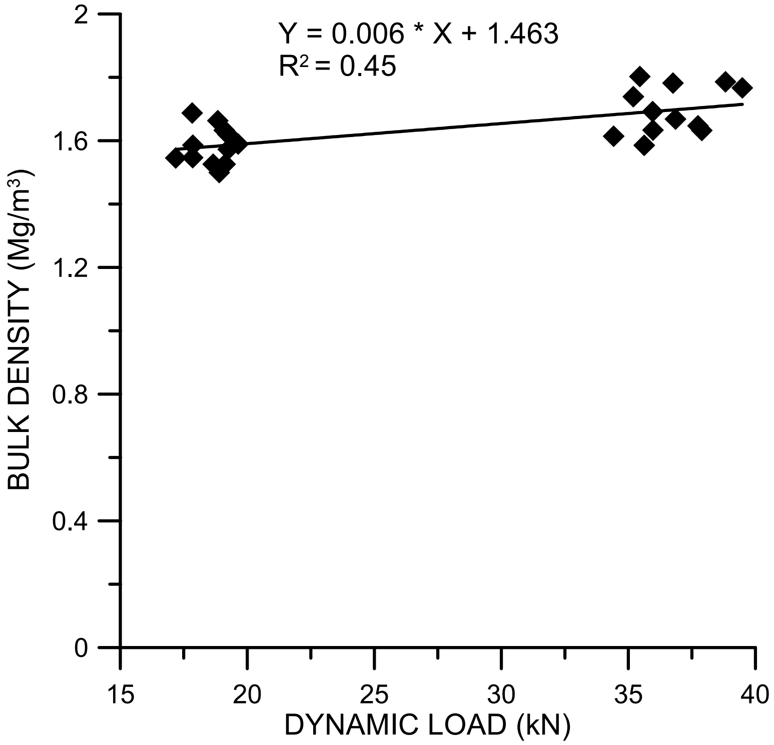

Figure 3. Linear fit of bulk density data to applied dynamic load.

Bulk Density

The initial bulk density measured before any tests were conducted were 1.21 Mg/m^3 at the 7.5 cm depth, 1.25 Mg/m^3 at the 15 cm depth, and 1.21 Mg/m^3 at the 23 cm depth (fig. 4). At the same depths of 7.5 cm, 15 cm, and 23 cm, gravimetric soil moisture was found to be 6.8%, 7.7%, and 7.5%, respectively. Both loads increased bulk density dramatically from its original state at all depths. The final values of bulk density were found to be affected by dynamic load ($P \leq 0.01$) but not by depth of burial with the 19 kN dynamic load resulting in a final average bulk density of 1.55 Mg/m^3 and 37 kN resulting in a final average bulk density of 1.67 Mg/m^3.

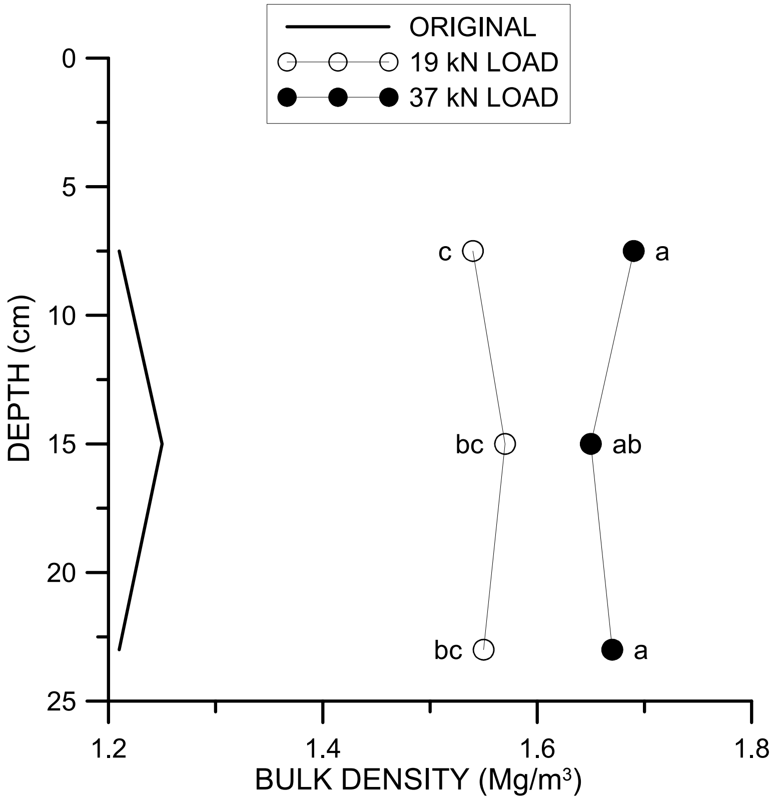

Figure 4. Bulk density plotted at original burial depths for original soil condition and after applied loading. Letters indicate statistical significance ($LSD_{0.1}$).

