CHAPTER 5

RESEARCH METHODOLOGY

The research methodology used included the field testing of the two instrumented apparatus described in Chapter 4, field experimentation to study the effect of tillage depth and bite length on the performance of the rotavator, and the validation the proposed analytical model for predicting the torque requirements for a down-cut rotavator. All the field testing and experimentation were conducted at the Hatfield Experimental Farm at the University of Pretoria in South Africa. This chapter describes the methodology used to achieve the stated study objectives.

5.1 Determination of soil properties

5.1.1 Soil textural classification

Textural classification of the soil was done by collecting adequate soil samples randomly from the designated experimental site. The samples were collected from the top 600 mm, which was beyond likely maximum reach of the experimental deep tilling rotavator. The standard sieve method (Bardet, 1997) was used for the textural classification. The textural classification of the soil at the experimental site was done using the UDSA soil classification system (McKyes, 1989; Gill & Vanden Berg, 1967).

5.1.2 Soil water content

Soil water content was determined using the standard oven drying procedure (Bardet, 1997; Mandal & Divshikar, 1994; Gardner, 1986). The soil samples for the determination of the water content were collected immediately upon the completion of a test-run. At least 10 soil samples of about 40 g were collected in metallic containers for each test-run from different located strata of the soil whose water content was to be determined. This was done to obtain a representative soil water content (Lambe, 1951), for a given condition. The mass of the collected moist soil samples was determined using a scale balance with an accuracy of 0.01 g, and placed in a ‘constant temperature’ oven for drying at a temperature of about 105 °C for a minimum drying period of 24 hours as described by Bardet (1997).

5.1.3 Soil bulk density

For the determination of the *in situ* soil bulk density, a field density test apparatus based on the principle of the core cutter method (Mandal & Divshikar, 1994) was fabricated, and used to collect soil samples at randomly selected spots within the experimental test area. The fabricated soil sampler had a volume of 820 cm^3. Prior to the collection of the soil samples the experimental site was irrigated for about 48 hours using a sprinkler irrigation system. The ground surface was thereafter levelled at depths of about 100 mm, 200 mm and depths greater than 300 mm using a shovel, after the irrigated area had attained its field capacity.

Soil samples for the determination of the soil water content were collected at the respective depths; at spots adjacent to where the soil samples for the determination of the bulk density were collected. A minimum of five samples were collected using the fabricated core sampler at each depth for a given level of soil water content for the determination of the bulk density of the soil. The collection of the soil samples at the prepared stretches of the levelled ground surface were then repeated after every two days, since the date of the last soil sample collection, until the soil water content dropped to about 8 % or less. The two days lapse was necessary for the test to be done at significantly different soil water contents levels. Initial trial tests had indicated that the soil water contents for soil samples of subsequent days were not statistically significantly different. Thus, field tests were done and soil samples were collected at two day intervals.

5.1.4 Soil shear strength

The torsional (rotational) shear apparatus described in §4.2 working on the principle of the shear ring (McKyes, 1989) was used to determine the soil shear strength parameters. The choice of this apparatus, among the many other possibilities, was based on the fact that in practice, the shear ring is more convenient to operate in the field because it is both manually and hydraulically easier to provide a forcing torque to the device than to find anchorage and strength needed to apply large horizontal forces to the shear plate. The apparatus was also the most suitable for the determination of the soil shear strength and soil-metal frictional characteristics at the tillage depths that the tiller was to be operated at during test runs as the design allowed the lowering and raising the head of the apparatus hydraulically (see §4.2).

An annulus ring with grousers was attached to the head of the device for the determination of the soil cohesion (C_c) and angle of internal friction (ϕ). A normal load was applied hydraulically as described in § 4.2 and held constant with the help of the special hydraulic circuit (Figure 4.9). After about 60 seconds, a torque load was hydraulically applied, to rotate the head of the soil shearing apparatus (Figure 4.7) and cause soil shear-failure, using a separate hydraulic power system (tractor hydraulic system). The measured data for determining the soil shear strength and soil-metal friction parameters were collected using the DAS described in §4.3.

The data for soil shear strength and soil-metal characterization was sampled at the rate 60 Hz. The data recording was done for a total period of 120 seconds as described in §4.3. At a given depth and soil water content level, a minimum of five (5) sets of normal and torque loads were obtained for the determination of the soil shear strength parameters. For a given level of the normal load, three replications of the torque load were done. This was done by holding the normal load constant at the set level, shifting the apparatus tool-frame carrier a short distance of about 30 cm from a sheared spot.

For each test, graphs of the normal force and the shearing torque were plotted using the interactive plot function in MATLAB. The plots showed the recorded normal force and the applied torque with time (see Figure 4.20). The voltage output response for the normal load and the applied torque were converted to the normal load (N) and torque (Nm), respectively, by multiplying the respective channel of the measured data by the calibration factors. Graphs similar to Figure 4.20 with the y-axis expressed in force and torque units were thereafter produced. From these graphs the maximum torque at which soil failure occurred for a given magnitude of normal load was read-off the using the interactive zoom function of the MATLAB computer program graphics.

Using the maximum torque obtained graphically, the maximum shear stress calculated using the following expression (Johnson *et al*., 1987; Bailey & Weber, 1965):

$$\tau_{\max} = \frac{3M}{2\pi\left(r_o^3 - r_i^3\right)} \quad \text{... (5.1)}$$

where:

τ_{max} = maximum shear stress at soil-soil failure surface (kPa)

M = the maximum torque or the maximum resisting soil moment (kNm)

r_i = inner radius of the annulus ring head with grousers (m)

r_o = outer radius of the annulus ring head with grousers (m)

The normal stress was determined from the expression (McKyes, 1989).

$$\sigma_n = \frac{F_n}{A} \quad \text{... (5.2)}$$

where:

σ_n = normal stress (kPa)

F_n = the applied 'constant' normal load (kN)

A = the effective area of the torsional shear apparatus grouser head in contact with the soil (m^2)

The soil shear strength parameters were determined by plotting a graph the values of the normal stress against the average value of the three maximum shear stress values. The graphs were plotted using the curve-fitting toolbox in MATLAB, and the least-squares fitting procedure applied to obtain the best fit regression line. The internal angle of friction of the soil, ϕ and the soil cohesion are given by the slope and the y-intercept, respectively of such a graph (McKyes, 1989).

5.1.5 Soil-metal friction

Soil-metal frictional parameters were determined by replacing the grouser ring head of the shear device with a smooth circular steel plate of the same internal and external radii as the grouser head (Figure 4.8). Thereafter the same procedure described in §5.1.4 above, for determining the soil shear strength parameters, was used. Like was the case with shear strength parameters determination, the test was repeated three times for a given level of the normal load at a given depth and level of the soil water content. Equation (5.1) was applied to calculate the maximum soil-metal friction resistance force, and the normal stress calculated using Equation (5.2). By plotting a graph the values of the normal stress against the average maximum friction force, the angle of the soil-metal friction and the soil-metal adhesion are respectively given by the slope and the y-intercept of the obtained graph (McKyes, 1989).

5.2 Field experiments

Field experiments were carried out at the experimental site at the Hatfield Experimental Farm, University of Pretoria. The experiments were done in winter because the experimental site is situation in an area that receives summer rainfall. Thus, it was easier to control the levels of the soil water content in winter by irrigating the area where the experiments were to be conducted. After a irrigating, field experiments were carried out on it at predetermined dates. The use of different dates (days), was a natural means of attaining different soil water content levels required for the experimentation. The experiments were only done for assessing the performance of the experimental tiller; and the provision of the data required for the validation and evaluation of the proposed model for a down cutting rotavator.

5.2.1 Experimental layout

The general experimental layout used is presented in Figure 5.1. During the tillage test trials, two tractors were used. The paths cut by individual blades for the down-cutting direction are illustrated in Figure 5.2. Tractor 1, to which the rotavator is connected, was towed by Tractor 2 through a tow bar. Using this layout (Figure 5.1), and the set-up

(Figure 4.17, §4.5.1), experiments were carried out for determining the effect of set tillage depth, forward travel speed, number of cutting blades on the flange and bite length for different soil water content levels on the torque requirements and the push/pull forces generated for a down-cut rotavator.

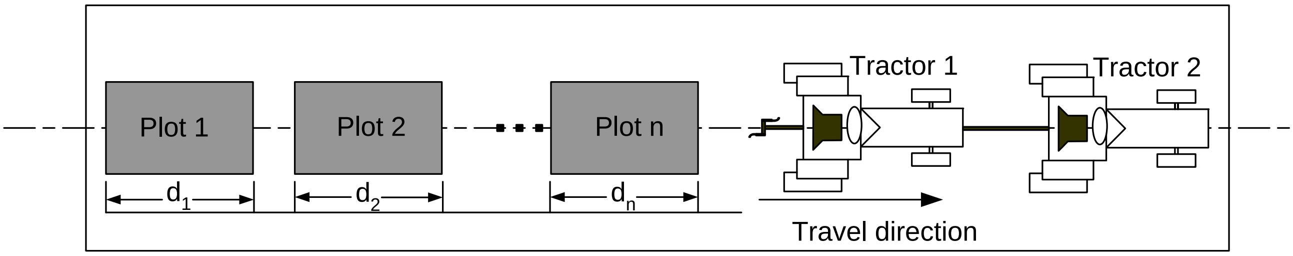

Figure 5.1: Experimental layout (d_1, d_2 … d_n – distance covered in respective plots during a test run)

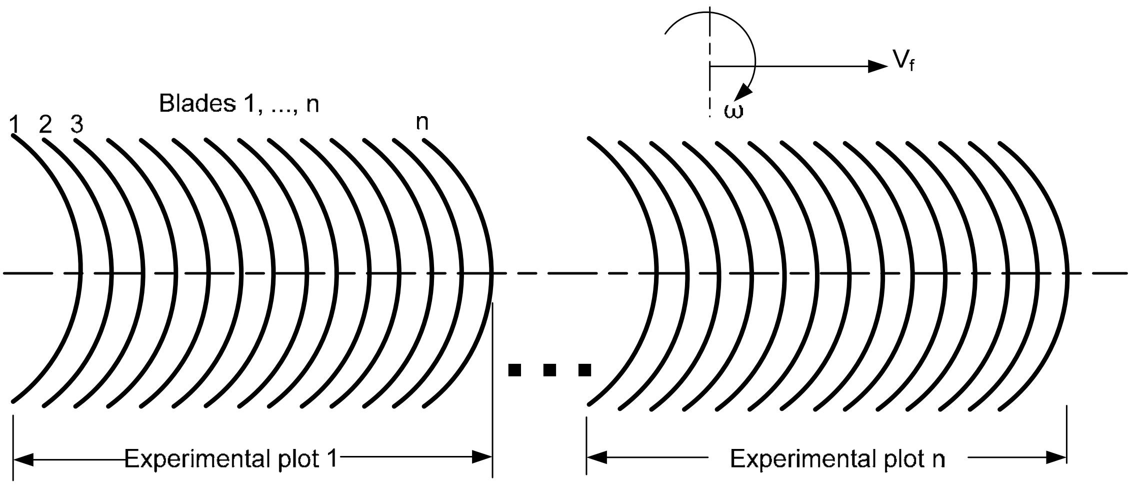

Figure 5.2: Illustrations of the cutting paths by individual blades within experimental blocks for experimental plots 1 … n.

All the field tests with the rotavator, irrespective of the variable whose effect on the performance parameters was being studied, required the same set-up (Figure 4.17). At the commencement of any test trial, for studying the effect of a given parameter on the tiller performance, the tiller tool-frame carrier was lowered to a point (Figure 5.3a) where a tip of a vertically positioned (aligned) blade came into contact with the ground surface. This was considered as the 'zero' or the reference depth. The DAS was then triggered and a test run was made with this set-up for the set length of time. The recorded data obtained at this depth constituted the initial channel values for all the seven channels on the tiller tool-frame carrier. The initial channel values so recorded were used for referencing changes in the respective transducer values during field experimentation at the desired experimental conditions. In most cases a test run lasted 10 or 20 seconds. However, in severe conditions the time was increased to 30 seconds to allow the equipment to achieve stability.

After completion of the initialisation test-run, the recorded data was exported and stored in a data file in the hard disk of the on-board PC. Subsequent desired set tillage depths (Figure 5.3b) at which test runs were to be made was set by cutting a furrow to that depth. The initial setting of the depth of tillage was done manually, using a metallic tape measure.

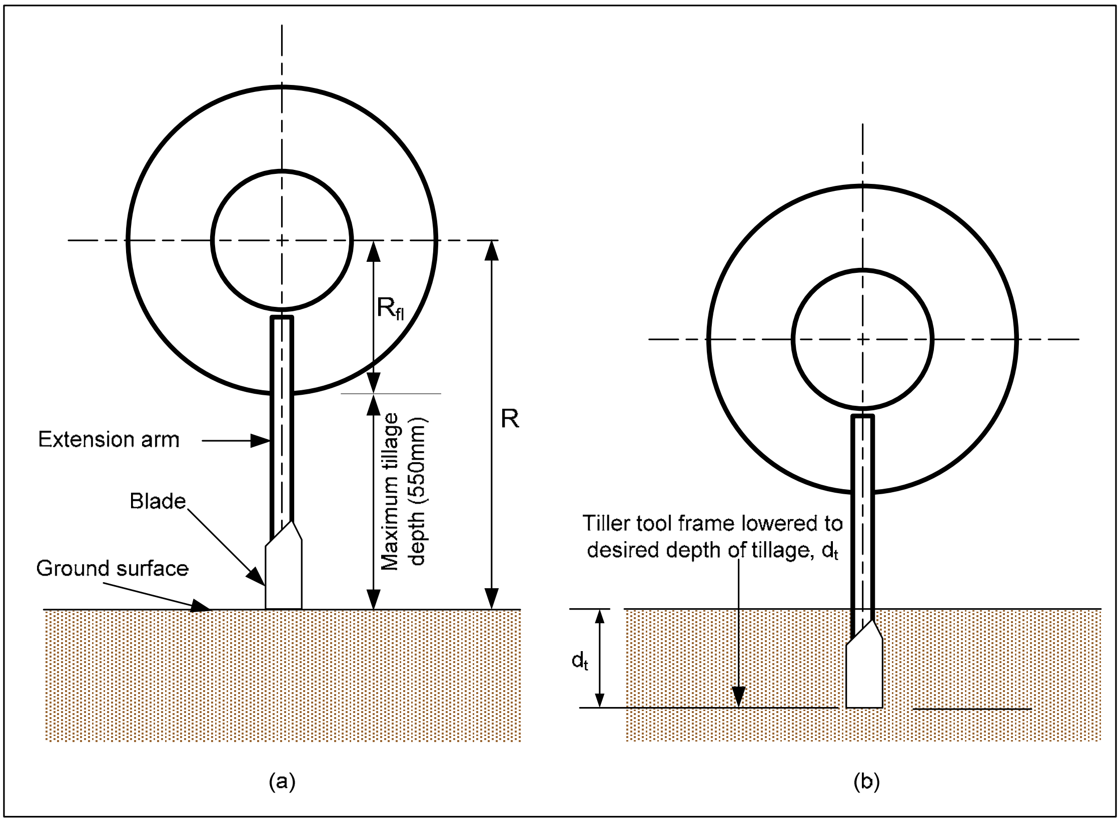

Figure 5.3: Initial and field test-run depth settings during experimentation

At the completion of the depth setting, the set-up was readied for collection of the desired data. The PTO gear was engaged and the engine speed of Tractor 1 (Figure 5.1) set to a constant value of 2000 rpm. A suitable forward travel gear of Tractor 2 was then selected and engaged, and its engine speed set to a constant value of 1000 rpm. The forward travel was then initiated and after about five complete rotations of the rotor, the DAS was started and the measurement started. The progress of the measurements for a test-run was monitored on the monitor of the on-board PC. At the completion of a run, the data was exported and stored in a data file in the hard disk of the on-board PC for later analysis.

For a given depth and soil condition, three sets of measurement of 20 seconds each was done. Once the forward motion had been initiated for a given depth, Tractor 2 was not halted until after the completion of the third replication. The in-built clock of the DAS software terminated the measurement after the set duration had elapsed. Graphs of the measured data were plotted at the end of a measurement for visual inspection, immediately after the completion of a test-run, before another test run was initiated. The test-runs were repeated for different depths with the same number of blades on the flange for the two forward travel gears.

5.2.2 Effect of tillage depth

Field trial test runs were conducted to determine the effect of the depth of tillage on the torque requirement and the resultant push/pull forces generated on Tractor 1. These tests were done at constant travel and rotational speed of the rotor and the towing tractor, (Tractor 2). Five depths of tillage, namely 250 mm, 300 mm, 350 mm, 400 mm, 450 mm, 500 mm and 550 mm were used. For each set tillage depth, three tillage tests were done.

