Variations of torque and specific tilling energy for different rotary blades

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Abstract: The torque characteristics and the specific tilling energies of three commonly used rotary blades in Thailand, i.e. the Japanese C-shaped blade, the European C-shaped blade and the European L-shaped blade, were studied to develop a suitable rotary blade for seedbed preparation in Thailand. The experiments were carried out in a laboratory soil bin at forward speeds of 0.034, and 0.069 m/s, and rotational speeds of 150, 218, 278 and 348 r/min (or 3.30, 4.79, 6.11 and 7.65 m/s) in sandy loam and clay soils. The results showed that the shape of the rotary blade influenced the torque characteristic and the specific tilling energy. For the Japanese blade, since its lengthwise curved portion tilled the soil first, the increase of tilling torque was less than the other two blades. For both European blades, the curved portion along the length and the tip was the first to impact the soil mass. The cyclic variation in torque could be observed distinctively, especially, for both European blades. The investigations indicated that the specific tilling energy of the Japanese C-shaped blade was the highest while the specific tilling energy of European L-shaped blade was the lowest.

Keywords: rotary tiller, C-shaped blade, L-shaped blade, torque, specific tilling energy

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1 Introduction

Soil tillage is the first and most important operation in agricultural work. The main objectives of tillage are to improve the physical conditions of soil, to destroy weeds and to prepare a suitable seedbed (Smith, 1955). In Thailand, the use of two-wheel tractors for agriculture has increased over the years. In 2004, there were 2,115,782 two-wheel tractors in use in the country (Office of Agricultural Economics, 2007). These two-wheel tractors have been installed with conventional plows (i.e. moldboard, disk plow) for primary tillage. Rotary power tillers have been imported since 1947 (Jarimopas, Senanarong and Tongsawatwong et al., 1999) and are still used in the dry field now. However, they have been used very rarely. Rotary tillers using Japanese C-shaped blades attached to two-wheel tractors have been developed (Senanarong and Sngiamphongse, 1994; Niyamapa and Rangdaeng, 1997). Ruangrungchaikul (1996) reported that numerous imported farm tractors had rotary tillers. Currently, rotary blades originally designed by foreign companies are produced in Thailand and the demand for rotary tillers is on the rise. The designs of these blades are still based on the original imported blades which are not so effective for local conditions. Consequently, there was a need to develop a rotary blade for use with the two-wheel tractor specifically for soil preparations in Thailand.

Hendrick and Gill (1971a, 1971b, 1971c, 1971d) studied the rotary tiller design parameters i.e. direction of rotation, depth of tillage, ratio of peripheral and forward velocity and blade clearance angle to present a simple technique for determining the necessary apparent

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clearance angle. Sakai (1977) developed the design equations of the edge-curve of the Japanese C-shaped blade to reduce the hooking character between the rotary blades and straws. Beeny and Khoo (1970) revealed that the shape of the tynes had great effect on the specific power requirement. L-shaped tynes were found to require 30% higher specific power than C-shaped tynes and L-shaped tynes also gave the greatest thrust on the vehicle. Beeny (1973) compared the performance of two sets of the different blades (i.e. the 'speed' and 'power' blades) under typical swamp rice conditions and found that the 'speed' blades used only 75% of the horsepower demanded by the 'power' blades. Salokhe et al. (1993) studied the effect of blade types (i.e. a rotor of C-shaped blades, a rotor of L-shaped blades and a rotor of C-shaped and L-shaped blades) on the power requirement and puddling of a rotavator in wet clay soil. The rotor of C-shaped blades consumed less power than the rotor of L-shaped blades and a rotor of a combination of C-shaped and L-shaped blades. Thakur and Godwin (1990) studied the cutting of soil by a rotating wire analogous to the tip of a rotary blade over a range of 'fetch-ratios' (bite length/depth ratio), with bite lengths from 50 to 250 mm and 100 mm tilling depth. A force prediction model on the basis of Mohr-Coulomb soil mechanics was proposed. Shibusawa (1992) proposed a qualitative model of clod formation for reverse-rotational tillage. The clod shapes from a simulation were confirmed to be fractal patterns in terms of the contour, crack curve and crack area distribution. Shibusawa (1993) developed a backward soil-throwing model which was applied to design the shape of a scoop surface of rotary blade. It indicated that the power requirement for reverse-rotational tillage with the new shaped blades was reduced by about half compared to forward and reverse rotational tillage with conventional blades. Kataoka and Shibusawa (2002) found that the crack formation process of adjacent rotation of reverse rotary blade was disturbed by the previous rotation. The results showed that the frequency of 120 Hz of the tillage resistance curve was nearly equal to the frequency which was calculated from the average value of 36 mm for the crack interval. Lee et al. (2003) developed a minimum tillage technique using Japanese C-shaped blades for preparing a rice seedbed to reduce the production cost. It was concluded that the four-blade rotor had the lowest torque requirement and the highest soil breaking (24.4%) ratio.

