XVII[th] World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

SOIL FAILURE MODE IN FRONT OF A MULTIPLE-TIP HORIZONTALLY-OPERATED PENETROMETER AFFECTED BY DEPTH/WIDTH RATIO OF ITS TIP AND SHANK

ABBAS HEMMAT[1], A. KHORSANDI[1], V. SHAFAIE[1]

1 Professor, Department of Farm machinery, Isfahan University of Technology, Isfahan 84156-83111, Iran
ahemmat@cc.iut.ac.ir
1 A. Khorsandi, farazesh@yahoo.co.nz
1 V. Shafaie, ahemmat@cc.iut.ac.ir

CSBE100536 – Presented at Section III: Equipment Engineering for Plant Production Conference

ABSTRACT Mechanical resistance of a soil to failure has been widely used to estimate the degree of soil compaction. Our previous study showed that the magnitude of force which was measured by the horizontally-operated penetrometer depends on the soil failure mode in front of the sensor. This research investigated whether the critical depth (d_c) where soil failure transitions from brittle to compressive was dictated by depth/width ratio (DWR) of the prismatic tip, or of the shank of the sensor. Two horizontally-operated soil penetrometers were developed. In the first sensor, the width of the shank was the same as the prismatic tip, which was 18 mm. In the second sensor, the width of the shank (36 mm) was twice as much as the tip. The sensors were tested in a field with a soil texture of silty clay loam and with gravimetric water content (WC) of 4 to 18% at forward speed of 0.5 m s^{-1}. The results showed that the d_c for 36 mm wide shank sensor was approximately 210 mm (a DWR of about 6), whereas for the 18 mm wide shank sensor, the d_c was at depth of 110 mm (a DWR of about 6). The d_c increased with an increase in the width of the shank and decreased with an increase in soil WC. There was no interaction between the adjacent 100 mm distance tips as long as they operated below the d_c. In both sensors, the d_c was dictated by DWR of the shank. Visual observations showed that, in some cases, when the prismatic tip was located slightly above the d_c, a trace of prismatic tip in undisturbed soil could be vividly seen. This revealed that the prismatic tip was moving ahead of the soil rupture planes which radiated from the shank shin to the surface. It can be concluded that for the tip which is located just above the d_c, the length of its rod can be selected so it can operate in undisturbed soil (inducing compressive failure) ahead of soil disturbance (i.e. brittle failure) imposed by the shank.

Keywords: Soil compaction, Cone penetrometer, Soil mechanical resistance, Precision farming, Brittle failure, Compressive failure.

INTRODUCTION Soil compaction is one of the factors that limits potential yield. Regions of high mechanical resistance in the soil may arise naturally, by compaction from heavy farm machinery, or by formation of plough pans. Excessive soil compaction has negative effects for agriculture and the environment. It adversely affects soil structure, reduces crop production, increases runoff and erosion, accelerates potential pollution of surface water by organic waste and applied agrochemicals, and causes inefficient use of water and nutrients due to slow drainage. Different energy-demanding field operations and other land management treatments have been performed to ameliorate unwanted soil compaction (Johnson and Bailey, 2002). Knowing both horizontal and vertical variability of soil compactness provides the ability to discover non-uniformity of soil conditions related to water holding capacity, root impeding layers, and other mechanical and physical soil characteristics within an agricultural field. Proper delineation of field areas where these characteristics are distinctly different from the rest of a field will allow growers to locate areas that may potentially benefit from differentiated treatments. However, intensive mapping of soil mechanical resistance using a standardized cone penetrometer (ASAE Standards, 1999, 2004) has proven to be labour-intensive (Raper et al., 1999) , which motivated a number of sensor developers to look into alternative on-the-go sensing technologies (Hemmat and Adamchuk, 2008). Therefore, for more efficient data collection, on-the-go soil compaction sensors allow for a substantial increase in measurement density. A number of prototype sensor systems are being developed by several research groups to map within-field variability of soil mechanical resistance (Hemmat and Adamchuk, 2008). On-the-go horizontal soil resistance sensors were used to obtain data at specific or multiple depths using single or multiple tips.