The setting of the depth at which the tillage test runs was done was achieved by cutting a furrow while the equipment was stationary until the required set tillage depth was reached. Once this depth was reached, the forward motion was initiated by engaging the appropriate forward travel gear of Tractor 2 (Figure 5.1). A minimum of three test plots were then processed without stopping. This was done to ensure that the stability of the experimental set-up was maintained for a set tillage depth. Soil samples were collected as described in §5.1.2 and the standard oven drying method (Bardet, 1997) used to determine the soil water content for the soil tilled at various depths.

5.2.3 Effect of bite length

The bite length was varied in two ways; by changing the forward travel gear ratio of the towing tractor (Tractor 2, Figure. 5.3) or by changing the number of blades on the flange of the rotor. Tractor 2 was only operated in two forward gears; Gear I and Gear II, in the low speed range.

The change in bite length by either operating the rotavator with six (6) or three (3) cutting blades on the same side of the flange, or by operating Tractor on the two forward travel gears for a fixed set of number of blades on the same side of the flange.

After changing the bite length using any of the above two approaches, the field tests using the experimental rotavator were thereafter performed at different depths of tillage (§5.3.1) for the set bite length. A minimum of three tests was done without for each set tillage depth. Again, soil samples were collected randomly at random depths within the tilled layer for each field test for the determination of the soil water content, as described earlier.

5.3 Calculating the bite length and the blade angular position

The bite length was calculated using Equation (3.8). The forward travel velocity and the rotor rotational speed was determined as explained in §4.4.2. The radius of the rotavator, R was 930 mm; and comprised the blade-extension arm length plus the flange distance to the centre of the rotor (Figure 5.3).

The angular blade position from the horizontal was calculated by counting the number of square-waves generated and multiplying this by 2.338, the angle equivalent for one square-wave. This enabled the determination of the torque values (measured and model generated) for the angular position of the tip of the blade during the soil cutting. The ability to determine the angular position is important because the comparison of the measured and model generated torque requirements at different set tillage depths will be done for the same angular positions.

5.4 Data processing and analysis

5.4.1 Experimental data processing

Processing of the field experiment data was done using MATLAB (*Matlab, Version 7, Mathworks, Inc. USA*) and MS Excel (*Microsoft, Inc., USA*). MATLAB was extensively used in the manipulation of the tillage data. The Curve Fitting Toolbox MATLAB was used for the development of regression relationships between the variation of the soil shear and frictional strength parameters with the soil water content for the two depths. The interactive zoom function in MATLAB graphics was used for the determination of the specific values at the points of interest, e.g., the determination of the maximum torque required for the determination of the stress and maximum frictional force values.

For the processing of the data for the rotor and the forward travel speed, a computer program was developed in MATLAB. The program counted the number of the square-wave pulses generated during a test run and converted them to their equivalent rotational or forward travel speed. The program was also used to calculate the kinematic parameter, λ and for the determination of the bite length, for all test runs.

Preliminary data analysis also involved the determination of the average pull/push force generated by the rotavator during the tillage trial and the determination of the mean torque requirements. Owing to the high sampling rate used for capturing the tillage test run data and the many data files to be pre-processed, a third computer program was developed in MATLAB for calculating the average values for reaction forces and torque requirement transducer channels and the depth transducer. The calculated average channel values were then transferred to a special spreadsheet with corresponding columns for the recorded data. The average resultant push/pull force was determined from the summation of the three-point link forces.

MS Excel was used for the manipulation of the soil water content and bulk density determination data. The spreadsheets for the collection and processing of the data for soil water content and the bulk density were prepared in advance.

5.4.2 Statistical data analyses

A combination of graphical and statistical analyses was used to analyse the experimental and model generated data (Chapter 6). Minitab (*version 15, Minitab Inc., USA*) was used to effect the required statistical analysis. The different graphs required for both the model generated and the measured field experiments data is done using MATLAB. The analysis was done for the model input parameters, experimental results, and the validation and evaluation of the proposed model. Different statistical techniques, highlighted below were used as appropriate in effecting the required analysis.

The least squares linear regression technique is used to determine the soil shear and soil metal friction parameters at 95 % confidence interval (or 5 % significance level). MATLAB's Curve Fitting Toolbox is used in analysing all the data to be analyzed using the linear regression technique. For example this technique will be used to fit the normal stress data against the corresponding maximum shear stress for both the soil shear stress and soil-metal friction parameters for the soil at the experimental site. The resulting empirical equals will give the parameters for both the shear stress and soil-metal friction at the specified levels of the soil water content.

Analysis of some of the data required the determination of simple means. The versions of Minitab and MATLAB used to analyse the data in this study were both capable of calculating the simple mean. The mean of the soil bulk density from different depth ranges was a required model input and was also used to define the soil condition. Mean values of the horizontal resultant thrust force generated and the torque requirements for different experimental conditions are also needed in the evaluation of the field performance of the experimental deep-tilling rotavator.

In order to verify, validate and evaluate the model; a significance test is performed (§6.5.3) for the difference between the model and measured torque requirements values for different set tillage depths. The test statistic applicable in this case is the paired Student t-test (Levine, Ramsey & Smidt, 2000; Johnson, 2000; Montgomery & Runger, 2003) Using this approach, it is possible to compare the model generated and measured torque requirement values for the same angular blade positions during soil processing. Misczak (2005) used this statistical approach in a study that involved the comparison of the measured and predicted torque values for a rotary subsoiler at the same angular positions from the horizontal.

In addition to the t-test, a conformity test was effected between the model generated and measured torque requirement values. This test assessed the degree of agreement between the measured and the model generated torque requirement using the least squares linear regression technique (Equation (5.3)).

$$T_{\mathrm{model}} = \alpha_r + (\beta_r) \times T_{measured} \quad \text{... (5.3)}$$

Equation (5.3) is used (§6.5.3) to evaluate the degree of agreement between the model generated and the measured torque requirement values at different blade angular position. The α_r and β_r in Equation (5.3) are determined for the following null *(H_0)* and alternative *(H_1)* hypotheses:

$$\left.\begin{aligned} H_o &: \alpha_r = 0,\ \ \beta_r = 1 \\ H_1 &: \alpha_r \neq 0,\ \ \beta_r \neq 1 \end{aligned}\right\} \quad \text{... (5.4)}$$

This approach of the least squares regression technique has been used in the past by many researchers (Misczak, 2005; Zhang & Kushwaha, 1995; Swick & Perumpral 1988; Perumpral *et al.*, 1983) to compare the predicted and experimental (measured) data for tillage tools.

CHAPTER 6

RESULTS, ANALYSIS AND DISCUSSION

6.1 Introduction

A mathematical model for predicting torque and power requirements of a rotavator fitted with L-shaped blades was proposed in Chapter 3. Field experiments were done in order to assess the performance of the deep-tilling experimental rotavator for the 200 – 500 mm tillage depth range; and to validate and evaluate the proposed model. Rotavator performance field tests in this tillage depth range were necessary due to the dearth of information on the performance of this tool in deep tillage (see Chapter 2).

6.2 Experimental site soil characteristics

6.2.1 Soil shear strength parameters

Figure 6.1 is a typical graph used in this study for the determination of the soil shear strength parameters for the soil at the experimental site at a given depth and soil water content, using the approach described in §5.1.4. The graph includes a fitted least square linear regression line for the mean of the maximum shear stress values and the respective normal stresses. The graph and the fitted line were generated using MATLAB's graphics and Curve Fitting Toolboxes (MATLAB version 14, *Mathworks Inc., USA*). The least squares fit gives the values for the slope, the *y*-intercept coefficient, and the coefficient of determination (R^2). The 95 % prediction bounds included in this graph is used for the visualization of any outliers in the experimental data obtained. Points located outside such prediction bounds are outliers; and usually have significant effects on the outcome of a least squares regression analysis results. In order that the results are within the state range, all the data points must be located within the stated bounds. The 95 % confidence interval (CI) is recommended for tests involving least square linear regression analysis (Montgomery & Runger, 2003).

In Figure 6.1, the slope and intercept of such graphs define the tangent of the angle of soil internal friction and cohesion (Ayers, 1987; McKyes, 1989), respectively, in the Coulomb's equation (Equation 2.47, §2.2.5). Therefore, the Coulomb's shear stress equation for Figure 6.1 is of the form:

$$\tau = 15.8 + 0.8058\sigma_n \qquad \text{... (6.1)}$$

In Equation (6.1), the soil cohesion (C_c) for the soil tested is 15.8 kPa and the internal angle of friction of the soil, ϕ is given by the tangent of the coefficient of the normal stress, σ_n, i.e., $\phi = \tan^{-1}(0.8058) = 38.86^o$.

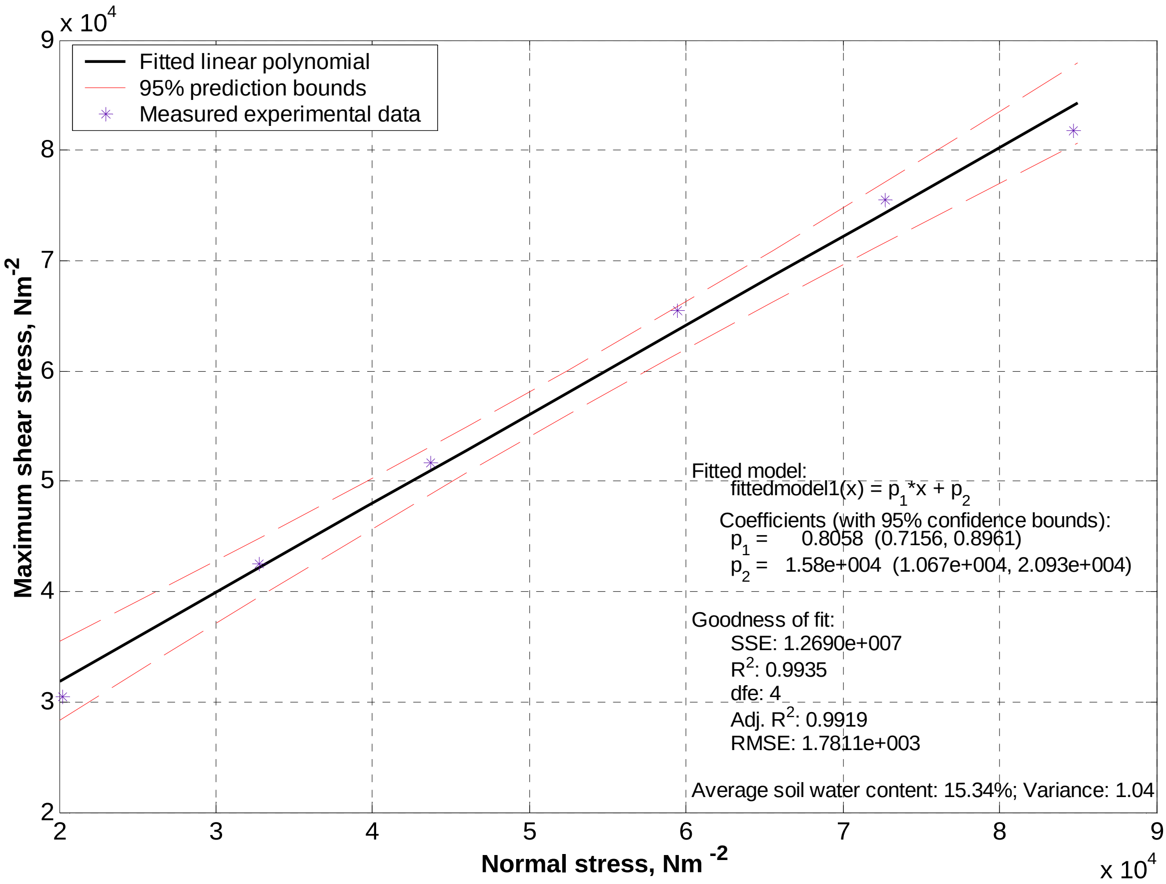

Figure 6.1: A typical graph of the average maximum shear stress versus the normal stress values at the soil-soil failure plane for the determination of soil shear strength parameters

6.2.2 Soil-metal friction parameters

The soil-metal friction parameters were determined using the method outlined in §5.1.5. Figure 6.2 is a typical graph of the average maximum frictional stress versus the normal stress for the soil at the experimental site at a given depth and soil water content. In this case, the slope and intercept for a graph of the average maximum friction shear stress against the normal stress defines the angle of soil-metal friction ($tan\,\delta$) and adhesion (C_a), respectively (Ayers, 1987; McKyes, 1989).

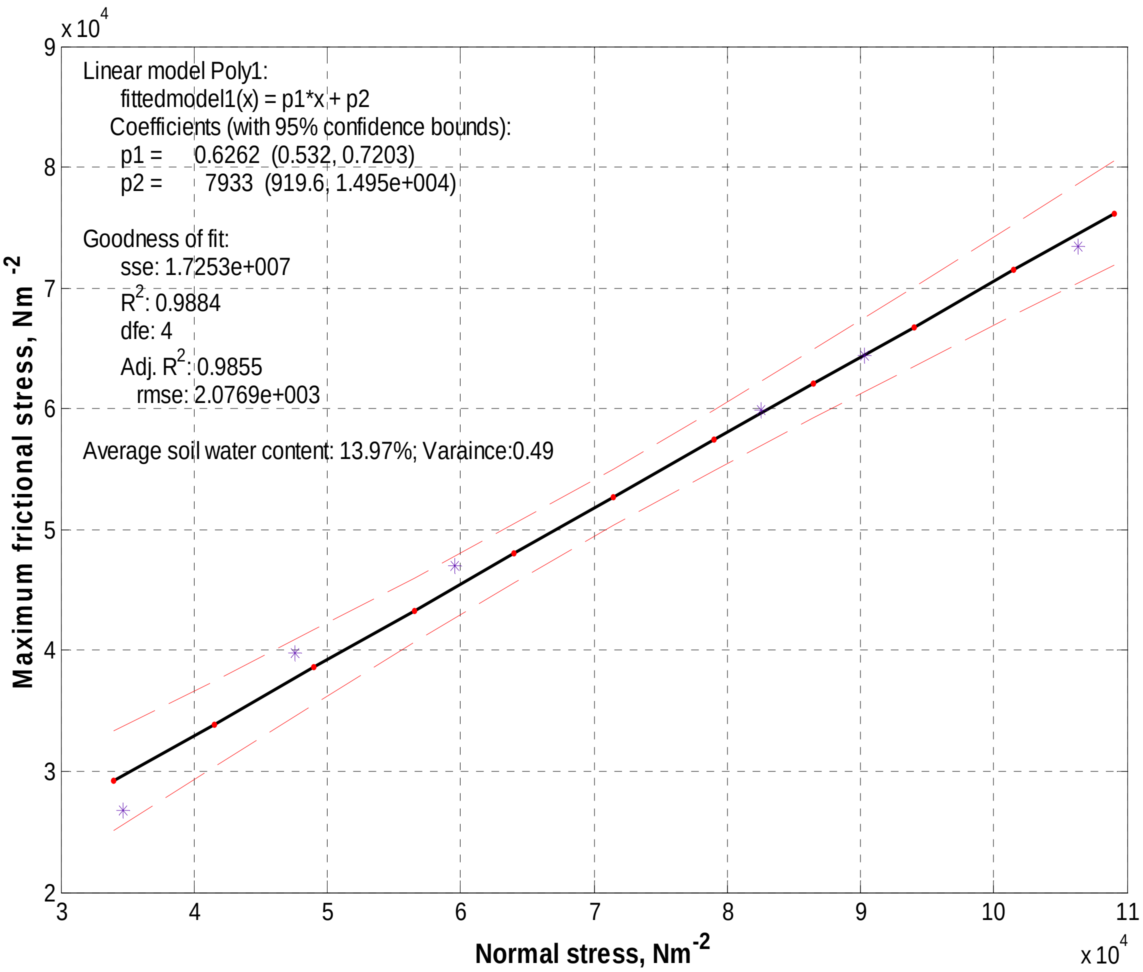

Figure 6.2: A typical plot of the average maximum frictional stress versus normal stress at the soil-metal failure plane (depth of 200 mm and 13.97 % soil water content)

The fitted least square linear regression line and the coefficient of determination (R^2=0.988) in Figure 6.2 indicate that a linear relationship fits the average maximum frictional stress and the normal stress data well. The Coulomb's equivalent expression for the soil-metal friction is of the form (Ayers, 1987; McKyes, 1989):

$$\tau_f = 7.933 + 0.6262\sigma_n \qquad \text{... (6.2)}$$

Using the approach of §6.1 and Equation (2.47), the soil-metal adhesion (C_a) at the stated soil condition (soil water content) is 7.933 kN/m^2. From the graph (Figure 6.2), the angle of the soil-metal friction is given by $\delta = \tan^{-1}(0.6262) = 32.06^o$.