Cone Index

Cone index was significantly increased by dynamic load ($P \leq 0.01$; fig. 5) as compared with the initial cone index values taken before the experiment was started. The largest load (37 kN) increased the cone index the greatest amount, with the smaller load (19 kN) having a reduced impact. The dynamic load increased cone index over the entire depth that measurements were acquired but its impact was greatest near the surface.

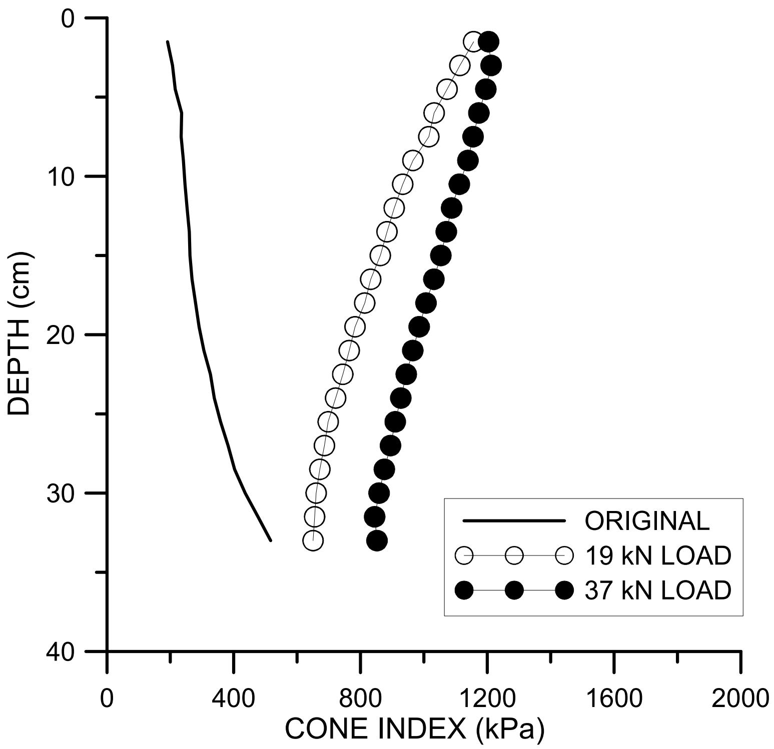

Figure 5. Cone index plotted for original soil condition and after applied loading.

SST Measurements

Depth to SST

The original soil placed above the SST after burial was compressed significantly by the loading process, however, the specific amount of the load (19 kN or 37 kN) did not affect the burial depth ($P \leq 0.52$). SST's originally placed at depths of 7.5, 15, and 23 cm were found at depths of 5.1, 8.8, and 14 cm, respectively.

Peak Mean Normal Stress

Peak mean normal stress was statistically affected ($P \leq 0.01$; fig. 6) by loading with 37 kN causing peak mean normal stress of 66.8 kPa and 19 kN resulting in 42.5 kPa when averaged across all depths. Maximum values of peak normal stress were measured closer to the soil surface. At the deepest depth of 23 cm, no difference was found between the two different loads applied at the soil surface. At all other depths, significant differences in stress were found.