These researches showed that there were very few attempts to study the influence of the shape of the rotary blade on its torque characteristics. Therefore, the objectives of this research were to study the characteristics of torque generated by the Japanese C-shaped blade, the European L-shaped blade and the European C-shaped blade, and investigate the actual tilling processes, specific tilling energies and soil throwing patterns of individual blades.

2 Materials and methods

2.1 Experimental apparatus

The experiments were conducted in a laboratory soil bin of 250 cm length, 50 cm width and 60 cm depth (Figure 1). A horizontal movable carriage was installed with the experimental apparatus. The experimental setup consisted of a power transmission system, a test rotary blade, an inverter, and a magnetic pickup. Two electric motors were installed on the carriage. The upper 7 kW electric motor was used for rotational speed adjustment. The other 0.7 kW electric motor was used as a driven-shaft of the carriage. Thus the rotary blade shaft was rotated and moved horizontally simultaneously. Three different types of rotary blades, i.e. Japanese C-shaped, European L-shaped, and European C-shaped blades were used in the experiments. The Japanese C-shaped blade imported from Japan was made from spring steel. Its chemical composition was 0.59% C, 1.64% Si, 0.84% Mn, 0.01% P and 0.01% S, which is classified in JIS-SUP6. Both European blades produced by a Thai manufacturer were made from the same grade of spring steel. Its chemical composition was 0.61% C, 0.30% Si, 0.82% Mn, 0.04% P, and 0.03% S, which is classified in JIS-SUP9A. In the experiments, the rake angles (α) and the tilling radius were maintained constant at 75° and 21 cm respectively. The forward speed of the carriage was varied by changing sprockets. The slippage of the four tires of the carriage was negligible since two driving gears which were mounted on both the ends of the driven shaft of the carriage, were moved on two guide rack rails.