From Figure (6.2) it is evident that the least squares linear regression technique can be applied to determine soil-metal friction parameters from the data collected using the torsional shear apparatus (§4.2). The results obtained returned a high value of the correlation coefficient *(R^2 = 0.9884)*. In addition, all the data points for the respective paired normal and soil-metal friction are within the 95 % prediction bounds. The high R^2 value and location of the data points within the 95 % prediction bounds indicated that the parameters obtained were statistically acceptable for the estimation of the soil-metal friction parameters. Therefore, the soil-metal friction parameters could be used with confidence as inputs to the proposed rotavator torque requirements model.

6.2.3 Soil texture and bulk density

Results of the standard sieve analysis obtained using the method described in §5.1.1 indicate that the soil within the top 600 mm contained 25 % clay, 11 % silt and 64 % sand. Using the USDA soil classification textural triangle for soil mixtures, the results indicate that the soil at experimental site is *sandy clay loam* (McKyes, 1989).

Table 6.1 gives a summary of the soil water content and the bulk density of the soil at the experimental site for the different depth ranges determined using the approaches described in §5.1.2 and 5.1.3, respectively. The analysis of variance (ANOVA) performed on the data (Tables 6.2 & 6.3) indicated that the soil bulk density and soil water content within the different depth ranges were statistically different. The respective mean values for the different depths are 11.86 % (± 0.86); 13.77 % (± 1.36) and 16.51 % (±1.52). The corresponding average soil bulk density within the depth ranges are 1804.6 kg/m^3 (±

53.9) for depths less than 150 mm, 1715.0 kg/m^3 (± 71.1) for the 150 – 300 mm, and 1625.0 kg/m^3 (± 25.7), respectively. The difference in the average bulk density and the soil water content is attributed to the drying of the soil which is more pronounced in the shallow depth ranges. The decrease in the soil bulk density with depth was therefore attributed to the increase in the soil water content with depth.

Table 6.1: Summary of the soil water content (swc) and soil bulk density results for different depth ranges at determined 48 hour intervals after stopping irrigation

Depth < 150 mm		150 mm < Depth < 300 mm		Depth > 300 mm	
swc (%)	density kg/m^3)	swc	density (kg/m3)	swc (%)	density (kg/m^3)
10.74	1886.53	11.96	1664.47	15.36	1621.30
11.31	1749.61	12.13	1833.25	15.53	1592.52
11.66	1749.61	14.32	1766.40	15.95	1640.48
11.94	1805.97	14.80	1705.24	16.61	1611.70
12.24	1844.35	14.91	1662.31	17.09	1658.87
13.26	1791.58	14.94	1667.47		

The observed higher values of soil bulk densities for correspondingly lower values of the soil water content (Table 6.1) was attributed to fact that drying of a soil results in more solids (soil) particles occupying the same volume. Since the soil particles are heavier than water, the drying of a soil results in increased mass of the soil occupying the same volume, e.g., the soil bulk density test apparatus used in this study. The systematic decrease in the soil bulk density with deeper depth ranges is due to the systematic differential drying rates of the soil for different depth ranges. The decrease and increase of the soil bulk density and soil water content, respectively, with depth within different depth ranges has been reported by other researchers (Gitau, *et al.*, 2005; Girma, 1989) for clay loam soils.

Table 6.2: Summary of ANOVA test performed on the soil bulk density for the different depth ranges

Source	Df	SS	MS	F	p-value
Depth	2	88249	44125	14.57	0.000
Error	14	42390	3028		
Total	16	130639			

Table 6.3: Summary of ANOVA test performed on the soil water content for the different depth ranges

Source	Df	SS	MS	F	p-value
Depth	2	49.25	24.63	22.92	0.000
Error	14	15.04	1.07		
Total	16	64.30			

6.3 Measured forces and torque requirements

One of the specific objectives of this study was to measure the torque requirements and determine the magnitude of the resultant thrust forces generated under field conditions for an experimental deep-tilling rotavator, operated in both the up- and down-cut directions of rotation. Preliminary field tests done for assessing this objective indicated that the up-cut rotary tillage left an open furrow, which was considered undesirable for the preparation of a seedbed. As a result of this observation, no further field tests were done in the up-cut directions for the determination of torque requirements and thrust forces generated for the experimental deep tilling rotavator.

This section, therefore, presents the results of the measured torque and horizontal forces on the tractor three-point links for the experimental deep-tilling rotavator operated in the down-cutting direction of rotation. A typical output of the response curves for the torque and the forces recorded on the top and the two lower tractor links for a given experimental condition is presented in Figure 6.3. Two distinctive sections of the measured torque and horizontal forces on the tractor links are shown in Figure 6.3. Sections A and B, respectively, are for measurements recorded when the rotavator was stationary and when processing the soil.

The torque and force values in section A (Figure 6.3) were expected to be zero. A scrutiny of this section, however, reveals that only the torque and the lower left link force values measured had the expected zero values in this section. The top link and lower right link transducers recorded values that were slightly greater and slightly lower than zero, respectively when the system was not subjected to tilling or soil processing forces. The effect of this 'non-zero' values at no load is however insignificant when compared to the magnitudes of the average of the forces recorded by the respective channels, during soil processing by the rotavator. The average force and torque requirements recorded when the rotavator is processing the soil, are the parameters used in this study to assess the performance of the experimental deep-tilling rotavator.

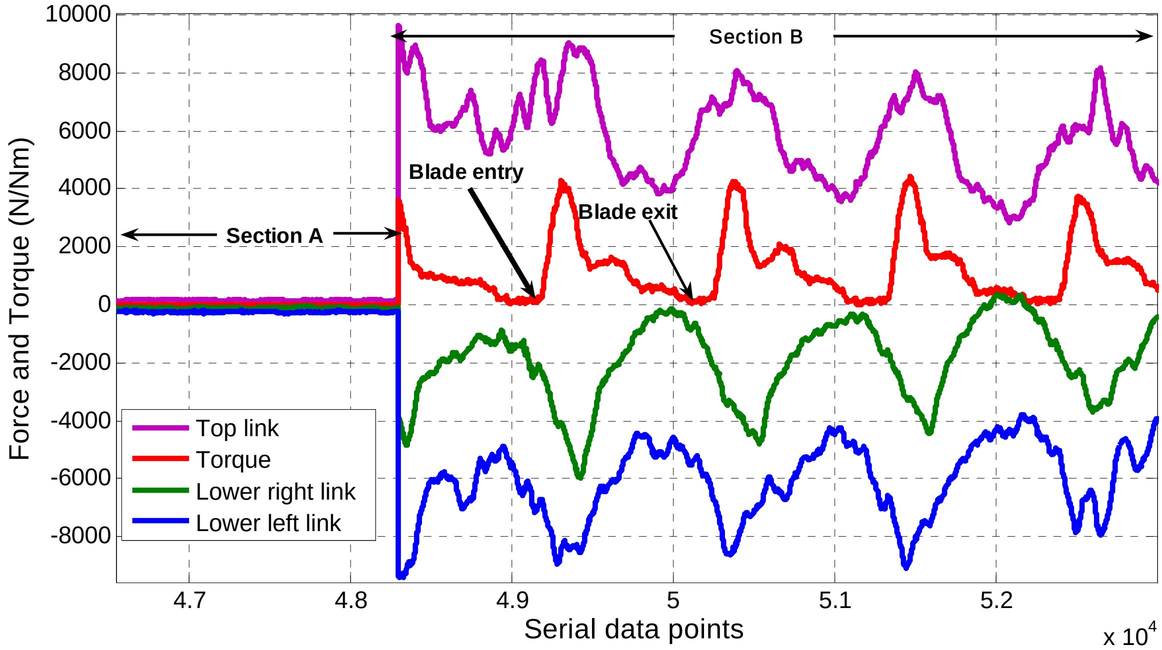

Figure 6.3: A section of the measured torque and horizontal forces on the top and lower links (A – rotavator is stationary; B – rotavator is processing the soil)

A strong association was observed between the values of the torque requirements and the individual horizontal reaction forces on the three links (Figure 6.3). This observation was such that upon the initiation of the soil cutting action by the blade, as the torque requirement, and the horizontal reaction forces at the top and the lower links are also increased with time for individual blade. Considering the processing of the soil by a blade, it is observed that the peak values in torque requirements and the respective horizontal forces measured on the three point links of the tractor occured at the same time.

Considering the torque response curve for a single blade only (Figures 6.5), the measured torque values increased rapidly at the commencement of the soil cutting, reaching a peak and then decreased gradually, to a minimum value at the end of soil cutting process. The rapid increase in torque values at the commencement of soil cutting is an indication of high resistances offered by the soil to the cutting blade upon the blade entry into the soil. The forces that contribute to this high resistance include the cutting and soil compression resistance, resistance due to soil shear strength and the soil-metal friction resistance between the blade and the soil. The decrease in the magnitude of the torque values after reaching the peak is attributed to the decreasing soil resistance due to the decreasing cross section of the cut soil slice as the blades moves through the soil (§3.2.4 & 3.2.5), and the continuous decrease in the rake angle of the blade.

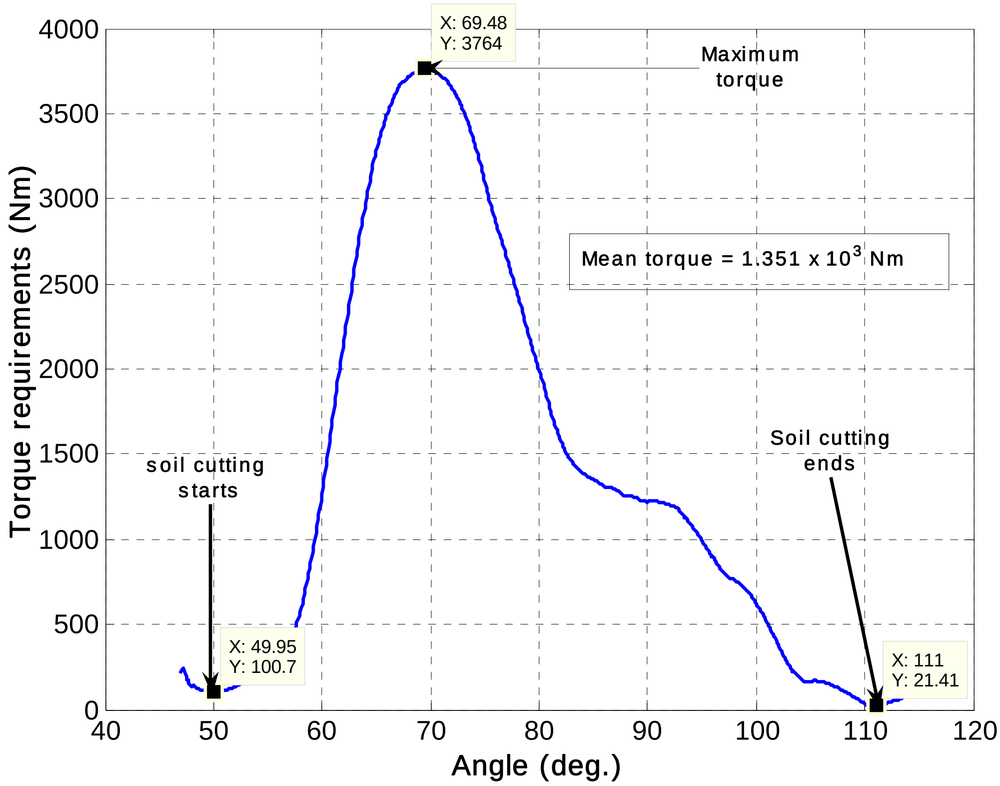

Figure 6.4: Typical variation of torque requirements with rotational angle for a single blade between the start and end of soil cutting process *[X-value = angle turned through by the rotavator blade from the horizontal position; Y-value = torque requirement value at position X]*

At the end of the soil cutting process by a single blade and before the start of soil cutting by a subsequent blade, the torque requirement values recorded/measured should be zero. However, measurement taken during rotary tillage test trials with the experimental rotavator show that the rotavator requires some torque, even when there is no blade cutting the soil (Figures 6.3 & 6.4). This observation was attributed to the presence of friction and other parasitic forces in the rotor assembly of the experimental rotavator.

The somewhat greater than zero torque requirement values recorded in-between successive blade cutting operations is associated with the turning effort required to overcome motion resistance of the rotor assembly, and to overcome the intrinsic parasitic forces in the rotavator assembly.

The response curves for the forces recorded on the top and the two lower links (Fig. 6.6) indicates that these forces are in opposite directions. Subsequently, at an instantaneous moment of time, the direction and magnitude of the resultant horizontal force is the difference between the sum of the forces on the two lower links and the force on the top link. Depending on the magnitudes of the respective instantaneous time moment forces in the three links, the resultant force can be positive or negative with respect to the forward travel direction of the rotavator.

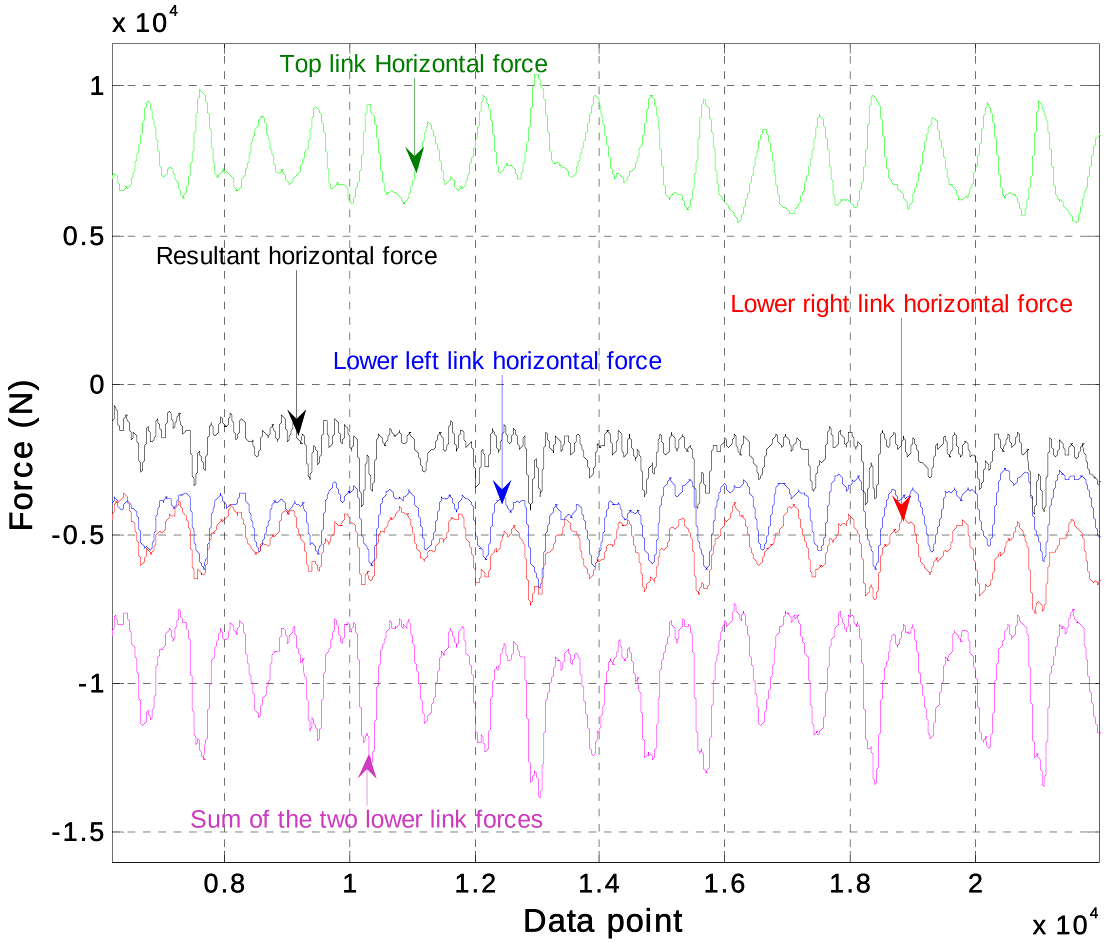

Figure 6.5: A section of a graph showing the variation of the horizontal forces recorded on the three links, the sum of the lower link forces and the resultant horizontal thrust force

At any instantaneous time moment, if the instantaneous time moment sum of the forces on the two lower links is greater than the instantaneous time moment force on the top link, the instantaneous time moment resultant force exerts a push. Similarly, if the instantaneous time moment force on the top link is greater than the sum of the instantaneous time moment forces on the two lower links, the instantaneous time moment resultant force exerts a draft or a pull force, like is the case, with passive tillage tools.

The magnitudes of the measured reaction horizontal forces on the two lower links were unequal (Figures 6.4 & 6.6). The horizontal force on the lower left link, on average, was about twice that on the lower right link. This difference was due to the unequal distances from the centre of the cutting force to the points at which the strain gauges measuring the thrust forces are placed on the tiller tool-frame. This observation, however, has no effect on the magnitude of the resultant thrust force generated during the operation of the experimental rotavator. The magnitude of the thrust force generated was the instantaneous difference between the instantaneous sum of forces of the two lower links and instantaneous force on the top link.