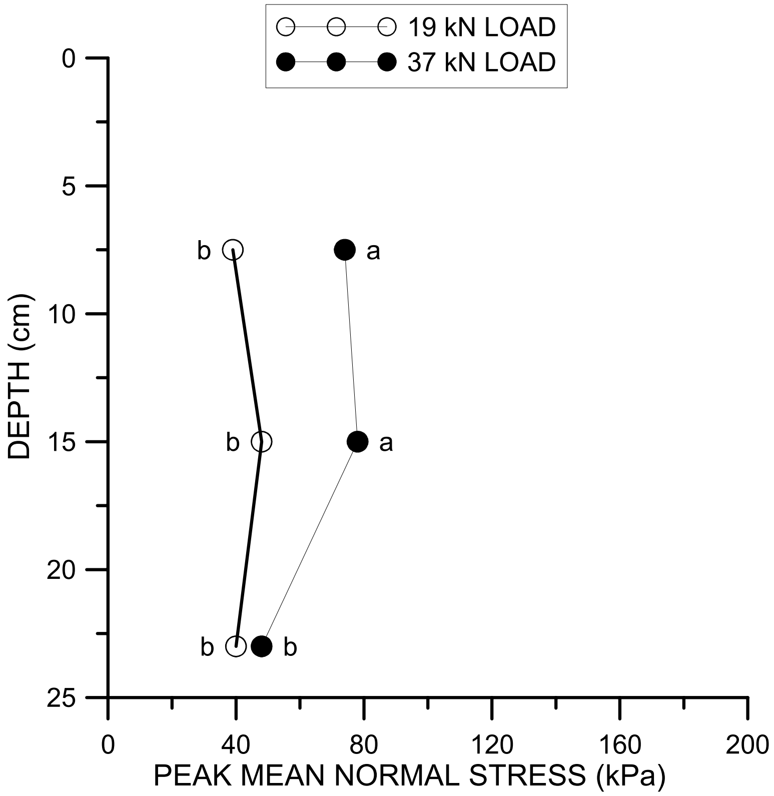

Figure 6. Peak mean normal stress by depth as measured with the SST after applied loading. Letters indicate statistical significance ($LSD_{0.1}$).

Pooling all peak mean normal stress measurements obtained from the SST and fitting a linear equation to this data and the applied tire loading resulted in a reasonable fit of the data (fig. 7). A correlation coefficient of 0.45 was found for the resulting equation. Fitting the SST peak mean normal stress for each depth at which they were obtained against the dynamic load gives a much better fit for the shallower data obtained at depths of 7.5 cm (0.76) vs. those data obtained at the medium depth of 15 cm (0.62), and those data obtained at the deep depth of 23 cm (0.30). As depths increased, the ability of the stresses to penetrate the soil decreased thus reducing the precision of the transducer.

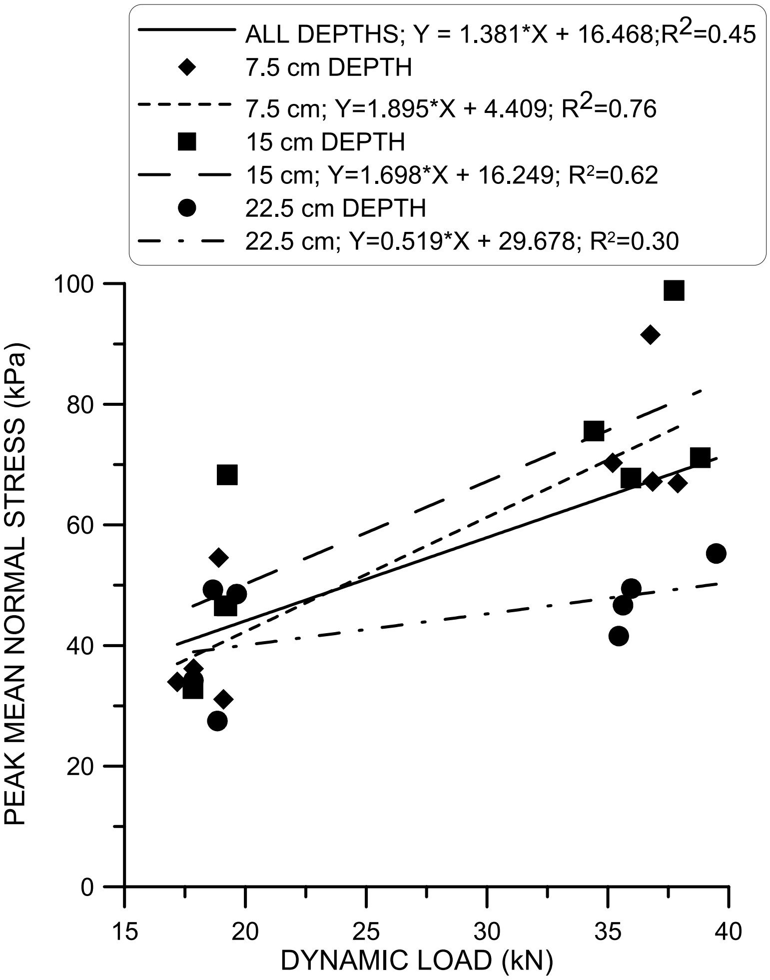

Figure 7. Linear fit of peak mean normal stress data to applied dynamic load for each SST burial depth.