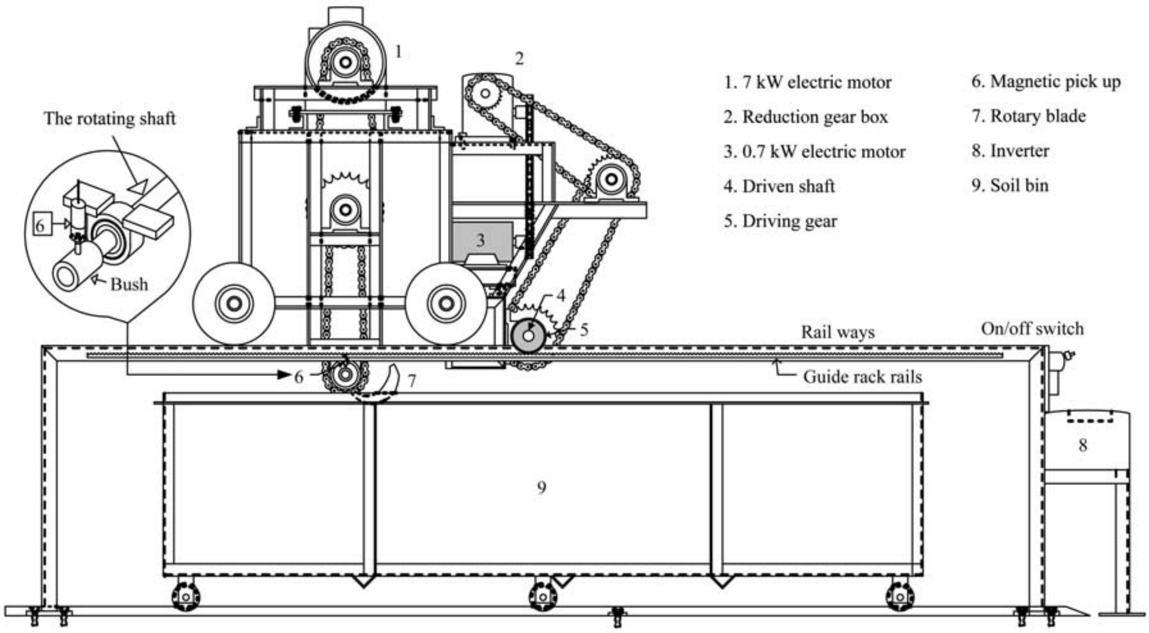


Figure 1 Schematic diagram of laboratory soil bin

2.2 Soils

Tests were carried out in sandy loam and clay soils. The soils were sieved through a 2 mm wire sieve. The average moisture content in all experiments was 11.3% (d.b.) just below the plastic limit (PL) of the sandy loam soil. The details of soils and their consistency limits are shown in Table 1. The wetted soil was stored in plastic bags at least 24 h to reach equilibrium and then transferred into a soil bin in layers to ensure uniform filling throughout the soil bin. Later, the soil was compacted uniformly to get the required specific weight. The initial soil conditions for the experiment are listed in Table 2. In these experiments, soil was prepared similar to dry-land conditions.

Table 1 Soil properties in the experiments

Soil type (USDA Classification)	Particle size distribution/%			Consistency limits/% d.b.		Source
	Sand (2–0.42 mm)	Silt (0.42–0.002 mm)	Clay (<0.002 mm)	Plastic limit	Liquid limit	
Sandy loam soil	59.83	25.14	15.03	12.89	16.01	Srisaket Province in Northeastern part of Thailand
Clay soil	4.88	32.18	62.94	23.2	38.7	Nakorn Pathom Province in Central part of Thailand

Table 2 Experimental conditions of soils

Soil type	Sandy loam soil	Sandy loam soil	Clay soil
Moisture content/% d.b.	11.3	11.3	11.3
Specific weight/kN · m^{-3}	9.81	11.67	9.81
Cone index (average)/kPa	250	330	1,150

2.3 Test conditions

The characteristics of the torque acting on the rotating shaft were studied in sandy loam and clay soils at a specific weight of 9.81 kN/m^3, a tilling depth of 12 cm, forward speeds of 0.034 and 0.069 m/s, and rotational speeds of 150, 218, 278, and 348 r/min (or 3.30, 4.79, 6.11, and 7.65 m/s). The angle between the radial direction and the tangent line of the inner scoop surface (α) was maintained constant at 75° (Figure 2). To study the effect of specific weight on the torque characteristic, the experiments were conducted at 9.81 and 11.67 kN/m^3 specific weights in sandy loam soil. To indicate the effect of the tilling depth, the experiments were conducted at 12 and 14 cm tilling depth in clay soil. A summary of the operating conditions is shown in Table 3.

Table 3 Operating conditions during the tests

Test conditions	Japanese C-shaped blade		European L-shaped blade	European C-shaped blade
Specific weight of soil/kN·m^{-3}	9.81	11.67	9.81	9.81
Forward speed/m·s^{-1}	0.034 and 0.069	0.034 and 0.069	0.034 and 0.069	0.034 and 0.069
Rotational speed/r·min^{-1}	150, 218, 278 and 348	150, 218, 278 and 348	150, 218, 278 and 348	150, 218, 278 and 348
Tilling depth/cm	12 and 14	12	12 and 14	12 and 14
Tilling width/cm	4.5	4.5	13.5	12
Soil type	Sandy loam and clay	Sandy loam	Sandy loam and clay	Sandy loam and clay
Rotor radius/cm	21	21	21	21
Rake angle, α/degree	75	75	75	75