In Figure 6.5, the resultant force is a push, since the sum of instantaneous forces recorded by the two lower links is greater than the force recorded by the top link. The direction of the resultant horizontal force is important in the performance of rotary tillage tools because it affects the energy requirements during the tool's tillage operation. Consequently, in this study, the magnitude of the resultant thrust force and torque requirement was used to assess the performance of the experimental deep-tilling rotavator for different sets of operational conditions (§6.4 below).

6.4 Performance evaluation of the experimental rotavator

Literature reviewed (Chapter 2) revealed that there is dearth of information on the performance of the rotavators in deep tillage, i.e., tillage at depths greater than 200 mm. Consequently, field experiments were done to evaluate the performance of the experimental rotavator described in Chapter 4 in the 200 mm – 500 mm tillage depth range. The performance factors measured were the torque requirements and the resultant horizontal force generated for the following rotavator operational conditions:

- Effect of depth at a constant kinematic parameter, λ, on the torque requirements and the resultant horizontal force generated
- Effect of bite length, i.e., different values of the kinematic parameter, λ, on torque requirements and the resultant horizontal force generated.

6.4.1 Effect of set tillage depth at constant kinematic parameter, λ

Figure 6.6 shows the variation in torque requirements curves for single cutting blades at tillage depths of 250 mm, 300mm and 450 mm. These curves indicate that rotavator torque requirements increase with the tillage depth. In terms of the rates of increase, it is apparent from the curves that torque requirements increase at a rate higher than the rate of increments in depth. A number of previous researchers (Hendrick & Gill, 1971a; Shibusawa, 1993; Manian & Kathirvel, 2001) made similar observations for rotavators operated within the 'normal' set tillage depth range, i.e., set tillage depths not exceeding 250 mm.

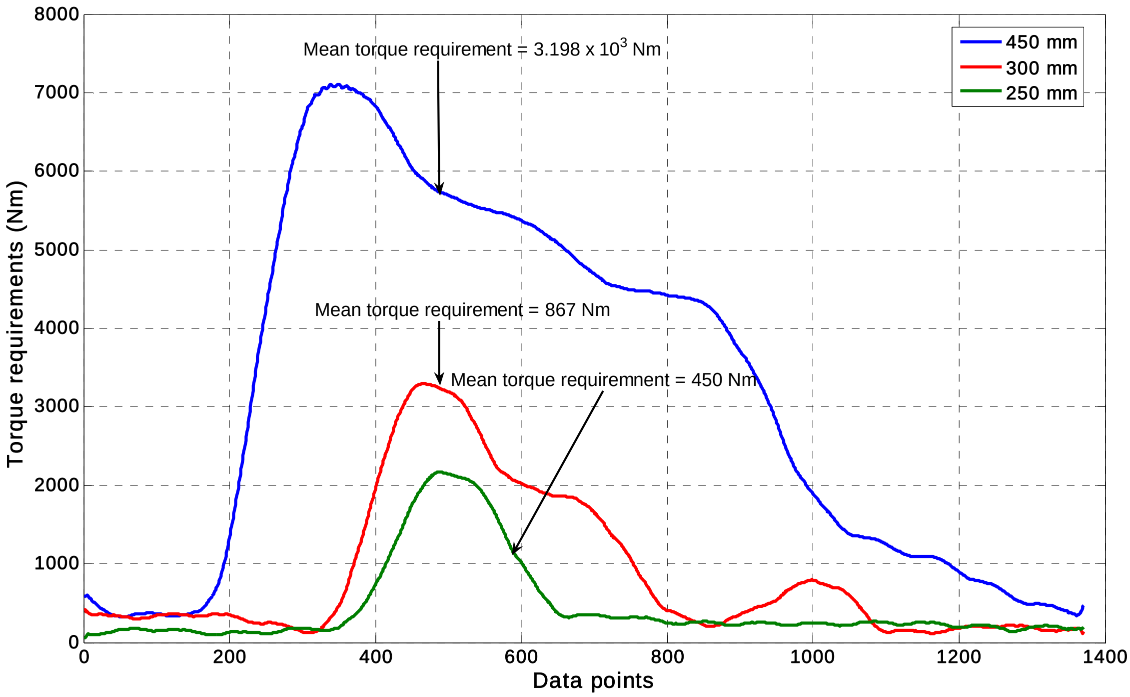

Figure 6.6: A graph showing the typical effect of depth on torque requirements for a down-cut tillage test-run for a given soil condition and fixed kinematic parameter, λ

Table 6.4 is a summary of the percentage increments in depth and associated mean torque requirements for the single blade data presented in Figure 6.6. From this data, excessive torque requirements accompany relatively small increments in the depth of tillage. This observation is consistent to that made by other researchers (Hendrick & Gill, 1971a; Shibusawa, 1993); and is responsible for the lack of adoption of the rotavator as an alternative primary tillage tool (Marenya, du Plessis & Musonda, 2003).

The causes of this excessive energy consumption by rotavators in deep tillage are many and varied, but the reported studies did not attempt to address them. The objective of such studies focused on the comparison of energy demanded or consumed by different primary tillage tools under specified conditions. In this study, the causes of the excessive energy consumption by the deep-tilling experimental rotavator were addressed by an analysis of the theoretical equations and the rotary motion of the rotavator during tillage. In this regard, two physical factors are considered to be responsible for observations made regarding the effect of tillage depth on torque requirements. These two physical factors are the tilling route length and the volume of the soil processed by a rotavator blade for different set tillage depths.

Table 6.4: Comparison of the percentage increases in depth and mean torque requirements for a fixed rotavator configuration and operational conditions; and a fixed soil condition

Tillage depth		Torque requirements	
Depth, mm	% increase	Mean torque requirement, Nm	% increase
250	0	450	0
300	20	876	93
450	80	3198	611

Increasing the set tillage depth, resulted in increased tilling route length and increased volume of soil processed by a blade. The increase in torque requirement values with increasing depth is possibly caused by the increase in both the tilling route length and the volume of the soil chips cut by a blade. As the set tillage depth is increased, both the tilling route length and the volume of the cut soil chips increased at constant kinematic parameter, λ.

The increase in the volume of cut soil slice is caused by the increase in depth (Equation 3.33) since the width of the blade (*w*) and the bite length (L_b) are fixed at a given level of the kinematic parameter, λ. Increasing the depth of tillage also decreases the angle (α_i), from the horizontal position, at which the blades starts cutting the soil, while increasing the angle at which the soil cutting stops (α_e). This results in increased length of cut (the tilling route length) as given by Equation (3.40). For the results presented in Figure 6.6, the increase in the tilling route length is reflected in the form of the increasing range of data points over which the values of torque is substantially greater than zero for different depths of tillage.

6.4.2 Effect of the bite length

The different bite lengths, L_b, were calculated using Equation (3.8) with three and six blades on the same side of the flange for two forward travel gears. The two forward travel gears resulted in two different forward speeds, V_f. Since the rotavator rotational speed was fixed, the combination of the two forward travel speeds and the two sets of the number of blades on one side of the flange, resulted in four different values of the kinematic parameter, and hence four different bite lengths. The forward travel speeds and the rotational speed used to calculated the different bite length using Equation (3.8) were presented in §5.2.2 The calculated bite lengths for the four different values of the kinematic parameter λ, are given in Table 6.5.

Table 6.5: Calculated bite lengths for different number of blades on the flange, *z* and the forward travel speeds, V_f

Combination of number of blades and forward travel speed	Bite length, m
1. Forward travel on gear I and 3 blades on the flange	0.323
2. Forward travel on gear I and 6 blades on the flange	0.162
3. Forward travel on gear II and 3 blades on the flange	0.392
4. Forward travel on gear II and 6 blades on the flange	0.196

The field experiments for investigating the effect of the bite length were done as outlined in §5.3.2. Figure 6.7 shows the variation of torque requirements for bite lengths of 0.323 m and 0.162 m (Table 6.5), respectively, with the rotavator traveling at a forward speed of 0.425 m/s (§5.2.2) ,and processing the soil at a set tillage depth of 250 mm. The comparison of the mean torque requirement values for the two bite lengths at the tillage depth of 250 mm indicate increasing the bite length by 0.162 m, resulted in more than 100 % increase in the mean torque requirement value for the experimental rotavator.

The observed effect of changing bite length on the torque requirement can be explained by Equation (3.20) and Equation (3.33), since they relate the area of the cross-section and volume, respectively, of the soil slice cut by a blade to the bite length. From these expressions, changing the bite length by either reducing the number of the blades on the flange, or increasing the forward travel speed, while holding the rotor rotational speed constant results in increased cross-section area and volume of the soil slice processed by a blade. The increase in cross-sectional area and greater volume of the processed soil translates to greater torque requirements and longer time durations during which a blade processes the soil.

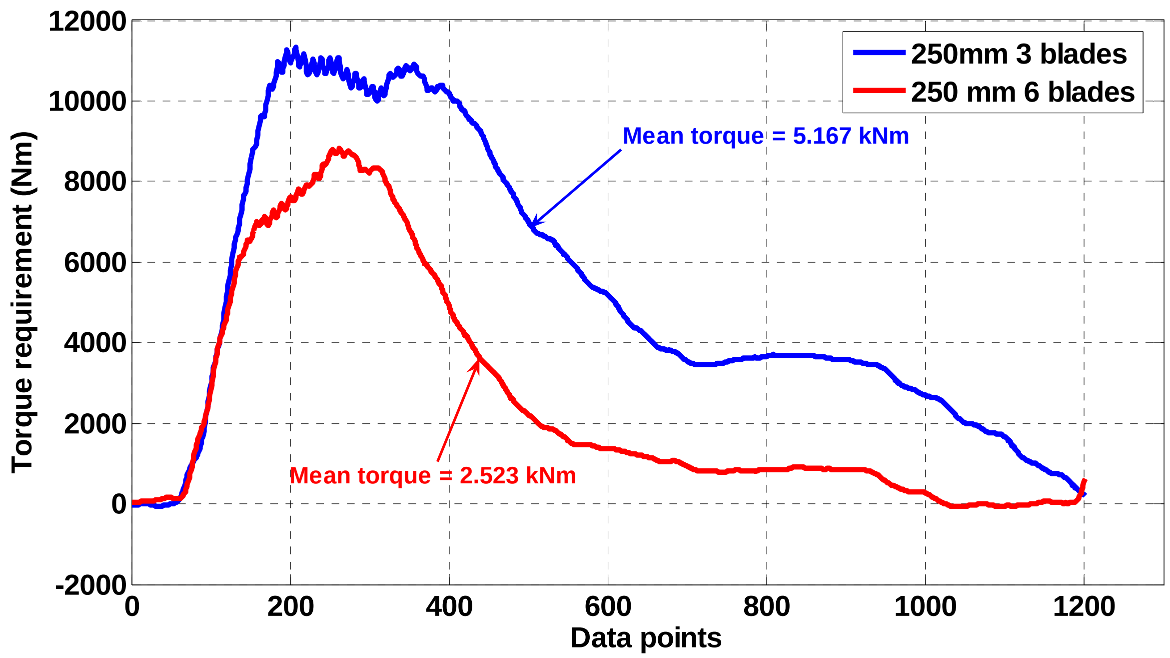

Figure 6.7: Effect of bite length on torque requirements

The sensitivity of torque to changing bite length, necessitates for a tighter control of this parameter in rotavator tillage. Since under practical conditions, the number of blades on a flange, depth of tillage and the rotational speed of the rotor can be held constant, the only possibility of changing the bite length during rotavator tillage is by operating at a varying forward travel speed. Lack of operating at the desired constant forward travel speed also results in tilth quality changes. This is because changes in forward travel speed results in changes in the resulting clod size and its distribution. Consequently, it is crucial that rotavator prime-movers are operated at a uniform forward travel speed in order to control both the torque requirement and the resultant tilth quality.

6.4.3 The generated resultant horizontal force

The magnitude of the thrust or pull forces generated is important in analyzing the overall power requirements and performance in rotavator tillage operations. This is because the resultant horizontal thrust force generated may assists in the traction of the prime mover. In the literature reviewed there was no information on the variation of the resultant horizontal forces generated for different rotavator configurations and tiller operational conditions. In addition, the literature reviewed revealed that studies on rotavator tillage has been limited to a tillage depth of 300 mm or less. This section, therefore, presents and analyzes the data on the thrust forces generated by the experimental rotavator in the 200 mm – 500 mm depth range i.e., deep tillage.

Figure 6.8 shows the variation of the magnitude of the resultant thrust forces generated for different bite lengths and different set rotavator tillage depths, for field experiments conducted on the same date. The purpose of conducting these experiments on the same date was to ensure that all the tests, for analyzing the resultant generated thrust, were done at approximately the same soil condition; which in this study was defined by the soil water content. The soil water content affects the soil dynamic and strength parameters (Marenya & du Plessis, 2006).

In Figure 6.8, the resultant horizontal thrust force generated for each combination of forward travel gear and number of blades on the rotor, increased with depth to a maximum value, and thereafter decreased with increasing set tillage depth. The depth at which the maximum generated horizontal thrust force occurred, is dependent on combination of the number of blades on the rotor and the forward travel speed, determined by the forward travel gear. The combination of these two parameters determines the bite length; and therefore, bite length has significant influence on the resultant thrust forces generated. Increasing the bite length, resulted in a decrease in depth, at which the maximum resulted horizontal thrust forces generated occurred.

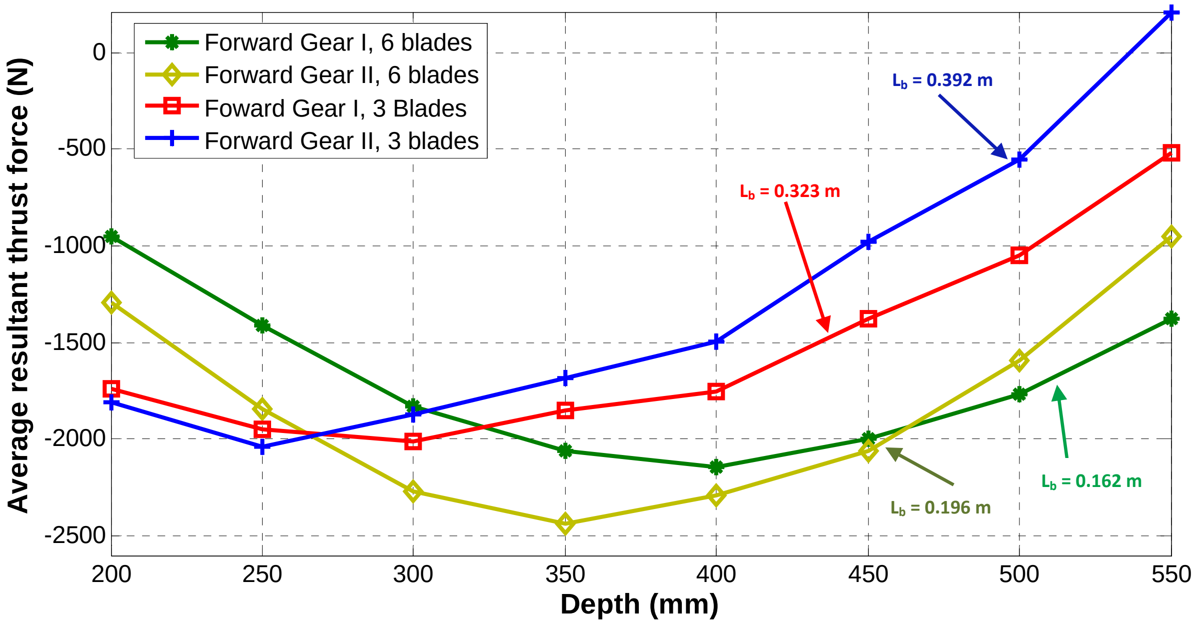

Figure 6.8: Variation of the resultant horizontal thrust forces generated at different tillage depths and different bite lengths at a constant soil condition (soil water content of 13.97 %)

The decrease in the magnitude of the maximum horizontal thrust force generated show that for the experimental blade used in this study, there exist a bite length at which increasing the set tillage depth will be accompanied by a decrease in the magnitude of the resultant horizontal thrust force. The respective curves (Figure 6.8) for the different rotavator operational parameter combinations indicate that there exists a set tillage depth at which the generation of the forward thrust force ceases. The results further indicate that as the set tillage depth increased, the magnitude of the resultant horizontal thrust generated decreased, and that operating the rotavator at increasingly deeper set tillage depths, may result in the exertion of a draft force instead. For example, operating the experimental operation on forward travel gear I with three blades on the same side of the flange at a set tillage depth of 550 mm, resulted in a draft force being exerted, on the prime-mover by the rotavator. A similarly shaped curve was obtained by Hendrik (1980) for draft power in a study of a powered rotary chisel for the downward direction.