Bulb Measurements

Final Depth

The original depths of bulb burial were also reduced from 7.5, 15, and 23 cm to 5.1, 9.9, and 13 cm, respectively. Greater compression of the soil seemed to occur as burial depths increased with the shallow burial depth (5.1 cm) being 68 % of the original burial depth (7.5 cm) and declining to 66% and 58%, respectively for the original burial depths of 15 and 23 cm.

Peak Pressure

Peak pressures as measured with the bulb were found to be significantly affected by load ($P \le 0.01$; fig. 8) with 37 kN causing peak pressure of 51.1 kPa and 19 kN causing peak pressure of 28 kPa. Almost constant values of peak pressure were noted at different depths with statistical significance being found between the loads at each depth.

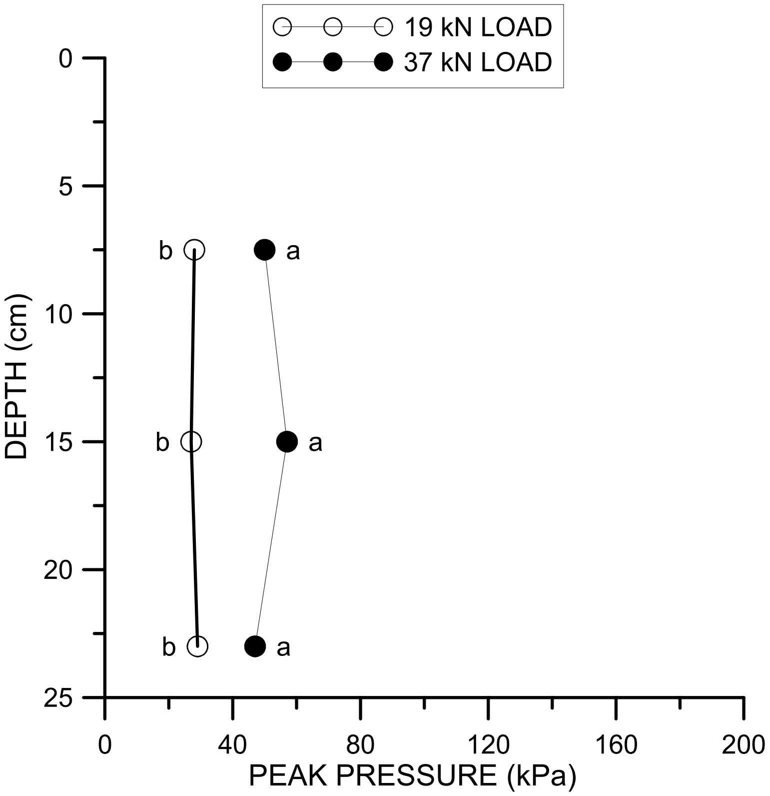

Figure 8. Peak pressure plotted by depth as measured with the pressure bulb after applied loading. Letters indicate statistical significance ($LSD_{0.1}$).

Fitting a linear equation to the dynamic load applied to the soil vs. all peak pressure measurements obtained with the bulb transducer resulted in a correlation coefficient of 0.63 (fig. 9). When analyzed by depth, similar correlation coefficients of 0.51, 0.80, and 0.69 were found for the peak pressure measurements vs. applied dynamic load for the three burial depths of 7.5, 15, and 23 cm. The largest correlation coefficient was found for the medium burial depth with the smallest correlation coefficient obtained at the shallow burial depth.