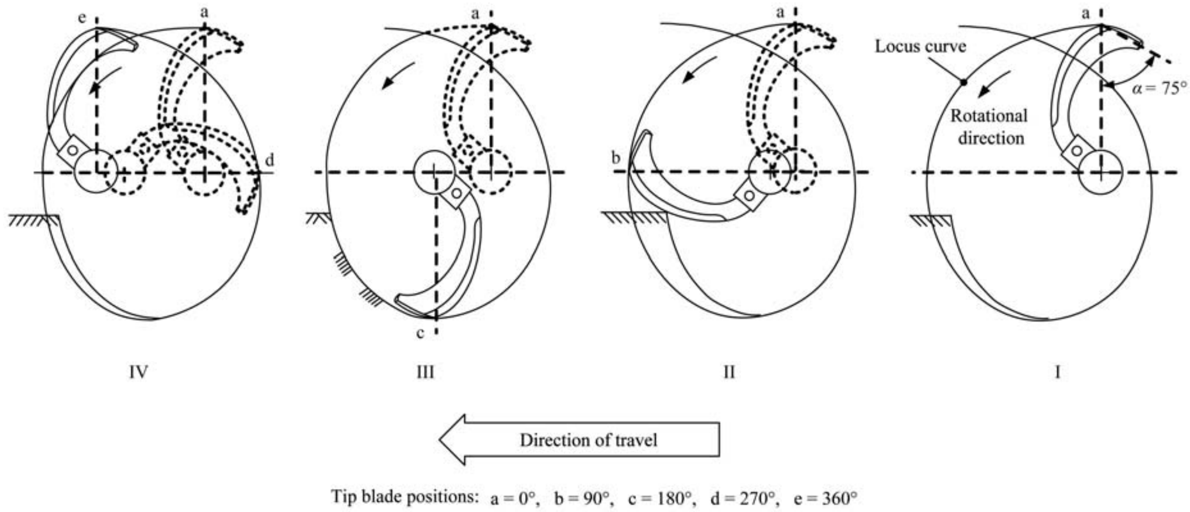


Figure 2 Schematic of the tilling process and the positions of blade tip

2.4 Measuring techniques

The torque acting on the rotating shaft during tilling by test blades was sensed by two cross-strain gauges (1, 2, 3, and 4) fixed at the opposite positions on the rotating shaft and connected into the Wheatstone bridge configuration as shown in Figure 3. The calibrations showed a high degree of linearity between the applied torques and the bridge outputs. The coefficient of determination (r^2) for the relationship between voltage output and torque was equal to 0.99. There was no the hysteresis effect between the calibration curves for increasing and decreasing applied torque. To measure the forward speed of the experimental set, two markers 120 cm apart (A, B) were placed approximately in the middle of the test run. Thus the forward speed was calculated from the time required for the carriage to travel the distance (120 cm) between both of the markers. The rotational speed of the shaft was measured by a magnetic pickup.

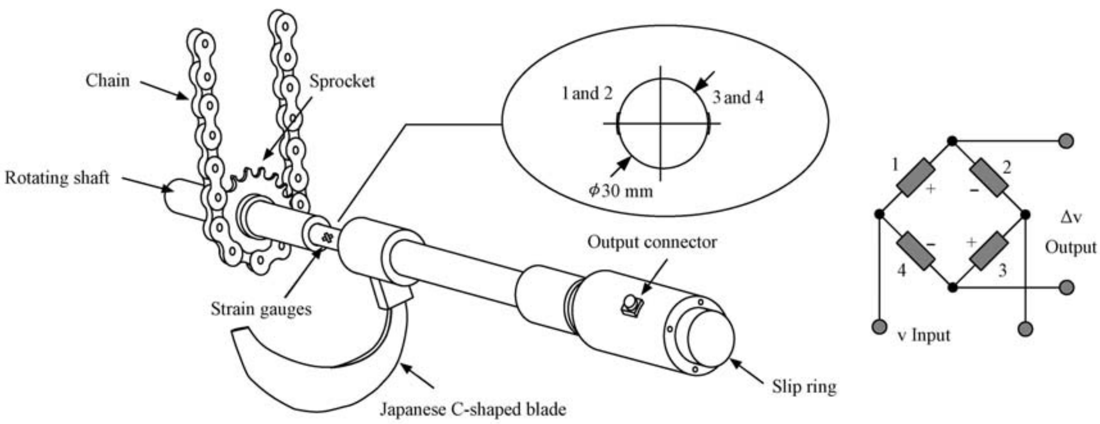


Figure 3 Schematic of two cross-strain gauges bonded on shaft surface

2.5 Data processing

During tilling, the soil reaction force (torque) was sensed by the strain gauged torque transducer, amplified and recorded on a tape recorder (TEAC MR-30). Simultaneously, the signals from the magnetic pick up were also recorded. Later these signals were analyzed at a sampling rate of 500 Hz.