A horizontal cone penetrometer was developed and tested by Alihamsyah et al. (1990) with the objective of providing a continuous signal for automatic control of soil interacting implements (Alihamsyah and Humphries, 1991). The effects of tip geometry, apex angle, tip extension, and operating speed on the measured soil resistance were studied in a soil bin. Measurements obtained using a prismatic tip with an apex angle of 30° related well to the standard cone index (CI). Later, Chukuw and Bowers (2005) modified this penetrometer so that it could measure soil mechanical resistance at three depths simultaneously. They used three prismatic tips with a 30° apex angle and three load cells similar to the one used in the single-tip horizontal penetrometer. A vertical tip spacing of 100 mm was selected to provide a 300-mm sensing profile and to minimize measurement interference from one tip to the next. When operated at a speed of 30 mm s^{-1} through soil layered with different degree of compactness, the sensor detected the difference in soil mechanical resistance with depth at a 5% significance level.

Another soil strength profile sensor (SSPS) was designed and tested by Chung et al. (2006). The SSPS had multiple prismatic tips with an apex angle of 60° and base area of 361 mm^2 (19 mm × 19 mm) mounted on a shank (vertical tine) with a width of 25.4 mm and cutting (wedge) angle of 60°. This on-the-go SSPS was designed and fabricated using an array of load cells interfaced with corresponding prismatic tips. The tips were extended forward from the leading edge of the tine and spaced apart. Different tip extension and tip spacing distances were tested; a 51 mm extension and a 100 mm vertical spacing were selected to minimize interference from the main shank and adjacent sensing tips.

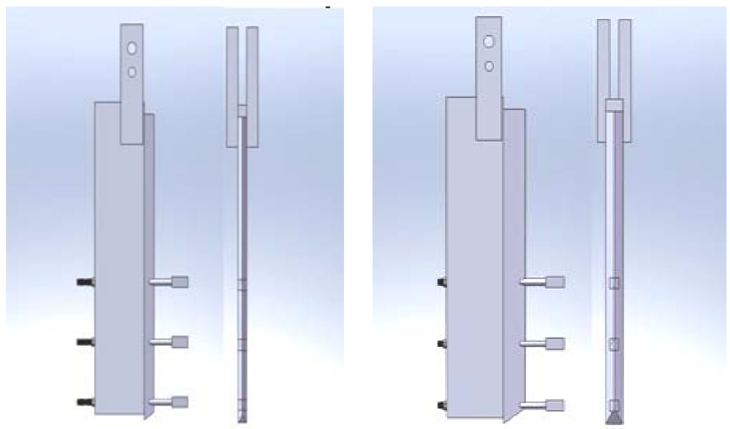
The performance of each of the sensors described above has generally been evaluated with respect to standard CI measurements. However, such a comparison can be problematic because the failure modes produced by on-the-go sensors and vertically operated penetrometers might be different. By nature, soil mechanical resistance sensors are of soil failure type. A shank (leg) equipped with a horizontal sensing tip (tip-based sensor) acts as a rigid tine with leading tip. The soil ahead of the cone tip of the vertically operated penetrometer is always in the bearing-capacity failure mode, whereas for tip based sensors, this type of failure would occur only if they operated under the critical depth (Hemmat and Adamchuk, 2008). The depth at which the soil failure mode changes from brittle to compressive is called the critical depth (d_c). Therefore, in validating on-the-go horizontally operated sensor data with respect to CI, the failure mode in front of the sensors should be documented.

Hemmat et al. (2009) developed a single-tip horizontally-operated soil penetrometer and observed the failure mode in front of it while penetrating soil at three different depths. The horizontal penetrometer was equipped with a 30° prismatic tip and had a base area of 324 mm^2. The prismatic tip was mounted horizontally to an S-shaped load cell housed inside a shank. The sensor was tested in a field with silty clay loam soil at three depths of 200, 250 and 300 mm. The results showed that average horizontal soil mechanical resistance index (HRI) values for both depths of 200 and 250 mm were similar due to the brittle failure mode in both cases. However, when the tip was operated below the critical depth of the sensor, the value of HRI at 300 mm depth increased three times when compared with 200 or 250 mm depth values. This was due to change in failure mode from brittle to compressive mode below the critical depth. There was a significant relationship between HRI and CI for the 300-mm depth, whereas for shallower depths the relation was not significant. In the extension of Hemmat et al. (2009) work, the effect of the shank width with respect to the tip width of the sensor on the failure mode in front of multiple-tip horizontally-operated soil penetrometer should be documented.