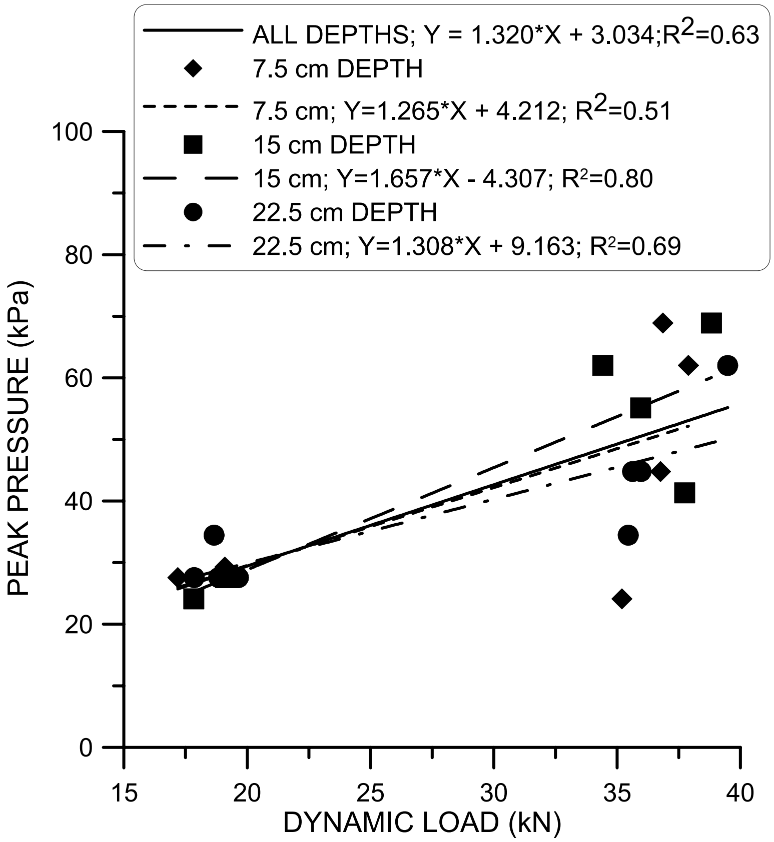

Figure 9. Linear fit of peak pressure data to applied dynamic load for each pressure bulb burial depth.

Residual Pressure

Residual pressures measured with the bulb showed similar trends to those found with peak pressures (fig. 10). Greater loading of 37 kN caused increased residual pressures of 38.6 kPa as compared to loading of 19 kN which caused residual pressures of 26.7 kPa. The two loads caused statistically different values of residual pressure to be measured at the two shallower depths (7.5 and 15 cm) except the deepest (23 cm) where similar values were found.

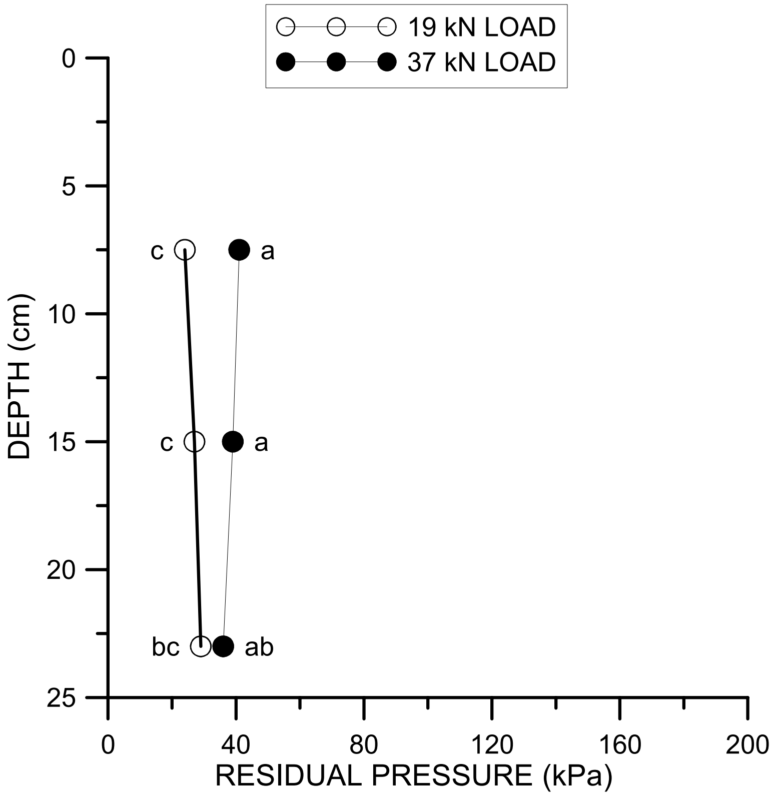

Figure 10. Residual pressure by depth as measured with the pressure bulbs after applied loading. Letters indicate statistical significance ($LSD_{0.1}$).