6.4.4 Analysis of torque and power requirements

The reviewed literature (Chapter 2) indicated lack of information on torque and power requirements of rotavators at set tillage depths greater than 250 mm. Accordingly, one of the objectives of this study was to characterize the torque and power requirements of rotavators at set tillage depths in excess of 250 mm. This section reports the findings of the measured experimental results, undertaken with the experimental rotavator described in Chapter 4. Both the rotary and the linear power requirements, which constitute the total rotavator power requirements were calculated for a given soil condition and different rotavator configurations and operational parameters.

The rotary power requirement at a given depth and level of the kinematic parameter, λ was calculated using Equating (6.1).

$$P_{sp} = T\omega \qquad \text{... (6.3)}$$

where:

P_{sp} = average power requirement for processing the soil (kW)

T = average torque requirement (kNm)

ω = average angular velocity (rad/s)

The power due to the resultant horizontal force was also determined for each field test using the standard force-velocity relationship (Srivastava, *et al.*, 1993; Goering, 1992). The volumes of soil slices cut by individual blades for different rotavator operational conditions tested in this study are presented in Table 6.6. The calculation of the soil slice volumes was done using Equation 3.35 (see §3.2.6), which approximates the actual volume of the soil slice volumes cut by individual rotavator blades. As expected, tillage depth had a direct and significant influence on the volume of soil processed for constant kinematic parameter levels.

Table 6.6: Theoretical actual soil chip volumes processed by the experimental rotavator for different experimental setups

Tillage depth (mm)	Soil volume processed (m³)			
	$\lambda_I = 6.026$		$\lambda_{II} = 4.944$	
	6 blades	*3 blades*	*6 blades*	*3 blades*
250	0.0032	0.0065	0.0039	0.0078
300	0.0039	0.0078	0.0047	0.0094
350	0.0045	0.0091	0.0055	0.0109
400	0.0052	0.0103	0.0062	0.0125
450	0.0058	0.0116	0.0070	0.0140
500	0.0065	0.0129	0.0078	0.0156
550	0.0071	0.0142	0.0086	0.0172

Table 6.7 presents a summary of the results obtained for using the approach highlighted above. The calculated parameters for analyzing the performance of the experimental deep-tilling rotavator included the average linear power generated by the resultant horizontal thrust force, the rotary power required for processing the soil slice, and the specific energy requirements at different depths for different tests. In order to provide a basis for comparing the specific energy requirements of this tool with other tillage tools, its specific energy requirements were determined. Specific energy requirements is a standard approach for comparing the energy performance of tillage tools (Gill & Van den Berg, 1967). In this study, the specific energy requirements were expressed in terms of the energy units per volume of the soil processed.

The power performance of the experimental tiller was determined by calculating the rotary and linear power requirements (see §3.4). The specific rotary tillage energy was calculated from the rotary power by determining the energy required for 10 complete revolutions for different conditions and then dividing this by the total volume of the soil processed. The total volume was obtained as the product of the number of blades on the flange and the respective theoretical volumes presented in Table 6.6 for a particular set tillage depth, multiplied by the number of complete revolutions.

The results presented in Table 6.7 indicate that increasing both the set tillage depth and bite length, influences the rotary power requirements and the specific energy. In general, change in bite length has a greater influence on power requirements and specific energy than the change in set tillage depth. These findings are consistent with those of previous researchers (Salokke & Ramalingam, 2001; Balock *et al.*, 1986; Bukhari *et al.*, 1996; Shibusawa, 1993) for relatively shallow tilling rotavators. A comprehensive review on literature, particularly from the then USSR by Hendrick and Gill (1971b) also revealed that both the set depth of tillage and the bite length affects the power requirements and the specific energy.

Table 6.7: Summary of average thrust, torque, power requirements, and specific energy requirements for down-cut deep rotary tillage test-runs (soil water content of 13.97 %)

Rotavator configuration (Travel gear and number of blades on the flange)	Depth (mm)	Thrust (N)	Torque (Nm)	Power requirements (kW)		Specific energy (kJm^{-3})
				Linear	Rotary	
1. Forward gear I with six (6) blade on the flange	200	- 936	360	- 0.398	0.991	105.554
	250	- 1409	401	- 0.599	1.104	117.734
	300	- 1807	581	- 0.768	1.600	107.604
	350	- 2092	632	- 0.889	1.741	135.117
	400	- 2100	870	- 0.892	2.396	127.192
	450	- 2020	941	- 0.856	2.591	156.978
	500	- 1798	1130	- 0.764	3.112	151.504
	550	- 1415	1318	- 0.601	3.629	166.559
2. Forward gear II with six (6) blades on the flange	200	- 1295	604	- 0.667	1.663	187.109
	250	- 1945	712	- 1.002	1.960	191.057
	300	- 2497	975	- 1.286	2.685	217.097
	350	- 2890	1062	- 1.488	2.924	202.073
	400	- 2905	1462	- 1.496	4.026	246.776
	450	- 2783	1581	- 1.433	4.360	236.663
	500	- 2478	1902	- 1.276	5.235	255.056
	550	- 1947	2211	- 1.003	6.083	268.810
3. Forward gear I with three (3) blades on the flange	200	- 1736	960	- 0.738	2.643	327.657
	250	- 1946	1059	- 0.827	2.999	350.664
	300	- 2010	1512	- 0.854	4.164	405.728
	350	- 1851	1685	- 0.786	4.640	387.557
	400	- 1750	2409	- 0.743	6.634	489.528
	450	- 1379	2509	- 0.586	6.909	452.710
	500	- 1050	3031	- 0.446	8.297	488.863
	550	- 517	3552	- 0.220	9.782	523.555
4. Forward gear II with three (3) blades on the flange	200	-1805	1598	- 0.930	4.397	615.145
	250	-2040	1820	- 1.051	5.008	642.133
	300	-1870	2555	- 0.963	7.031	717.486
	350	-1686	2778	- 0.868	7.645	707.381
	400	-1495	3998	- 0.769	11.002	880.200
	450	-979	4212	- 0.504	11.591	827.959
	500	-549	5063	- 0.283	13.933	893.165
	550	210*	6036	0.108	16.611	965.760

* - For this setting, a draft force is exerted on Tractor 2

The greater influence of changes in bite length on the specific energy is attributed to changes in several factors that lead to the increase in volume of the cut soil slices. Changes in bite length have significant effects on the tilling route length, the maximum soil chip thickness, and the absolute velocity of the rotor blade tip. All these three factors individually affect the torque requirement and therefore any changes in bite length, in combination with any of them, would significantly impact the rotavator torque and power requirements. From Table 6.6, change in volume of the worked soil, owing to increase in depth, is relatively small in comparison to the change in the worked volume due to bite length changes. Hence change in torque and power requirements owing to changes in depth, in general are lower than changes due to an equivalent change in bite length.

The foregoing analysis indicate that changing bite length affects a number of factors with a combined effect of greater torque and power requirements when compared to changes in depth for a fixed level of the kinematic parameter, λ. Thus, it is important that the kinematic parameter is maintained constant after the set tillage depth at which the rotavator is to be operated at, has been decided. As is evident from the presented results, any change in the kinematic parameters would result in increased torque and power requirement of rotavators. However, the findings indicated that minor changes in depth, for example due to unevenness of the ground surface can be tolerated well in rotavator tillage. It is therefore vital that the ratio of the forward travel speed to the rotational speed, which determines λ, is maintained constant throughout a rotavator tillage operation.

6.5 Model verification and validation

The proposed analytical model (Chapter 3) is validated by comparing the measured and calculated (model generated) torque requirements. Owing to the complexity of the calculations required to calculate a single torque requirement value at a specified rotavator blade position from the horizontal ($\alpha = 0°$, Fig. 3.11), a computer program based on the developed mathematical expressions (§3.4) was coded in MATLAB

(*Mathworks Inc., USA*) to solve the model. The steps used in this process and the resulting outputs obtained are presented in the subsequent subsections.

6.5.1 Model inputs

The model inputs required to calculate the torque requirements were identified in §3.4. They can be categorized into two types, namely 'constant' and 'varying' inputs. The constant model inputs remain unchanged, whereas the varying inputs change with regard to the position of the blade from the horizontal position during the rotavator operations. The constant and varying model inputs were derived from both the soil and rotavator operational parameters.

The constant model inputs that are dependent on the soil type and condition were further categorized as soil or rotavator input.

- o Inputs that are dependent on the soil condition, i.e., the soil water content. These include the soil strength parameters of cohesion, internal angle of friction, soil/metal adhesion, soil and metal friction angle, soil bulk density, and the calculated dimensionless N-factors, i.e. $N_c^{'}$ and $N_q^{'}$. The N-factors were determined using the graphical approach (Godwin & Spoor, 1977). Variation of these factors with the internal angle of friction is presented in Figure 6.9.

- o Input variables obtained by measurement of different rotavator dimensions or predetermined levels, and remain constant throughout a rotary tillage process. These include input variables such as the set tillage depth and pertinent rotavator dimensions including the rotavator radius, blade cutting width, and blade thickness.

- o Rotavator operational inputs that remain unchanged during rotary tillage operations. These include the set depth of tillage, the forward travel and the rotor rotational speeds, the bite length, blade thickness, the number of blades on the rotavator flange, and the kinematic parameter, λ.

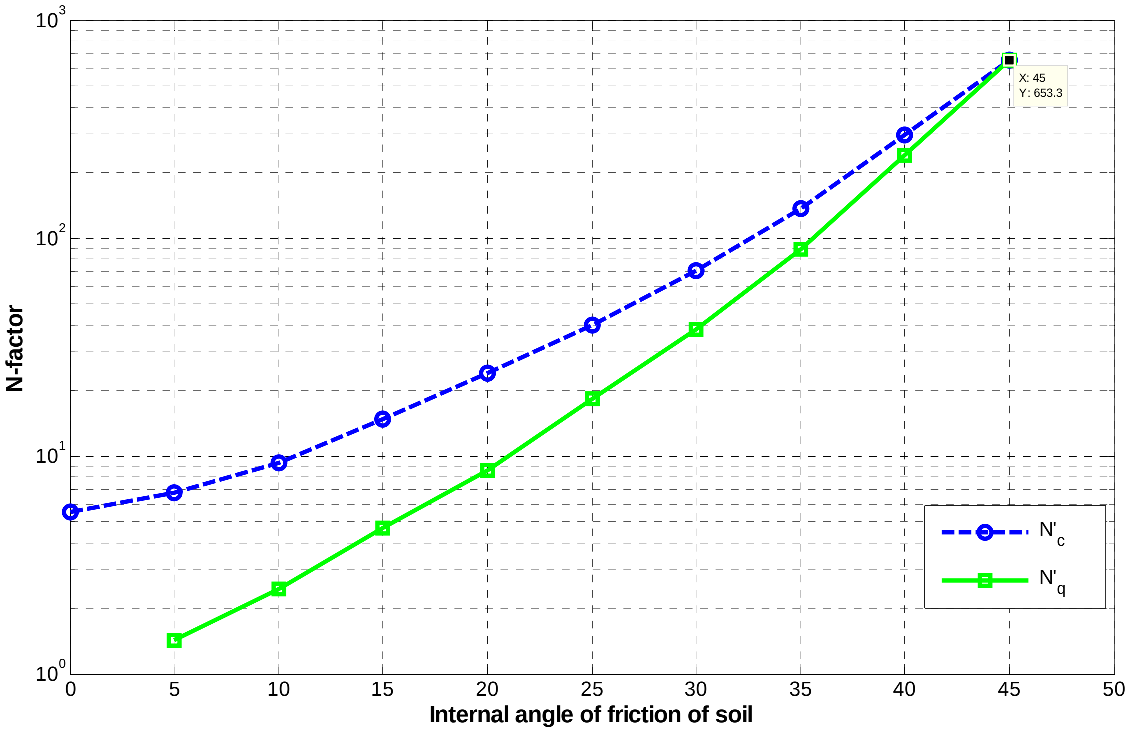

Figure 6.9: Graph used for the determination of dimensionless N-factors for lateral soil failure (Godwin & Spoor, 1977).

Table 6.8 gives the constant model input variables; their notations and numerical values assigned to the respective variables. Owing to the sensitivity of the soil related inputs to the soil water content, all the 'constant' model input variables affecting the soil's strength and dynamic parameters were determine at an overall average soil water content level of 13.97 %, for the 200 – 550 mm tillage depth range. The 13.97 % was the average soil water content, at the experimental site, at which the field experiments for assessing the performance of the experimental deep-tilling rotavator were undertaken.

The varying model inputs arise from the varying portions of the blade that interact with the soil between the angle of blade entry and exit during rotavator tillage (Figure 3.10). This soil-blade interaction results in the change of the values of the rake angle (β) and the rupture angle (ρ) as shown in Figure 3.15 and Figure 3.16 in §3.4.2. These two angles vary with the position of the rotavator blade from the horizontal position (Figure 3.11) during the soil cutting process. At any position from the horizontal, the blade rake angle for the span of the L-shaped blade was given by Equation 6.4.

$$\beta = 2\pi - \left(\alpha + \frac{\pi}{2}\right) \tag{6.4}$$

Table 6.8: Listing of the model input variables and their assigned values

Description of the model input variable	Notation	Value(s)
Soil dynamics and strength parameters:		
Angle of internal soil friction (°)	ϕ	38.86
Soil cohesion (kN/m²)	C_c	15.8
Soil-metal friction angle (°)	δ	32.06
Soil-metal adhesion (kN/m²)	C_a	7.93
Set depths of tillage (m)	d	0.250, 0.350, 0.500
Soil bulk density (kN/m³)	γ	17.200
Rotavator parameters		
Rotor radius (m)	R	0.93
Width of blade (m)	w	0.130
Leg length of the blade (m)	L	0.100
Thickness of the blade (m)	t	0.007
Forward travel speed (m/s)	V_f	0.425, 0.515
Rotor speed (rad/s)	ω	2.754
Number of blades on flange	z	3 or 6
Bite length (m)*	L_b	0.323, 0.162; 0.392, 0.196
Kinematic parameter (dimensionless)	λ	6.026, 4.944
Calculated N-factor soil strength parameters:		
Cohesion N-factor (dimensionless)	$N_c^{'}$	257.52
Surcharge N-factor (dimensionless)	$N_q^{'}$	203.94

* Bite length was calculated using Equation (3.8) as explained in §5.3.2.

After determining the rake angle, the rupture angle (ρ) was calculated using the approach of Perumpral *et al*. (1983). These two angles were calculated and utilized by the computer program internally, in the computation of the total resultant force P_s (Equation 3.57). With the model inputs determined and the computer program developed, the next step was to verify the proposed model.

6.5.2 Model and computer program verification

The computer program developed for solving the proposed analytical model performed all the required computations, and produced several outputs using, the values assigned to the inputs (Table 6.8) and the derived mathematical expressions (Chapter 3). The outputs from the program are also used as a means of verifying that both the program itself and the analytical model are producing the expected outputs. Selected program outputs required to build confidence in its computational process and assess the suitability of the derived mathematical expressions are discussed in this section.

One of the important outputs of the program is the trochoidal path followed by the tip of the rotavator blade during field operations (Figure 6.10). The graph plots the (*x, y*) coordinates of the tip of the blade from the horizontal position at predetermined time intervals. The inputs required to generate the coordinates of the tip of the blade at different angular blades are the rotor radius, the rotational and the forward travel speeds. The ability of the program to trace the path followed by the tip of the blade for different set tillage depths is important because it serves as the basis for the other computations required to predict the torque requirements at different blade positions. The graphical output also included additional important data required in the calculation of the torque requirements. The additional outputs included the following:

- A - The position of the centre of the rotor when the cutting edge of the blade comes into contact with the ground surface.
- B - The point at which the cutting edge of the blade comes into contact with the ground surface, i.e α_i. The set depth of tillage is then the difference between the y-coordinate at this point and the y-coordinate of the lowest point on the cutting path. In the case shown in Figure 6.10, the y-coordinate at point B is -580 m, which correspond to the set depth of tillage of 350 mm. By simultaneously taking the (*x, y*) coordinates at points A and B, respectively, the program computes the angle at which the tip of span part of the blade comes into contact with the ground surface.