The objectives of this research were: (a) to develop two multiple-tip horizontally-operated soil penetrometers with two different shank widths, (b) to observe the soil failure modes in front of each of them while operating at different depths, (c) to investigate whether the critical depth (d_c) was dictated by depth/width ratio (DWR) of the prismatic tip, or of the shank of the sensor and (e) to study the effect of adjacent prismatic-tip distance on soil failure interactions in front of the tips

MATERIALS AND METHOD

Multiple-tip horizontally-operated soil penetrometer Two multiple-tip horizontally-operated soil penetrometers with two different shank widths were developed. Each sensor consisted of a shank that could be equipped with one, two or three tips. The tips had three effective measuring depths of 100, 200 and 300 mm. In the first sensor, the width of the shank was the same as the prismatic tip, which was 18 mm (Fig. 1a). In the second sensor, the width of the shank (36 mm) was twice as much as the prismatic tip (Fig. 1b).



(a) (b)

Figure 1. Two multiple-tip horizontally-operated soil penetrometers: a) the width of the shank was the same as the prismatic tip, which was 18 mm and b) the width of the shank (36 mm) was twice as much as the prismatic tip.

The height of the shank was 500 mm for both sensors. The shank was designed such that the prismatic tips could be attached or removed from the shank so that the distance between two adjacent tips could change from 100 to 200 mm. The shank was designed to be pulled at a perpendicular rake angle to the soil surface. To limit the formation of a soil wedge in front of the advancing shank, it was equipped with a shin having a 45° prismatic wedge angle. The shank was designed to penetrate vertically into the soil profile with minimum downward force. To facilitate the penetration of the shank into the soil profile, the bottom of the shank was cut on a 45° angle and bevelled to a 45° prismatic wedge. The prismatic tips were made of stainless steel and had an 18 mm × 18 mm base area with 30° apex angle based on research conducted by Alihamsyah and Humphries (1991). Their rods had diameter of 10 mm. The lengths of the rods were such that the tip bases were 40 mm ahead of the shin. The shank was mounted to a frame, using a safety mechanism, and it was attached to a tractor through the three-point hitch.

Field experiments The field experiments were conducted at the Isfahan University of Technology Research Station Farm. The soil texture was silty clay loam. The soil classified as: fine-loamy, mixed, thermic Typic Haplargids, according to USDA system (Lakzian, 1989). It was formed on alluvial sediments of the Zayandeh Roud river initially low in organic matter, and with a history of intensive conventional cultivation and cropping of cereals, hay, and silage corn (*Zea mays* L.) rotation.

Two sets of experiments were conducted in two phases. Each experiment was carried out along a 10 -m long transect while the sensor was pulled with a speed of 0.5 m s^{-1}. The purpose of the phase I tests was to observe the failure mode ahead of the sensors and to find out how the critical depth changes by changing the shank width while the sensors operating at three different depths (100, 200 and 300 mm). Soil disturbance was assessed by direct excavation. After each pass, all disturbed soil perpendicular to the direction of travel was removed and trenches were opened up to observe the failure mode. The major failure planes were located manually by removing disturbed soil from the vertical profile surface. The dimensions of the exposed profile were quantified using a profile meter (Fig. 2).

Figure 2. Soil disturbance pattern, the dimensions of the exposed profile was quantified using a profile meter.

To investigate whether the critical depth (dc) was dictated by depth/width ratio (DWR) of the prismatic tip, or of the shank of the sensor, the sensors were operated at three depths. In this case, if the 18-mm tip initiating the crescent soil failure, the critical depth would be at around 108 mm (≈6×18) for both sensors. On the other hand, when the crescent soil failure was induced by the shank, the critical depth would be approximately at 216 mm (≈6 × 36) and 108 mm (≈6×18) for 36- and 18-mm wide shanks, respectively. Upward failure dominates above the critical depth and lateral disturbance below. Below the critical depth, the extent of lateral soil disturbance is limited to the width of the tine (Spoor and Godwin, 1978).

The purpose of the phase II tests was to study the effect of adjacent prismatic-tip distance (100 or 200 mm) on the soil failure interactions of the tips. For this purpose, at the end of each transect, all disturbed soil was taken out from the path of the sensor and then the trace of the prismatic tips or shank on the profile vertical surface was observed. To locate the sensors tips, profile trenches were also opened up parallel to the direction of operation.