2.6 Regulation of the rotational angle

A schematic of the tilling process of the rotary blade is shown in Figure 2. Zero degree of rotational angle ($\theta = 0°$) means that the position of the blade tip and the center of rotation are in line on the vertical plane, that is position a. The positions b, c, d and e show the rotational angles of 90°, 180°, 270° and 360° respectively. In this paper, the tilling process is classified into four quadrants. The first quadrant is the range of rotational angle from 0° to 90° and the rotational angle ranges from 90° to 180°, 180° to 270° and 270° to 360° were the second, the third, and the fourth quadrants respectively.

2.7 Calculation of tilling energy and specific tilling energy

Tilling energy means the energy per revolution of the blade. It was calculated by the forces acting on a rigid body. The tilling energy is produced by torque acting on the rotating shaft so the work done is obtained by multiplying force by length. The work done is obtained by integrating the initial value θ_1 of the angle θ to its final value θ_2 as shown by Eq. (1).

$$U_{1\to 2} = \int_{\theta_1}^{\theta_2} M\, d\theta \tag{1}$$

Where, $U_{1\to 2}$ is a work of all forces acting on the various parts of the body; M is a moment (or torque); $d\theta$ is the angle expressed in radian.

The torque function in each experiment was determined and expressed in polynomial regression. Then it was used to calculate tilling energy used per soil cutting round.

The specific work was used for comparison between the performances of the three different types of rotary blades (Beeny, 1973). The specific tilling energy was calculated by using Eq. (2).

$$\text{Specific tilling energy} = \frac{\text{Tilling energy per bite}}{\text{Soil volume worked per bite}} \tag{2}$$

2.8 Estimation of position of soil clods in tilling process

The relationship between the distance in a photograph and the actual distance in the laboratory were used to estimate the position of thrown soil clods. The soil clod position in the photo (imaginary plane) was determined by referring to the reference lines on a background screen and soil surface. Figure 4 shows the methodology of estimating the soil clod position from a photograph. A point A is defined as an estimated central point of soil clod on the imaginary plane. The lines ee' and ff' on the imaginary plane were drawn along the nearest reference lines on a background screen. Then the line ef which was parallel to the horizontal reference line on the background screen was drawn through the point A. Since the distances Ae, and Af were directly measured, the relation between Ae, Af, and ef can be expressed as in Eq. (3).

$$\frac{Ae}{ef} + \frac{Af}{ef} = 1 \tag{3}$$

Be' or Bf' are obtained by the distance ratio, as expressed in Eq. (4), to determine the position of B.

$$Be' = e'f' \cdot \frac{Ae}{ef} \quad \text{or} \quad Bf' = e'f' \cdot \frac{Af}{ef} \tag{4}$$

The position of B is calculated once again with the nearest reference lines gg' and hh' which were selected on the soil surface.

$$\frac{Bg}{gh} + \frac{Bh}{gh} = 1 \tag{5}$$

Similarly, C, Cg' or Ch' was calculated to specify the position of C.

$$Cg' = g'h' \cdot \frac{Bg}{gh} \quad \text{or} \quad Ch' = g'h' \cdot \frac{Bh}{gh} \tag{6}$$

Since the soil clod position must be located on the 4 cm square-grid screen, the position of C was determined by reference to lines ii' and $h'j$. In this case, specially, both lines of ee' and $h'j$ are the same line.

$$\frac{Ci}{ih'} + \frac{Ch'}{ih'} = 1 \tag{7}$$

To specify the position of D on any of the chosen horizontal reference line on the screen, the line $i'j$ is drawn, so its position can be specified by the distance ratio Di' or Dj.

$$Di' = i'j \cdot \frac{Ci}{ih'} \quad \text{or} \quad Dj = i'j \cdot \frac{Ch'}{ih'} \tag{8}$$

Finally, the position of soil clod is determined by the line drawn from C passing D to E with its length equal to the length of AB.