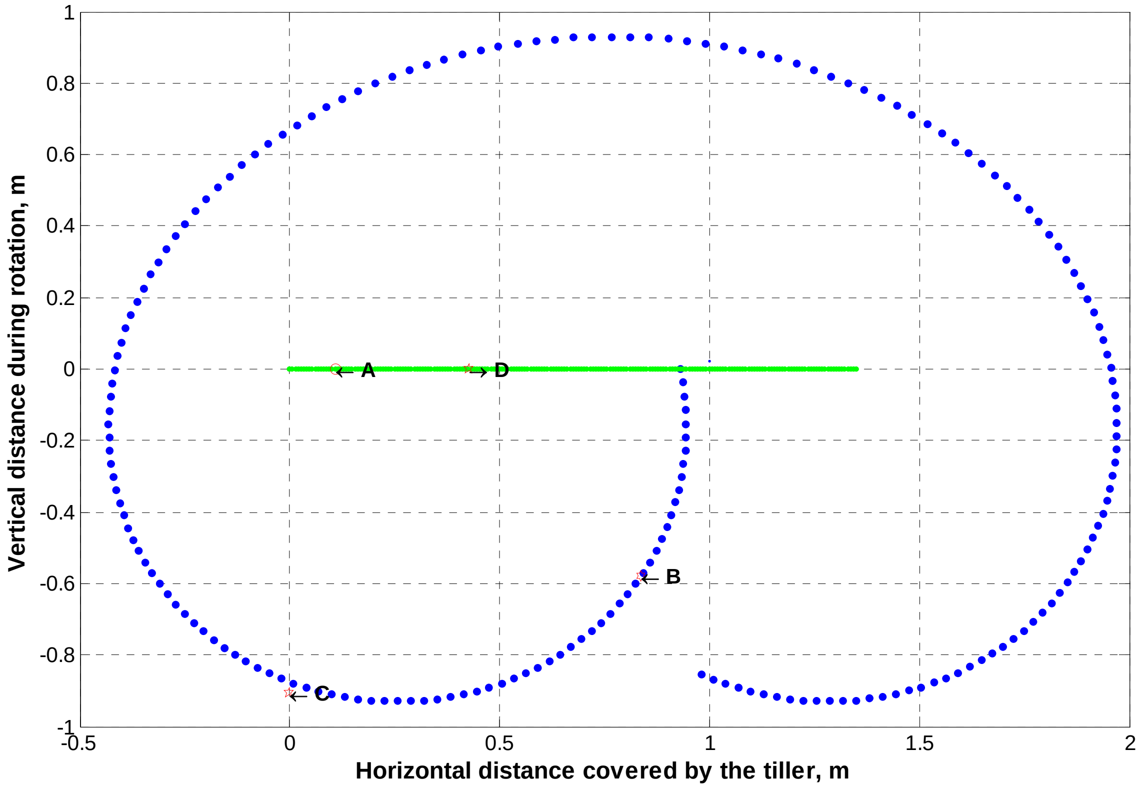

Figure 6.10: A typical graphical output of the path followed by tip of the span of the blade produced by the computer program for a set tillage depth

- C – This is the point at which the cutting edge of the blade stops cutting the soil. It is the point that forms the crest (Figure 3.4). By taking the coordinates of this point and those of point D, which is the position of the centre of the rotor at the end of the soil processing by the blade, the program calculates the angle α_e, the angle at which blade stops processing the soil. With these two angles, i.e., α_i and α_e, the tilling route length is determined for the set depth of tillage.

- The other important parameter determined using the pairs of *(x, y)* coordinates is the instantaneous length of the blade in contact with the soil. This calculation is necessary because the length of the blade in contact with the soil at different time moments, which varies instantaneously for a given set depth of tillage, is the basis for the computation of the total instantaneous soil-tool interaction forces P_s (Figure 3.15, p70). This force is then used to calculate the torque requirements for single blades at predetermined positions of the rotor between the angle of entry (α_i) and exit (α_e). The weight of the soil supported by the span of the blade depends on the length of the blade in contact with the soil.

- The final program output is a tabulation of the angle, α and the torque requirements at different positions of the tip of the blade during the soil cutting process. The program also generated a graphical output of these two parameters for different set depths of tillage and rotavator operational parameters. Figure 6.11 is a typical graphical output for the torque requirements for a single rotavator blade at different angular rotor positions from the horizontal during the soil cutting process for a 350 mm set tillage depth.

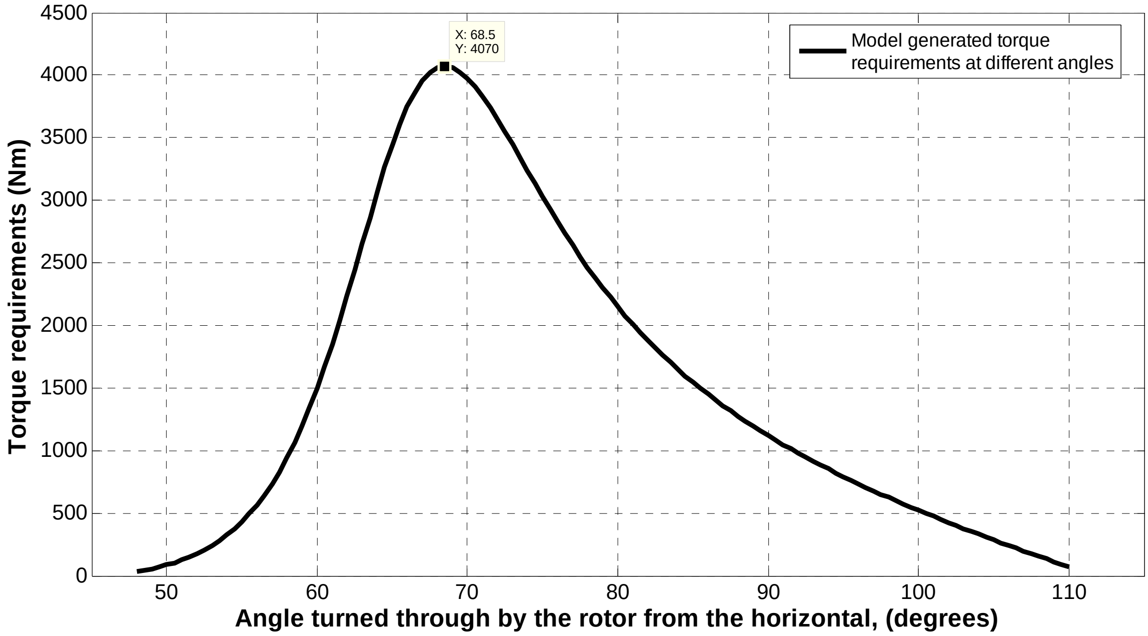

Figure 6.11 Model generated torque requirement values at different angular positions of the tip of the blade during soil processing at set tillage depth of 350 mm.

From Figure 6.11, it is evident that the shape of the graphical output of the model generated torque requirements at different angular rotor positions, closely resembles, Figure 6.4. The choice of set tillage depth of 350 mm for the verification of the model was based on the fact that Figure 6.4 was used for analyzing the measured torque requirement. Therefore, it allows for the visual comparisons and the general verification of the proposed model. Like is the case of the measured (experimental) torque requirements, the model graphical output shows that immediately after the commencement of the soil processing, there is a steep increase in torque requirements, before a peak value is reached after about 20 degrees. This is followed by a decrease in torque requirements at a decreasing rate until up to the point where the soil processing by a blade stops.

The model was tested with different set tillage depths and bites but similar soil conditions; and in all cases a similar shape (Figure 6.11) was obtained for all the conditions. This is different for the measured torque requirements data for single blades which showed differences, particularly after the peak torque requirements values had been reached. The measured torque requirements curve, after the peak value had been reached, was not as smooth as that of Figure 6.11. There appeared to be some increase or in some cases the torque requirements values being constant with increasing angular position towards the end of the soil cutting process by a blade (Figure 6.4).

6.5.3 Model validation and evaluation

The proposed model is validated by comparing the model generated and measured (field experiments) torque requirement values as explained in §5.4.2. The validation and evaluation of the model is done for selected set tillage depths of 250 mm, 350 mm and 500 mm at a constant average soil water content of 13.97 %. In addition to the statistical analysis techniques described in §5.4.2, visual comparisons of the measured and model generated torque requirements is also used to assess the degree of agreement between the two sets of data.

The visual comparison is used to compare the variation of both the measured and model generated (predicted) torque requirement values, at different angular rotavator blade positions during the soil cutting process. This was done by plotting the model generated and measured torque requirements on the same axes at specified angular rotavator blade positions, for a given set tillage depth. The selected set tillage depths used for these comparisons are 250 mm, 350 mm and 500 mm, respectively. The measured torque requirements used for the visual comparison are averages of soil processing by an individual blade at five different positions along the cut furrow.

6.5.3.1 Measured and predicted torque at 250 mm set tillage depth

Figure 6.12 is a combined graph showing the measured and model generated torque requirement values for 250 mm set tillage depth at different angular rotavator blade positions during the soil cutting process. Visual comparison between the measured and predicted torque requirements (Figure 6.12) indicated that in general the predicted torque requirements are greater than the corresponding measured torque values.

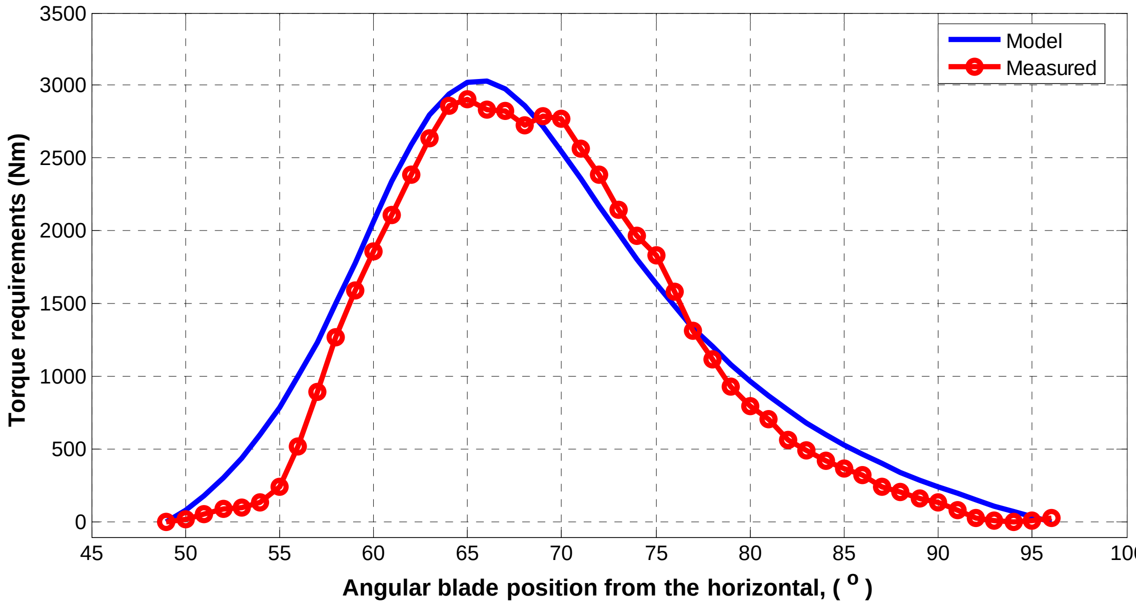

Figure 6.12: Comparison of predicted and measured torque requirement at 250 mm set tillage depth

Two statistical tests, namely, the least squares regression analysis and the paired t-test was effected on the model and torque generated data to evaluate the agreement between the two sets of data (see §5.4.2). The results obtained for this set tillage depth are presented in Figure 6.13, and Tables 6.10 and 6.11. From the paired t-test, the mean generated and measured torque values are 1.269 kNm and 1.15 kNm, respectively. The respective standard deviations are 1.007 kNm and 1.063 kNm. The large standard deviation values returned for both the predicted and the corresponding measured torque requirements is due to the large variations in torque requirements between the initiation and end of the soil cutting process by a rotavator blade.

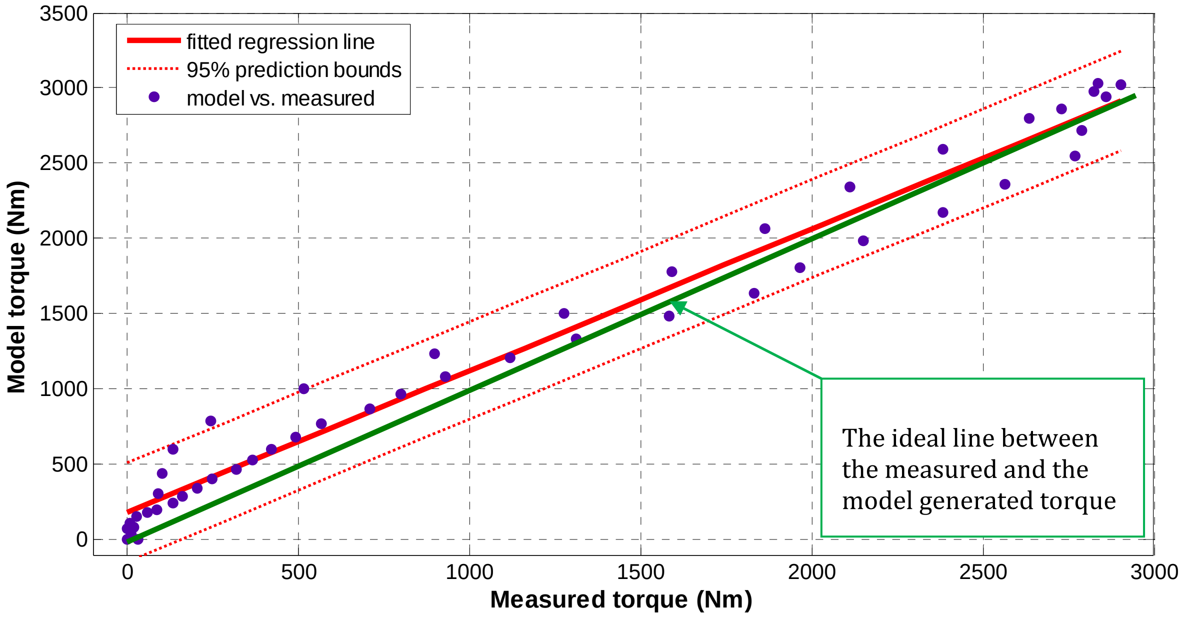

Figure 6.13: Results of the least squares linear regression of the model and measured torque requirements at different angular blade positions for 250 mm set tillage depth

The statistical analyses performed (Tables 6.10 and 6.11) on the two sets of torque requirements indicated that the difference between the measured and predicted torque requirements for this set tillage depth is statistically significant ($p < 0.05$). This result implies that the model and measured torque requirements at the same angular rotavator blade positions, for this set tillage depth, are different at the 0.05 level of significance. This finding confirms the wide disparities that are evident from Figure 6.12 at different angular rotor positions.

The results of the least square regression analysis for predicted and measured torque requirements for the set tillage depth of 250 mm are presented in Figure 6.13 and Table 6.11. If there was no discrepancy between the measured and the predicted torque requirements, all the point would lie on a straight line with a slope of one (1), and pass through the origin, i.e., a zero (0) vertical intercept. In Figure 6.13, the fitted regression line between the measured and predicted torque requirements has a slope of 0.936 and an intercept of 0.192 with an R^2 value of 97.5 %. The tabulated linear regression analysis results are given in Table 6.11, and indicate that both the slope and the vertical intercept are significantly different from one and zero, respectively ($p < 0.05$). These results indicate that at the significance level of *α = 0.05,* the measured and the model generated torque requirements for this set tillage depth are significantly different.

Table 6.10: Paired *t*-test results for torque requirement for the 250 mm set tillage depth

	N	*Mean (kNm)*	*SD**	*SE Mean***
Model torque, kNm	47	1.269	1.007	0.147
Measured torque, kNm	47	1.150	1.063	0.155
Difference	47	0.1183	0.1699	0.0248
95 % CI for mean (0.0684, 0.1681)				
T-Test for mean difference = 0 (vs not = 0): T-value = 4.77, p-value = 0.000				

T_{mod} = model generated or predicted torque requirements; T_{meas} = measured torque requirements; *SD** - Standard deviation (kNm); *SE Mean*** - Standard error mean

Table 6.11: Results of the least squares regression of the model generated torque requirements on the measured torque for 250 mm set tillage depth

The least-squares regression equation is: $T_{\text{mod}}(kNm) = 0.192 + 0.936 \bullet T_{meas}(kNm)$

Predictor	*Coef*	*SE Coef*	*T*	*P*
Constant	0.19188	0.03402	5.64	0.000
Measured, kNm	0.93600	0.02183	42.88	0.000
S = 0.1574	R^2 = 97.6 %	$R^2_{adj} = 97.6\%$		

Analysis of Variance

Source	*df*	*SS*	*MS*	*F*	*P*
Regression	1	45.561	45.561	1838.93	0.000
Residual Error	45	1.115	0.25		
Total	46	46.676			

Unusual observations

Observation	T_{meas}*, kNm*	T_{mod}*, kNm*	*Fit*	*SE Fit*	*Residual*	*SE Residual*
7	0.25	0.788	0.4220	0.0303	0.3661	2.37R
8	0.52	1.0003	0.6753	0.0268	0.3250	2.10R
R denotes an observation with a large standardized residual						

Coef – coefficient; **SS** – Sum of Squares; ***df*** – degree of freedom ***P*** – p-value, ***T*** – t-value

The foregoing findings of the least squares linear regression test is in agreement with the paired Student t-test results (Table 6.10), i.e., the model and measured torque requirement values for the set tillage depth of 250 mm are significantly different. The least square linear regression results (Table 6.11) indicate that observations 7 and 8 fall outside the 95 % confidence interval; and are, therefore outliers. According to Montgomery and Runger (2003) outliers can significantly influence the outcome of selected statistical tests. Probably the significant results obtained for the two test statistics reported for this set depth of tillage was partly due to the presence of outliers between the two sets of torque requirements data.