To measure the moisture content, soil samples were taken from 50 to 150 mm, 150 to 250 and 250 to 350 mm depths for operating depths of 100, 200 and 300 mm, respectively. The samples were weighed, and oven dried at 105° C for 48 h. At the end of the drying period, soil samples were weighed, and moisture content calculated on an oven dry basis.

RESULTS AND DISCUSSION

Field tests

Phase I Figure 3 shows the cross-sectional of the soil disturbance perpendicular to the direction of travel created by the sensor with 36-mm wide shank when the sensor tip was operated at 100 mm depth. The soil disturbance profile ahead of the sensor showed that the soil was displaced forwards, sideways and upwards, failing along well defined rupture planes which radiated from the shank base to the surface. Therefore, the failure mode was a crescent-failure type (Spoor and Godwin, 1978) and the sensor tip was working in the disturbed soil above the critical depth of the sensor shank.

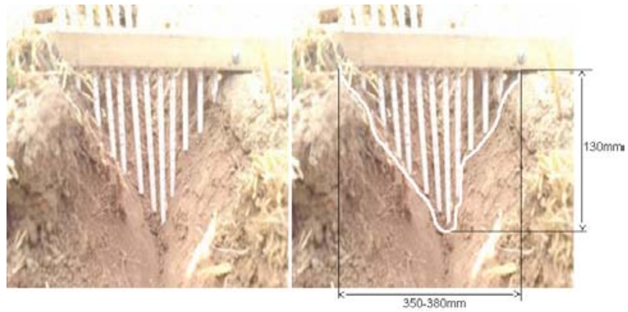


Figure 3. Soil disturbance profile for the sensor with 36-mm shank and equipped with a single tip while operating around 100 mm depth (WC= 7.2%). The direction of travel is perpendicular to plane.

Figures 4 and 5 show the soil disturbance profiles of the sensors with 18- and 36-mm wide shanks while equipped with three tips and working at 300 mm depth, respectively. The critical depths of the sensors with 18- and 36-mm wide shanks were observed at depths of 110 (at WC=11.8%) and 180 mm (at WC=17.8%), respectively. Below the critical depth, the failure mode changed from brittle to compressive type and soil began to flow forwards and sideways only (lateral failure) and channels with the same size as the shank widths were developed.