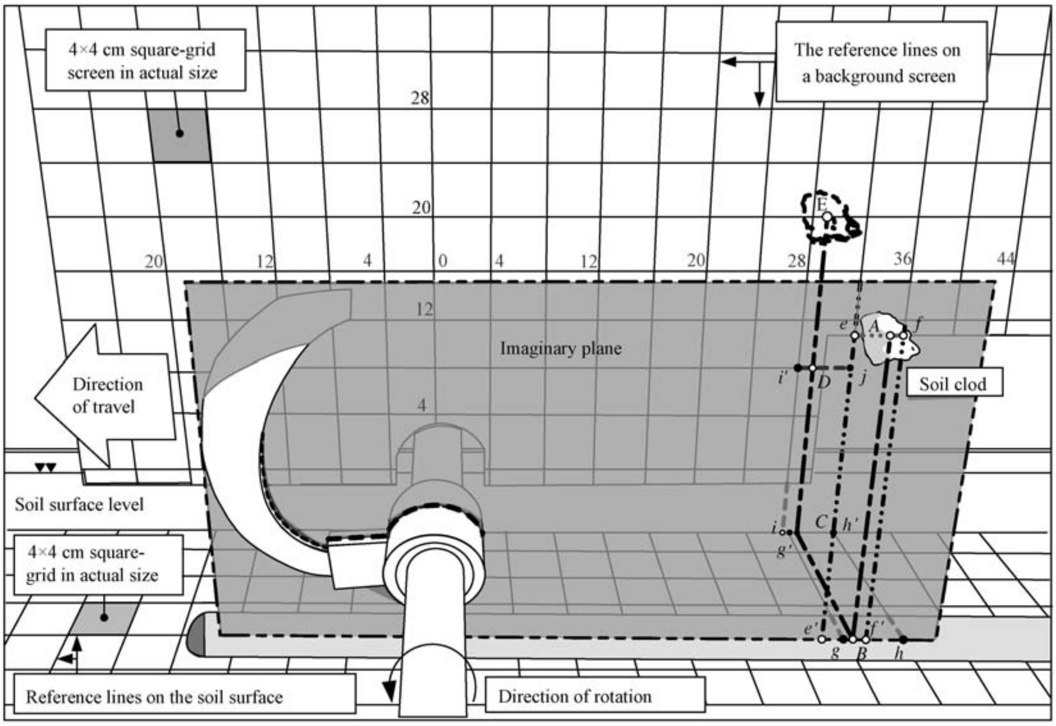


Figure 4 Schematic of the method to estimate the position of soil clods

3 Results and discussion

3.1 Tilling process by the rotary blades

The down-cut tilling process of three rotary blades could be divided into four quadrants as shown in Figure 5. In the 1st quadrant, the no-tillage stage, the blade was still rotating in the uncut soil. The tilling stage was the place where the blade cut into the soil mass as shown in the 2nd quadrant. The 3rd and 4th quadrants show the soil being held and thrown by the blades. In these quadrants, some parts of the tilled soil were held on the scoop and another part was thrown in the air.

Especially for the European L-shaped and the European C-shaped blades, an important observation in the 3rd and 4th quadrants was that a part of the tilled soil was thrown from the front of their scoop surface. This behavior was affected by the occurrence of the soil wedge adhering to the scoop surface of the European blades as shown in Figure 6. The soil which was sliding from the head of the tine tip to the end of the tip along the scoop surface was interrupted by this soil wedge.

3.2 Characteristics of tilling torque

Figure 7 shows the characteristics of torque of the three rotary blades tested. These typical graphs were obtained during a single rotation of the test blades for both soils at 12 cm tilling depth, 150 r/min rotational speed, 0.069 m/s forward speed, and 9.81 kN/m^3 specific weight of soil. It was clearly observed that there was a higher torque acting on the rotary shaft in clay soil than in sandy loam soil. The difference of the torque characteristics between the Japanese C-shaped blade and the European rotary blades could also be observed clearly.

In the 1st quadrant, although the tip of blade never cut the soil, there was torque acting on the rotary shaft due to friction and inertia. In the case of the Japanese C-shaped blade, there was a rise in torque with its approach to 90° rotation angle. As it approached this point, the soil was slightly tilled by the curve of the straight blade portion before it was tilled by the tip of blade. In the 2nd quadrant which was the tilling stage, the torque increased during the actual tilling process and reduced during soil throwing and loosening. In the case of the Japanese C-shaped blade, the torque acting on the rotary shaft increased continuously until it reached the maximum value at rotational angle from 108° to 125° and then it decreased. For both European blades, the tilling torque suddenly increased as the tine tip touched the soil. The maximum torque values appeared during 102° to 120° rotation of these blades. After the maximum torque was obtained, it immediately decreased with further rotation. The torque curves were characterized in the form of somewhat sinusoidal curves due to the cyclicity of the reaction force between soil and tool which could be observed more clearly in clay soil conditions since the shear strength of clay soil is determined primarily by cohesive forces (Yong and Warkentin, 1975).