The conclusion that can be drawn from the analysis of the measured and predicted torque requirements data for the 250 mm set tillage depth is that the two sets of data are significantly different at the 0.05 level of significance. This is evident from both the visual comparisons and the two statistical analyses test effected on the two sets of data. The possible causes of these disparities are the unsteady interaction between the soil-tool at the commencement and toward the end of the soil cutting process and the variations in soil strength parameters owing to variation in the soil water content with depth.

6.5.3.2 Measured and predicted torque at 350 mm set tillage depth

Figure 6.14 is a combined graph showing the measured and model generated torque requirement values for 350 mm set tillage depth at different angular positions of the rotavator during the soil cutting process. Compared to the graph for the 250 mm set tillage depth, there is a better agreement between the measured and the predicted torque requirements for this set tillage depth. Since the field tests for verifying the model were done on the same day, and at almost the same time, the relatively better agreement between the measured and the predicted torque requirement results, for this set depth, compared to that for 250 mm set depth is attributed to a more uniform soil strength in the portion of the land tilled when the verifications test was done.

The variation in the soil strength at the experimental site at different locations was possible because the soil at the selected site was not conditioned. Conditioning the soil however, is not a guarantee for the uniformity in soil strength as this phenomenon was reported in tillage studies conducted in conditioned soil (Girma, 1989; Owende & Ward, 1996). Soil strength variations, even within the short distance such as the bite lengths encountered in rotary tillage, for set test conditions, are not unusual under field conditions, because the soil is not a homogeneous material.

The results of the statistical analysis done on the model generated and measured torque requirements at this set tillage depth, are presented in Tables 6.12 and 6.13, and Figure 6.15. The paired student's t-test statistic for the difference between the measured and predicted torque requirements for this set tillage depth indicate that there is no statistical difference at *α = 0.05* significance level. This result confirms the closeness of the two predicted and measured torque requirement curves presented in Figure 6.14.

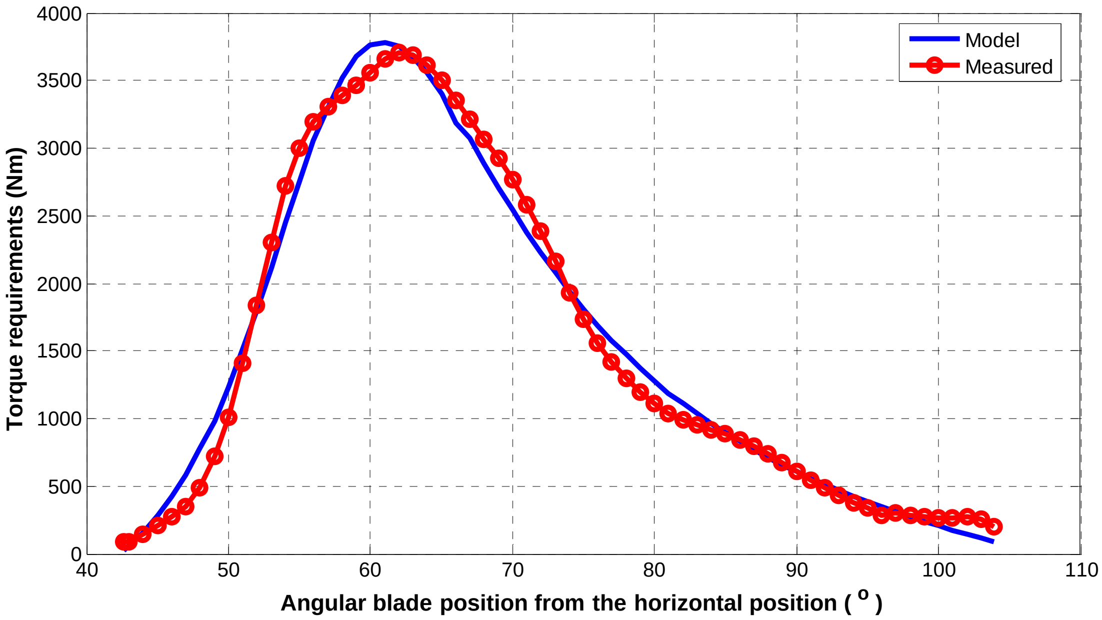

Figure 6.14: Comparison of the predicted and measured torque requirement at 350 mm set tillage depth

Table 6.12: Paired t-test results for torque requirement for the 350 mm set tillage depth

	N	*Mean (kNm)*	*SD**	*SE Mean*
Model torque, kNm	63	1.521	1.219	0.154
Measured torque, kNm	63	1.515	1.248	0.157
Difference	63	0.006	0.1353	0.017
95 % CI for mean (-0.0280, 0.0401)				
T-Test for mean difference = 0 (vs not = 0): T-value = 0.35, p-value = 0.725				

The least squares linear regression results (Table 6.13), however indicate that the slope between measured and predicted torque requirements are not a perfect replica of one another at the same angular positions. The values of the slope of 0.972 though close to 1, has a p-value = 0.00, which indicates that the measured and model generated torque requirements at the same, angular blade positions is statistically significant. The analysis of variance for the least squares regression also indicated that the measured and predicted torque requirements are significantly different for this tillage depth, as was the case for the 250 mm set tillage depth.

Table 6.13: Results of the least squares regression for the predicted versus the measured torque requirements for 350 mm set tillage depth

The least-squares regression equation is: $T_{\text{mod}}(kNm) = 0.0488 + 0.972 \bullet T_{meas}(kNm)$

Predictor	*Coef*	*SE Coef*	*T*	*P*
Constant	0.0488	26.23	1.86	0.067
Measured, kNm	0.972	0.0134	72.48	0.000

$S = 0.132$ $R^2 = 98.9$ % $R^2_{adj} = 98.8\%$

Analysis of Variance

Source	*df*	*SS*	*MS*	*F*	*P*
Regression	1	91.46	91.146	5253.97	0.000
Residual Error	61	1.058	0.017		
Total	62	92.204			

Unusual observations

Observation	*T_{meas}, kNm*	*T_{mod}, kNm*	*Fit*	*SE Fit*	*Residual*	*SE Residual*
18	3.47	3.68	3.4184	0.0310	0.2616	2.04R

R denotes an observation with a large standardized residual

In Figure 6.15, minor disparities between the ideal line and the fitted regression line are noted at the low- and high-end torque requirement values. In the in the 500 – 2500 Nm torque requirements range, the fitted linear regression and the ideal line more or less coincide. The observed deviations between the ideal and the regression line indicated that the model under- and over- predicted the torque requirement values at the start and towards the end of the soil cutting process by a rotavator blade for the 350 mm set tillage depth.

Although the foregoing analyses indicate that the two sets of torque requirements data are significantly different, both the visual comparison and the results of the least square linear regression show that the deviations are minor. In general, the shapes (Figure 6.14) of the curves for the measured and predicted torque requirements, at different angular blade position, followed the same trend. The minor differences in these curves can be attributed to lack of uniformity in the soil strength parameters within the set tillage depth. The difference noted in the torque value at the commencement and towards the end of the soil cutting process; and which were the major causes of the disparities observed between the measured and predicted torque requirements for this set tillage depth, could be due to dynamic instability between the soil and the blade. At both ends during the rotavator tillage, there is a continual change in the mass of the soil in contact with the blade. In conclusion, the model generated torque requirements for this depth are comparable to the measured values; save for the inevitable minor differences noted.

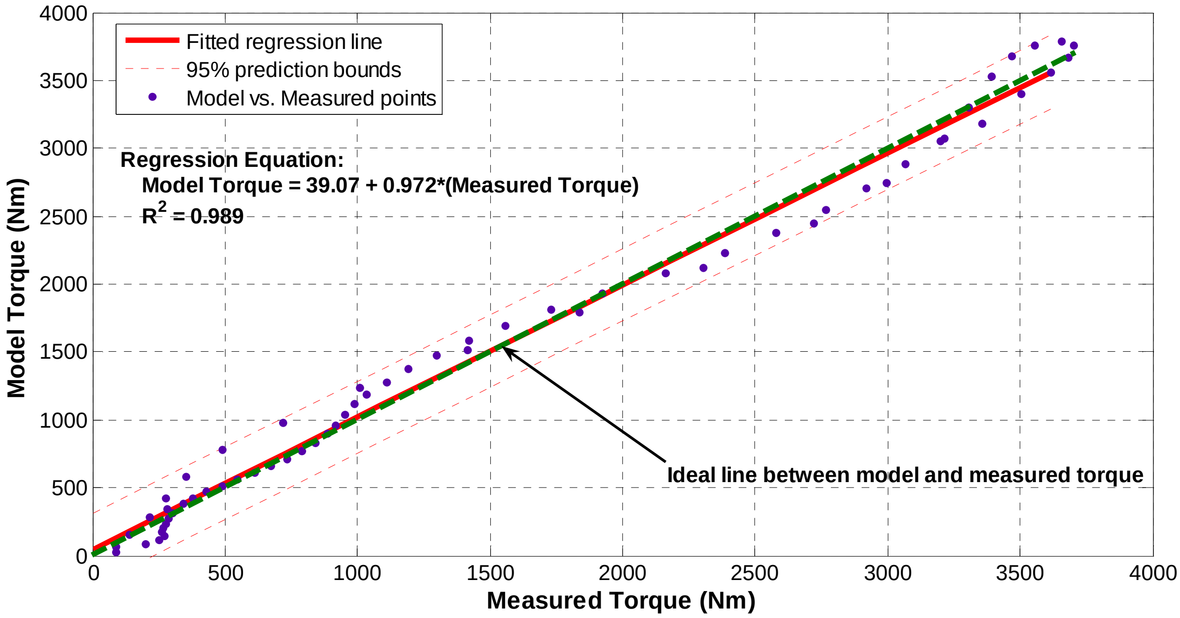

Figure 6.15: Results of the least squares linear regression of the model and measured torque requirements at different angular blade positions for 350 mm set tillage depth

6.5.3.3 Measured and predicted torque at 500 mm set tillage depth

Figure 6.16 shows the variation of the measured and model generated torque requirement curves for the 500 mm set tillage depth at different angular positions of the rotavator blade during the soil cutting process. Compared to similar graphs for the 250 mm and 350 mm set tillage depths, there appear to be greater disparities between the measured and model generated torque requirements, at this set tillage depth. In particular, the inconsistency between the predicted and the measured torque requirements are greatest at the blade angular positions in the 35^{o} – 50^{o} range, after the commencement of soil cutting. Within this angular position range, the measured torque requirements curve indicated a sudden drop in the torque requirements, followed by a sudden increase in torque requirements which persists until the peak value is reached.

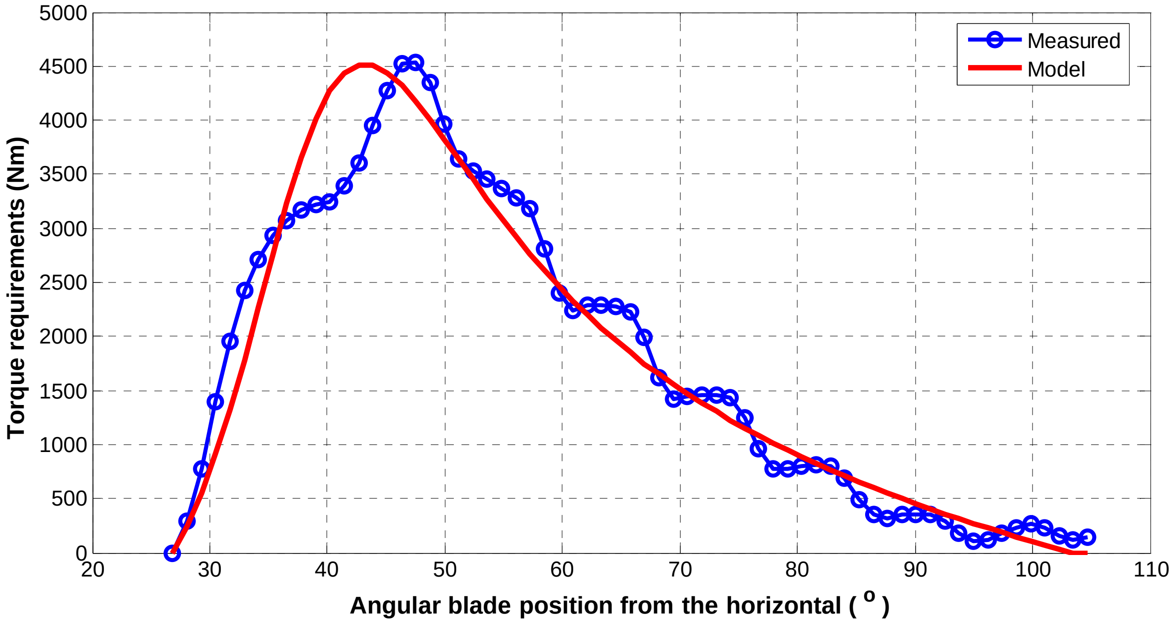

Figure 6.16: Comparison of the predicted and measured torque requirement at 500 mm set tillage depth

Given that measured data curve (Figure 6.16) is for an average cutting by the same blade at five different locations along the tilled path, this observation cannot be explained by the inconsistencies due to the soil strength. The possible explanation of the observation made could be the instability of the test equipment (tool-frame carrier onto which the rotavator was mounted) at set depths of tillage in excess of 450 mm. It was noted beyond this depth, the entire test equipment became unsteady and the degree of unsteadiness increased with further increase in depth.

After the peak torque requirement value has been reached, for this set tillage depth, an interesting observation in the form of vacillations in the measured torque requirement is apparent until the end of the soil cutting process by a blade. The nature of the observed vacillations is such that constant torque requirement levels are maintained at seemingly regular blade angular position intervals to the end of the soil cutting process. In some instances, relatively greater torque requirements, relative to previous angular blade positions, were observed. The maintenance of constant torque requirements or its increment with the increase in the blade angular position (blade advancement), after a peak torque requirement level has been registered reached, resulted in higher average torque requirements values for this set tillage depth. Some of the possible causes of this behaviour are analyzed below, based on the findings by Shibusawa (1993).

In the said study by Shibusawa (1993) it was reported that deep rotavator tillage demanded excessive energy owing to the possibility of re-tilling of soil massed that fall back into the furrow. While this was not visually observable during the field experiments undertaken in this study, the observed vacillations in the measured torque requirements after the peak value has been reached (Figure 6.16) are an indication of an increase in resistance to cutting of the soil by a blade. From the kinematics of rotavators fitted with L-shaped blades (Chapter 3), as the blade moves through the soil, the cross-section of the soil slice initially increases to a maximum value and thereafter decreases until the end of the soil cutting process. Therefore, possible and logical explanation for observation made in Figure 6.16, could be due the falling-back of the already cut and thrown soil mass onto the blade cutting path. The effect of this would be the increase in the dynamic mass of the soil in contact with the blade, increased soil cutting resistance, and increased soil chip thickness. All these three would result in the overall increase in resistance, which would manifest itself as increased torque requirements.

The predicted and measured torque requirement data obtained for this set tillage depth was also subjected to the two statistical tests (§5.3.2) in order to compare the degree of agreement between the measured and the predicted torque requirements. The results of the paired t-test and the least squares linear regression are presented in Table 6.14 and 6.16, and Figure 6.17. The paired t-test results indicated that the difference between the two sets of torque requirements data for this set tillage depth was statistically insignificant ($p > 0.05$).

Table 6.14: Paired t-test results for torque requirement for the 500 mm set tillage depth

	N	*Mean (kNm)*	*SD**	*SE Mean*
Model torque , kNm	65	1.796	1.407	0.174
Measured torque, kNm	65	1.792	1.458	0.181
Difference	65	0.0045	0.3358	0.0417

95 % CI for mean (-0.0787, 0.0877)

T-Test for mean difference = 0 (vs not = 0): T-value = 0.11, p-value = 0.914

The results of the least square linear regression (Table 6.15), between the measure and predicted torque requirements data, showed that the intercept was not significantly different from zero, while the slope was significantly different from 1. The regression analysis of the predicted and measured torque requirement data, for this set tillage depth, indicated some of the data sets (corresponding data) were outliers. Specifically, there were four pairs of data that fell outside the 95 % confidence interval (95 % CI, Figure 6.17). These points are identified in Table 6.15 under unusual observations.