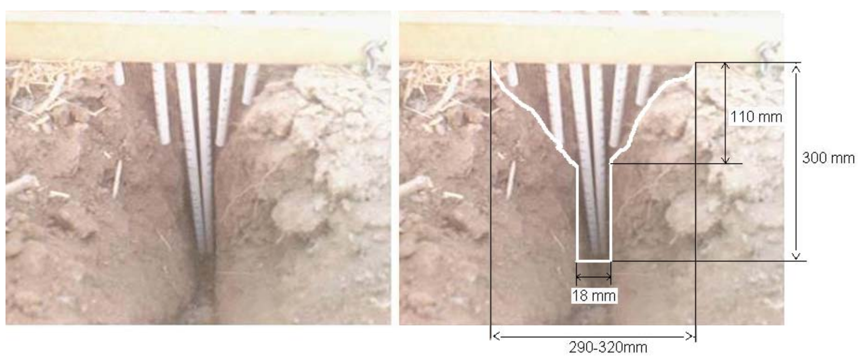


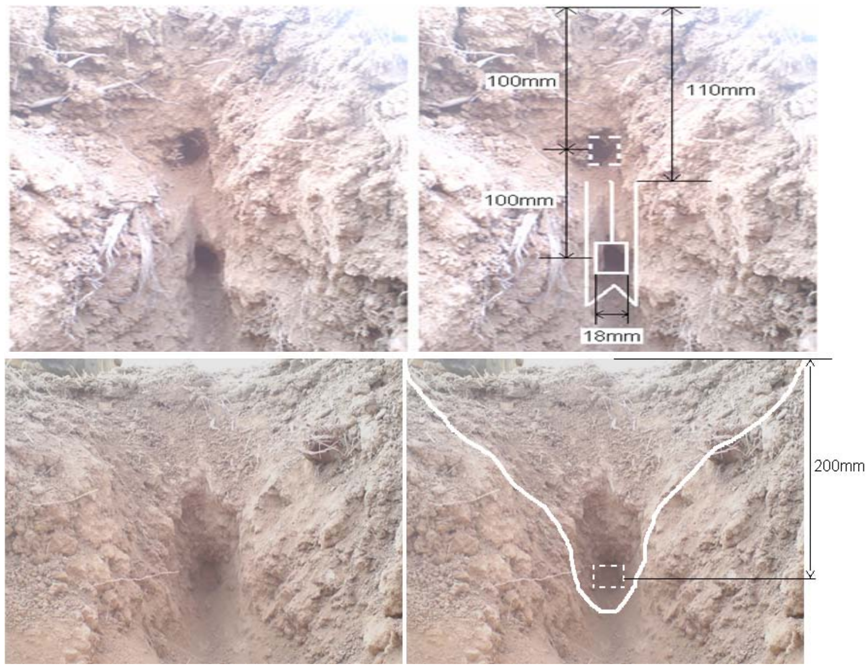
Figure 4. Rear view of soil disturbance for the sensor with the shank width of 18 mm and equipped with three sensing tips at depths of 100, 200 and 300 mm and operated at depth of 300 mm (WC=11.8%). Below the critical depth, the width of compacted zone is equal to the shank width. The direction of travel is perpendicular to plane.

Figure 5. Rear view of soil disturbance for the sensor with the shank width of 36 mm and equipped with three sensing tips at depths of 100, 200 and 300 mm and operated at depth

of 300 mm (WC=17.8%). Below the critical depth, the width of compacted zone is equal to the shank width. The direction of travel is perpendicular to plane.

In both cases, the sensor acted as a vertical rigid tine and not as a rigid tine with leading tip. It can be noted that the critical depth is dependent on the working depth/tine width (aspect ratio) of the shank and not the tip.

Fig. 6a, b shows two sensors with two sensing tips at depths of 100 and 200 mm, operating at depth of 200 mm. For the 18-mm wide sensor (Fig. 6a), critical depth (dc) is at depth of 110 mm therefore, one of the sensing tips was working below the dc and the first one is just working above the dc. But for the 36-wide sensor (Fig. 6b), the critical depth was below the depth of 200 mm, thus both sensing tips were working in the disturbed area (i.e. above the dc).



(a)

(b)

Figure 6. Photograph of developed channels with square cross-sectional area for the sensor a) with the shank width of 18 mm and with two sensing tips at depths of 100 and 200 mm, operating at depth of 200 mm (WC=12.7%) and b) with the shank width of 36 mm and with two sensing tips at depths of 100 and 200 mm, operated at depth of 200 mm (WC=10.8%). The squares with solid and broken lines edges are traces of prismatic tips in undisturbed and disturbed soil s, respectively. The direction of travel is perpendicular to plane.

Figure 6 also shows that for the prismatic tip which was located slightly above the critical depth, a trace of prismatic tip in disturbed soil could be vividly seen. This revealed that the prismatic tip might be moving ahead of the soil rupture planes which radiated from the shank shin to the surface.

Phase II For the sensor with three sensing tips while operating at approximately 300 mm depth, the profile trenches, which were opened up perpendicular to the direction of sensors operations, showed that the tips working below the critical depth of the sensor shank were confined in the undisturbed soil. The soil at the tip began to flow forwards and sideways only (lateral failure) and developing a channel with square cross-sectional area, the same size as the sensing tip base (Fig. 7). As shown in Fig 8, there would be no interaction between the adjacent 100-mm spacing tips as long as they were operating below the critical depth.