A similar fit for the pooled residual bulb stresses vs. dynamic load was also found with a correlation coefficient of 0.58 being obtained (fig. 11). When analyzing the pooled residual bulb stresses by depth vs. dynamic load for the three burial depths of 7.5, 15, and 23 cm, correlation coefficients of 0.61, 0.91, and 0.35 were found, respectively. Again, the highest precision for this transducer was found at the medium burial depth of 15 cm. When analyzing the residual stresses, the depth at which the poorest correlation occurred was found at the deep depth of 23 cm.

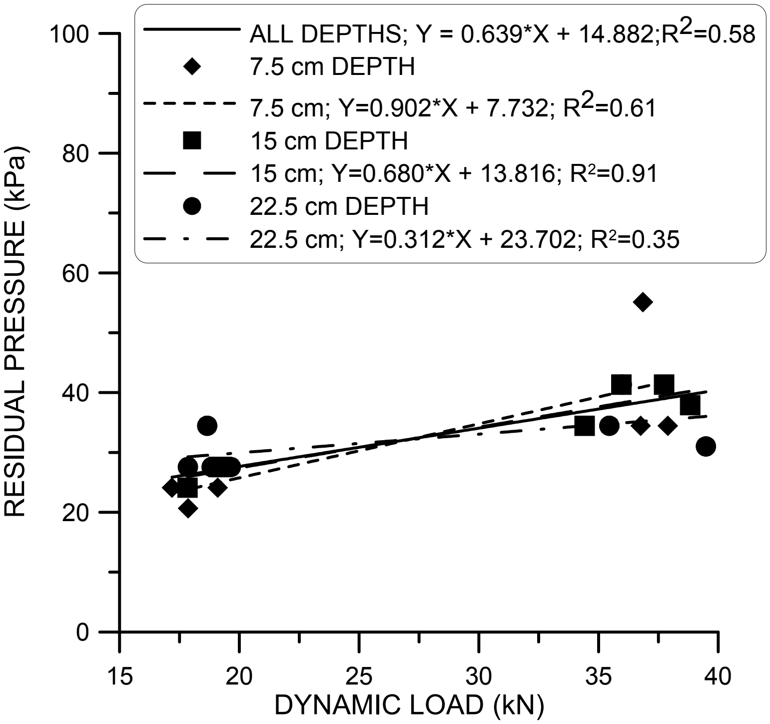

Figure 11. Linear fit of residual pressure data to applied dynamic load for each pressure bulb burial depth.

Comparisons of SST and Bulb Measurements

A slight reduction in magnitude was found with the bulb measured values of 20-60 kPa in peak pressure as compared to the SST measured values of 35-80 kPa in peak mean normal stress. However, increased precision may have been found with the bulb able to distinguish between loads at all three depths of burial while the SST was only able to distinguish between loads at the shallower two depths of burial. At the deepest depth of burial (23 cm), no difference was found between the two loads of 19 and 37 kN for the SST measurements. This coincides with the poor linear fit between the peak mean normal stress and dynamic load at the burial depth of 23 cm. Particularly at this depth, the SST was unable to distinguish between loads while peak pressure measured with the bulb was able to fit the data equally well at all depths.

The residual pressures measured with the bulb were also decreased in magnitude from the peak pressures measured with the bulb as well as the peak mean normal stresses calculated from the SST measurements. However, the precision afforded to these measurements were similar to SST measurements with no differences in residual pressures being found at the deepest burial depth of 23 cm.

The linear fit of the residual pressures was strikingly similar to that of the peak mean normal stress data obtained from the SST. Poorest fits were found at the deepest depth of 23 cm for both data sets while pressures and stresses at shallow depths were adequately predicted.

Conclusion

The conclusions of this experiment were:

1) The SST and the rubber pressure bulb were both able to distinguish differences in tire loading at shallow transducer burial depths of 7.5 and 15 cm. However, at the deepest transducer burial depth of 23 cm, the pressure bulb was still able to distinguish differences in applied load while the SST could not.
2) Peak pressures as measured with the rubber bulb were more able to discern differences in soil pressures at the deepest depth of 23 cm while residual pressures could not. Better fits of the data were obtained with the peak pressure as compared to the residual pressure at all depths of burial.

Disclaimer

The use of trade names or company names does not imply endorsement by USDA-ARS.

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