Although the least square regression results for the model and measured torque requirements for this set tillage depth are inconclusive, it is noteworthy that the fitted and ideal line are difficult to separate visually. In addition, given that the intercept of the regression equation is not statistically different from zero, it can justifiably be concluded that the model gives a good approximation of the torque requirements for the experimental rotavator at this set depth of tillage. The significant difference from 1, of the slope of the regression line between the two sets of torque requirement data, for this set tillage depth predicted torque is probably due to the presence of outliers.

Table 6.15: Results of the least squares regression of the model generated torque requirements on the measured torque for 500 mm set tillage depth

The least-squares regression equation is: $T_{\text{mod}}(kNm) = -0.0204 + 1.01 \bullet T_{meas}(kNm)$

Predictor	*Coef*	*SE Coef*	*T*	*P*
Constant	-0.0204	0.0684	-0.30	0.767
Measured, kNm	1.00885	0.03006	33.56	0.000

S = 0.338244   *R*² = 94.7 % $R^2_{adj} = 94.6\%$

Analysis of Variance

Source	*df*	*SS*	*MS*	*F*	*P*
Regression	1	128.86	128.86	1126.32	0.000
Residual Error	63	7.21	0.11		
Total	64	136.07			

Unusual observations

Observation	*T_{meas}, kNm*	*T_{mod}, kNm*	*Fit*	*SE Fit*	*Residual*	*SE Residual*
11	3.22	4.0094	3.2280	0.0599	0.7814	2.35R
12	3.24	4.2705	3.2521	0.0605	1.0184	3.06R
13	3.39	4.4363	3.3976	0.0636	1.0387	3.13R
14	3.61	4.5133	3.6215	0.0688	0.8898	2.69R

R denotes an observation with a large standardized residual

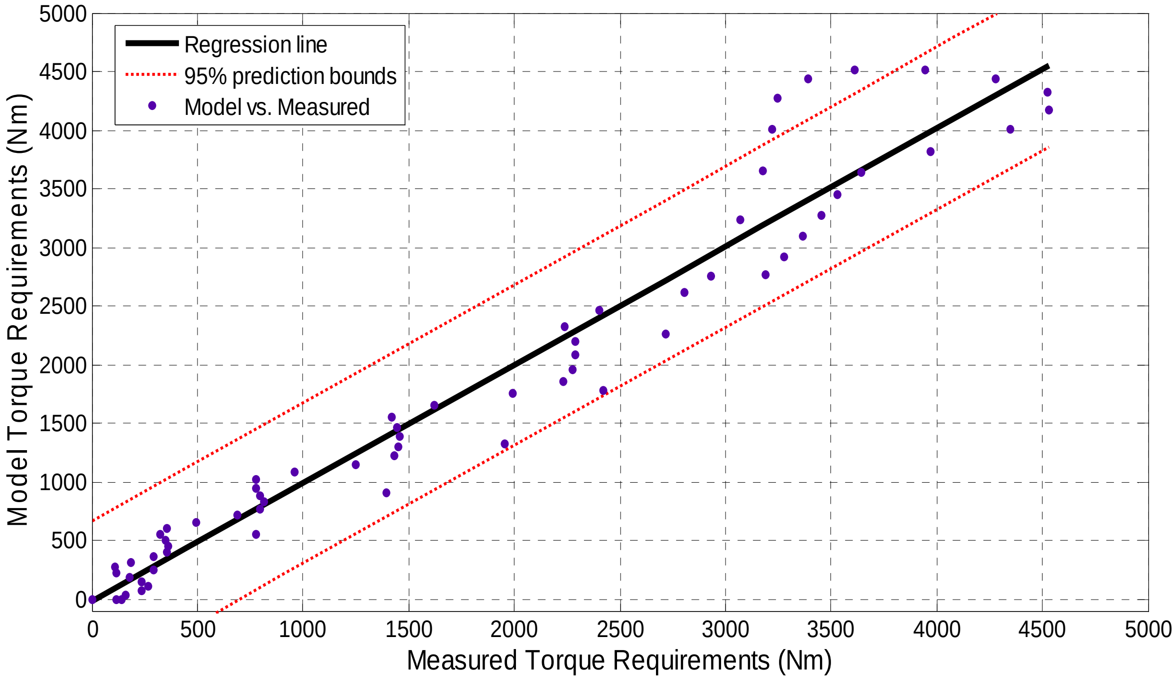

Figure 6.17: Results of the least squares linear regression of the predicted and measured torque requirements at different angular rotavator blade positions for 500 mm set tillage depth

6.6 Chapter Summary

In this chapter, the results of the field measurements and proposed model were presented. The field experiments indicated that the soil at the experimental site is sandy loam. The results also indicated that the soil strength properties could be satisfactorily characterized using the torsional shear apparatus.

Characterization of the deep-tilling experimental rotavator was only done for the down-cut direction of rotation. The results indicated that torque and power requirements as well as the specific energy increased with depth. On the generated forward thrust the results indicated that the magnitude of the thrust forces generated was dependent on the set tillage depth for a given rotavator configuration and operational conditions.

The torque requirements prediction model proposed on Chapter 3 was verified, validated and evaluated. The model was solved using a specially developed computer program, written in MATLAB. The model was validated and evaluated by comparing the model generated and measured torque requirement data. Model validation was done for 250 mm, 350 mm and 500 mm set tillage depths by comparing the torque requirement values at chosen suitable rotavator blade angular positions from the horizontal position, during the soil cutting process. The results for the 250 mm and 350 mm set tillage depths were statistically different at the 0.05 level of significance for the paired t-test and the least squares regression, statistical tests. For the 500 mm set tillage depth, the paired t-test produced results that were not statistically different, while least square regression results produced inconclusive results at the 0.05 level of significance.

In general, it was observed that the graphs for the model and measured torque requirements for the three set tillage depths of 250 mm, 350 mm and 500 mm had similar shapes. However, some discrepancies in the measured torque requirement values at the same rotavator blade angular position were noted. The likely causes for the noted discrepancies could be the assumptions regarding the constancy of the soil dynamic and strength parameters used in the model; and the unsteady interaction between the soil-tool interface arising from tool-frame instability and the soil movement over the blade during the rotavator tillage operations.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

From literature, it was evident that no studies had been undertaken in the past that documented the performance of rotavators in deep tillage. In addition, the literature reviewed revealed that there are no analytical models for predicting the torque requirements of rotavators. There is also a lack of suitable research equipment and techniques for studying the performance of deep tilling rotavators, particularly under field conditions. This study was therefore designed to provide information on the performance of rotavators in deep tillage under field conditions, and to develop an analytical model capable of predicting the torque requirements. The predicted torque requirement is precursory for the prediction of power and specific energy requirement of rotavators.

In order to accomplish the research goals, two instrumented tool-frame carriers; one carrying an experimental deep-tilling rotavator and the other carrying the soil strength characterisation apparatus were developed. The tool-frame carrier, onto which the experimental rotavator was mounted, was instrumented for the measurement of the instantaneous tillage depth, the thrust or pull forces on the tractor three-point links, the angular position of the rotavator blade, the forward distance travelled and speed, the rotor rotational speed and the instantaneous rotavator blade torque requirements.

Soil strength characterisation and soil/steel frictional characteristics was facilitated by measuring the normal and shearing torque using a torsional shearing device fitted, alternatively, with a circular grouser head and a smooth circular flat steel plate. The recorded loads when the torsional shearing device was fitted with the circular grouser head and the circular plate, respectively, was used for the determination of the soil shear strength and soil-metal frictional parameters, respectively. For all field experiments, soil water content and the soil bulk density were also determined using standard procedures at different depth ranges.

A computerized data acquisition system (DAS), comprising the two instrumented tool-frame carriers, a eight-channel commercial data logger and a personal computer, was used to acquire the measured data under field conditions. The combination of the DAS and the instrumented tool-frame carrier used for soil characterisation enabled the measurement and recording of the normal, shear and frictional loads; and the storage of the measured data for the determination of the soil strength and friction parameters directly into the hard disk of a computer. Soil strength parameters are some of the inputs required by the proposed torque requirements analytical model. Using the same DAS and the tool-frame carrier onto which the rotavator was mounted, measurement of the rotavator torque requirements, the forces on the three tractor link points, the rotational speed of the rotor, the angular position of the rotavator blade, the forward distance travelled and the times was made. From the time-distance relation, the speed of tillage trial-test run was determined.

From literature, it was possible to modify existing models for passive blades and apply the basic soil-tool equilibrium analysis to develop an analytical model for predicting the torque requirements of a rotavator fitted with L-shaped blades. This possibility was based on the fact that, at an instantaneous time moment, the soil-tool interaction between the span of the L-shaped rotavator blade is similar to that of a passive tool when processing the soil. The modification effected considered the continually changing tillage depth of a rotavator blade and the changing rake angle of the blade, while processing the soil and the presence of the leg part of the blade.

Through field measurements, the performance of the experimental deep tilling rotavator was evaluated for different rotavator operational conditions. The performance was evaluated in terms of the variations in the magnitude of the resultant thrust force generated for different rotavator configuration and operational conditions; and the torque and power requirements, and the specific energy under the stated conditions.

Finally, the proposed analytical model and the computer program developed to solve it was verified and evaluated. The evaluation was done by comparing the experimental and model generated torque requirements for the same angular rotavator blade positions using appropriate statistical analyses and graphical presentation techniques.

Considering the inherent variability of both the soil water content and the soil bulk density under field conditions; and the fact that the experimental site was not conditioned prior to the experimentation, the torque requirements prediction results obtained are promising.

The study addressed the performance characteristics of the experimental rotavator for the 200 mm - 550 mm tillage depth range. The application of the model data proved that the adoption and modification of existing analytical models for passive blades produced a model that was capable of predicting the torque requirement of a down-cutting rotavator fitted with L-shaped blades. Based on the measured torque requirements and resultant horizontal thrust forces generated, it was possible to quantify the performance of the experimental deep tilling rotavator. The analysis of the thrust forces generated under different experimental conditions and rotavator configurations indicated the existence of an optimum depth, for each set of operational conditions. Consequently, all the study hypotheses postulated could not be rejected.

7.2 Conclusions

Based on the field experimental results for characterising the performance of the experimental deep tilling rotavator, and performance of the proposed analytical torque requirements prediction model, the following conclusions were drawn:

1. The field tests undertaken with the soil characterisation apparatus for the determination of soil strength parameters produced acceptable results. The apparatus could therefore be used confidently for the determination of the soil shear strength and soil-metal friction parameters required by the proposed torque requirements prediction model.

2. The instrumented tool-frame carrier, onto which the experimental deep-tilling rotavator was mounted, is suitable for studying the performance of rotavators for a wide range of set tillage depths. In combination with the computerized DAS, this tool-frame carrier provided a suitable means for acquiring all the pertinent data necessary for characterising the experimental deep tilling rotavator. In

particular the ability of the DAS to accurately acquire the measured data at a frequency of 2.4 kHz suits it for the measurement of the instantaneous rotavator blade angular position and torque data, which can be problematic if the systems used cannot record data at frequencies in excess of 2 kHz.

3. The accuracy of the measured data recorded using the computerised DAS from the two tool-frame carriers together with the measured soil bulk density is adequate as model inputs for the prediction of soil-tool interaction resistance forces and the prediction of torque requirements for a rotavator fitted with L-shaped blades.

4. The soil bulk density and the soil water content at the experimental site significantly changed with depth from the soil surface. The soil water content increased with depth while bulk density decreased.

5. Since the soil shear strength and the soil-metal frictional characteristics are affected by the soil water content, the use of fixed values for these parameters, as model inputs introduced some error.

6. The magnitude and variations of the resultant forward thrust force generated for a down-cut tillage operation depended on bite length, set tillage depth, and the kinematic parameter, λ. Therefore, the rotavator configuration and operational parameters must be controlled precisely in order to realize and maintain the desirable resultant thrust force for a down-cut rotavator.

7. There exist a unique depth for each rotavator configuration and operational condition at which the thrust force generated is greatest. This depth is influenced by the bite length, and decreased as the bite length is increased. Therefore the realisation and maintenance of the maximum forward thrust generation, where required, can only be realised by strictly operating a rotavator at the correct set tillage depth for a given set of rotavator configuration and operational conditions.

8. In general, the specific energy requirements of the rotavator increased with increment in both the set tillage depth and bite length. However, bite length had a greater influence on the specific energy requirements than the set tillage depth. Therefore, operating a down-cutting rotavator at greater bite lengths, even at relatively shallow set tillage depths required excessive energy, and hence excessive input power requirements than operations done at relatively deeper set tillage depths at lower values of the bite length.

9. The computer program developed for solving the proposed analytical torque requirements model, accurately generated the path followed by the tip of the rotavator blade, the blade leg length and blade span in contact with the soil, the location of the centre of the rotor as the soil processing by a blade progressed, and torque requirement values at specified angular rotavator blade positions.

10. Based on the statistical and visual evaluation, effected between the measured and predicted torque requirements data, the proposed model generated acceptable torque requirements at selected rotavator blade angular positions for a rotavator fitted with L-shaped blades when operated in the concurrent (down-cut) direction.

7.3 Recommendations

The following recommendations based on findings of this study are made for possible future studies on rotavators in deep tillage:

1. Only the L-shaped blade was used with the experimental deep-tilling rotavator, characterised in this study. The other types of blades, particularly those currently used in the Asian sub-continent should also be tested for deep rotavator tillage. The performance results of the experimental deep-tilling rotavator, when fitted with different types of blades can, thereafter be compared and the blade type(s) with better performance characteristics recommended.

2. There is need to develop a method for measuring only the torque required by the blade for the processing of the soil, that does not involve the use of the Torque Arm. The torque requirements measured by the approach used in this study, included the torque required to overcome the hydraulic motor parasitic forces and the inherent friction forces in the rotavator assembly. The parasitic torque component was considered to be responsible for the non-zero torque requirements recorded when there was no blade processing the soil during the trial test-runs.

3. There may be a need to undertake similar studies in a conditioned soil to avoid the variations noted in the measured torque requirements and the resultant push/pull forces. These variations were difficult to explain, particularly when they occurred between subsequent blade cuttings within a test-run block. Soil conditioning of the experimental site should result in the creation of a uniform condition within the experimental site. This would reduce the variations of the differences in the magnitudes of both the rotavator torque requirements and the thrust forces generated for different blade cuttings for a set tillage depth within a test-run block. This would result in a more realistic performance characterisation of the experimental deep-tilling rotavator.

4. The tool-frame carrier on which the rotavator is mounted should be adjusted to ensure that the magnitude of the thrust forces on the lower left and lower right links are balanced. The imbalance noted in the data recorded for these two links, was suspected to be the cause of the instability of this tool-frame carrier, particularly during field test-run for set tillage depths beyond 350 mm.

5. The application of the proposed rotavator torque prediction model required the availability of accurate soil dynamic, soil/steel frictional and soil strength parameters. The collection and processing of such data for the determination of these parameters was laborious and time consuming. Therefore, better experimental techniques and faster data processing methods should be developed. This can be achieved by employing real-time methods for the

determination of the soil water content and soil bulk density; and developing computer program modules that would read and process the data immediately upon the completion of an experiment.

6. Some rotavator performance characteristics, such as the effect of the operational conditions and rotavator configuration on the ridge heights at the bottom of the tilled furrow, were not evaluated. An additional computer program module should be developed, and integrated with computer program developed for solving the proposed rotavator torque requirements prediction model, to evaluate the effect of rotavator kinematics on the irregularities produced at the bottom of the cut furrow for different configurations and values of kinematic parameter, λ. The bottom-of-the furrow irregularity produced by rotavators are important performance indicators for rotavator tillage, but was not evaluated in this study deep rotavator tillage.

7. The tool-frame carrier, onto which the rotavator was mounted, should be used to study the performance of alternative experimental rotavators with different radii, and blade configurations, and number of blades on the same side of the flange; and assess their performance characteristics in the concurrent (down-cut) direction of rotation. This may lead to the optimization of the performance characteristics of the down-cutting rotavator in deep tillage.

8. The proposed analytical model should serve as a basis for the development of improved models for predicting the performance of down-cutting rotavators fitted with L-shaped blades. Modifications can also be made in the current model to develop a torque requirements prediction model for the up-cut (reverse) direction of rotation for rotavators fitted with the same type of blades. The model can also serve as a basis for developing torque predictions models for the types of rotavator blades.

9. Although preliminary observations made ruled out further investigations of the performance characteristics of the experimental rotavator, when operated in the

reverse direction of rotation, studies should be undertaken to evaluate both the torque requirements and the generation of thrust forces in this tillage direction. Additional investigation for this direction of rotation of the rotavator should include an investigation of the tool's soil amendment materials mixing, and the mixing of tilled soil from different soil depth ranges.