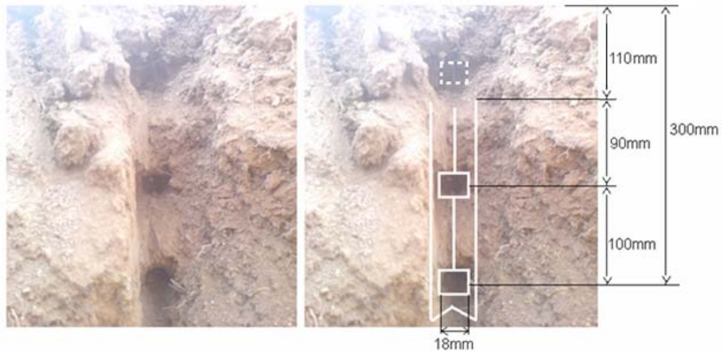
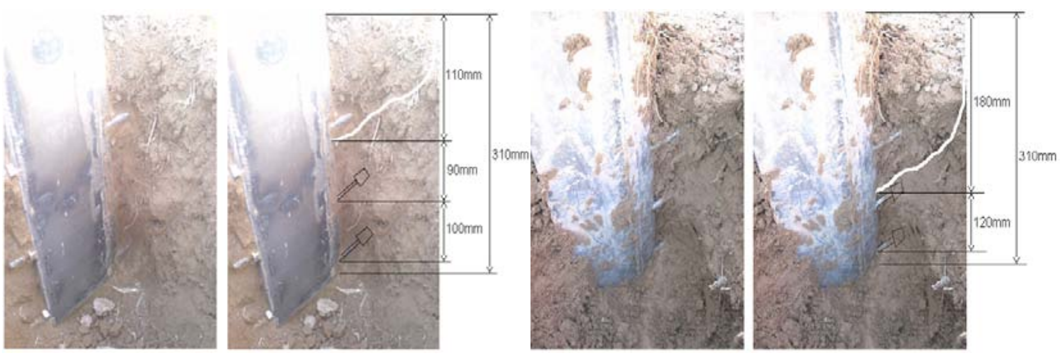


Figure 7. Photograph of developed channels with square cross-sectional area for the sensor with the shank width of 18 mm and with three sensing tips at depths of 100, 200 and 300, operating at depth of 300 mm (WC=11.5%). The channel is the same size as the sensing tip base, as the tip was working below critical depth. The squares with solid and broken lines edges are traces of prismatic tips in undisturbed and disturbed soil s, respectively. The direction of travel is perpendicular to plane.

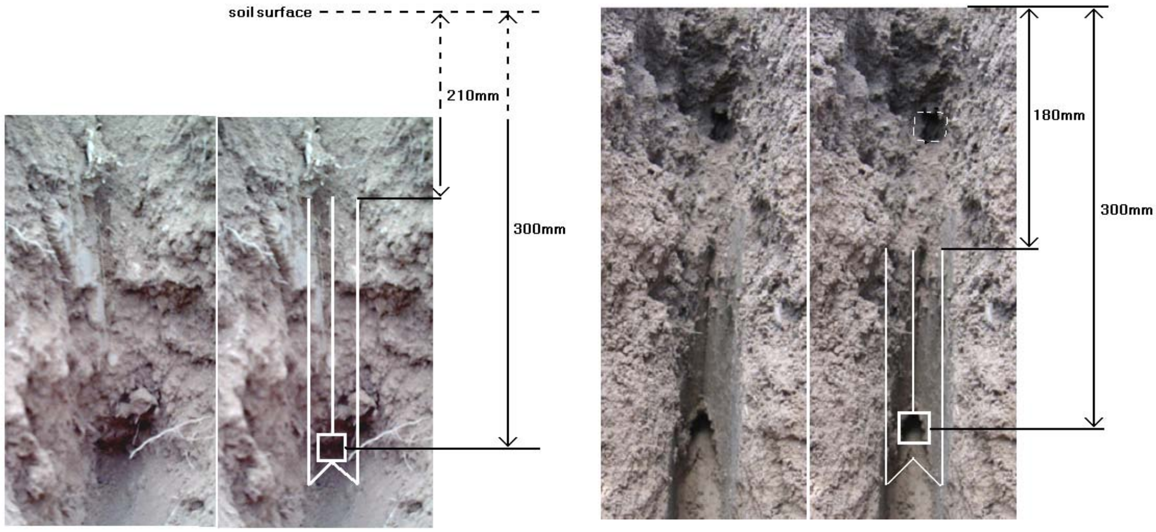
Figure 8 a,b shows the side view of the disturbed area for both sensors. For the sensor with the shank wide of 18 mm, the dc is at depth of 110 mm and both of the tips are completely below the dc. For the sensor with the shank wide of 36mm, the dc is at depth of 180 mm and one of tips is completely located at the disturbed soil.



(a) (b)

Figure 8. Photographs show the side view of the disturbed area of the sensor with the shank width of a) 18 mm and b) 36 mm and with three sensing tips at depths of 100, 200 and 300 mm, operating at depth of 300 mm (WC= 11.8 and16.5%), respectively.

Figures 9 a and b show that the critical depth decreased as the soil water content (WC) increased. For example, for the sensor with 36 mm width, when the soil WC increased to 17.8%, the critical depth, decreased to 180 mm (Fig. 9b), whereas for dryer condition (WC= 7.6%) was around 210 mm (Fig. 9a).



(a) (b)

Figure 9. Photograph of developed channels with square cross-sectional area for the sensor with the shank width of 36 mm that operated at depth of 300 mm with a) WC=7.6% and b) WC=17.8%, respectively.

As shown in Fig. 9b, a trace of prismatic tip in the disturbed soil could be observed at the depth of 100 mm. This reveals that if the water content is near the plastic limit, (WC=17.8%), a channel could be formed while the tip was moving through the disturbed soil. This could be due to the high cohesion of the moist soil. However, the soil strength which measured by the prismatic tip while moving through the moist disturbed soil would not be as high as if the tip was moving through the undisturbed soil.

CONCLUSION Results showed that the critical depth (d_c) of the horizontally-operated penetrometer is dependent on the aspect ratio (working depth/width) of the shank and not the tip.The d_c increased with an increase in width of shank and decreased with an increase in soil water content. There was no interaction between the adjacent 100-mm distance tips as long as they operated below the dc. Our observations showed that when the prismatic tip was located slightly above the dc, a trace of prismatic tip in undisturbed soil could be plainly seen. This revealed that the prismatic tip was moving in the undisturbed soil ahead of the soil rupture planes which radiated from the shank to the surface. Therefore, in order the tip of the horizontally-operated penetrometer, which is located slightly above the d_c of the shank, could measure the mechanical soil resistance similar to those working below the d_c, the length of its rod should be increased. However, when the soil is moist, the trace of the prismatic tip could be observed as a channel even in the disturbed soil (well above the critical depth) due to the high cohesion of the soil. The soil strength measured in this case could not be as high as if the tip was moving through the undisturbed soil.

REFERENCES

Alihamsyah, T., E. G. Humphries and C. G. Bowers, Jr. 1990. A technique for horizontal measurement of soil mechanical impedance. Transactions of the ASAE. 33: 73-77.

Alihamsyah, T. and E.G. Humphries. 1991. On-the-go soil mechanical impedance measurements. In: Proc. 1991 Symposium: Automated Agriculture for the 21st

Century, St Joseph, Mich.: ASAE, pp. 300–306.
ASAE Standards, 1999. EP542. Procedures for using and Reporting Data obtained with the Soil Cone Penetrometer. 43rd ed., ASAE, St. Joseph, MI.
ASAE Standards, 2004. S313.3. Soil Cone Penetrometer. 50th ed., ASAE, St. Joseph, MI.
Chukuw, E. and C. G. Bowers, Jr. 2005. Instantaneous multiple-depth soil mechanical impedance sensing from a moving vehichle. Transactions of the ASABE, 48: 885-894.
Chung, S. O., K. A. Sudduth. and J. W. Hummel. 2006. Design and validation of an on-the-go soil strength profile sensor. Transactions of the ASABE, 49: 5-14.
Hemmat, A. and V. I. Adamchuk. 2008. Sensor systems for measuring spatial variation in soil compaction: review and analysis. Comput. Electron. Agric. 63, 89–103.
Hemmat, A, A. Khorsandy, A. A. Masoumi and V. I. Adamchuk. 2009. Influence of failure mode induced by a horizontally operated single-tip penetrometer on measured soil resistance. Soil and Tillage Research 105 (2009) 49-54.
Johnson, C. E. and A. C. Bailey. 2002. Soil compaction. Advances in Soil Dynamics. vol. 2. ASAE, St. Joseph, MI, pp. 155–178.
Raper, R. L., B. H., Washington, J. D., Jarrell. 1999. A tractor-mounted multiple-probe soil cone penetrometer. Appl. Eng. Agric. 15 (4), 287–290.
Spoor, G. and R. J. Godwin. 1978. An experimental investigation into the deep loosening of soil by rigid tines. J. Agric. Eng. Res. 23, 243–258.