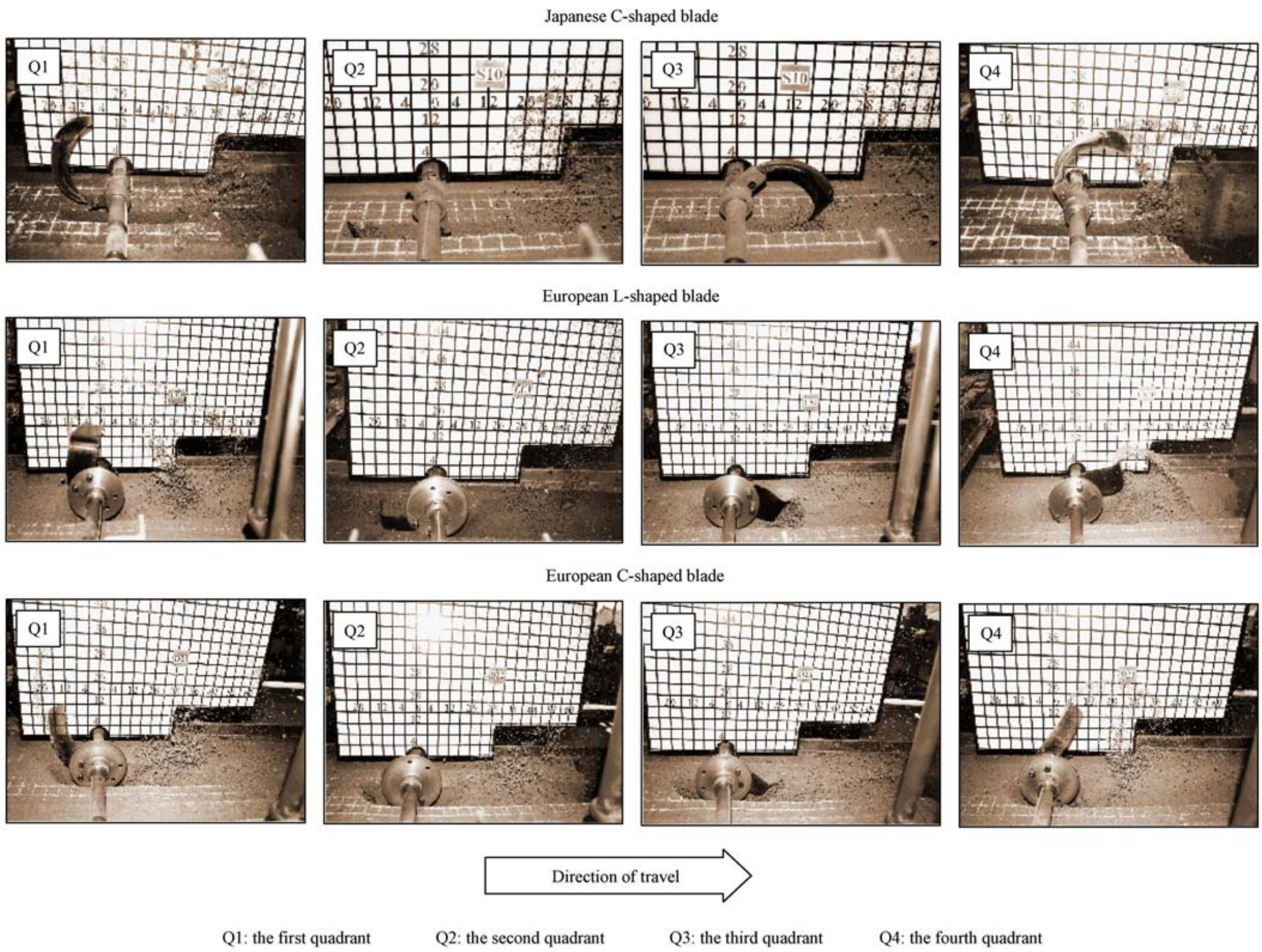
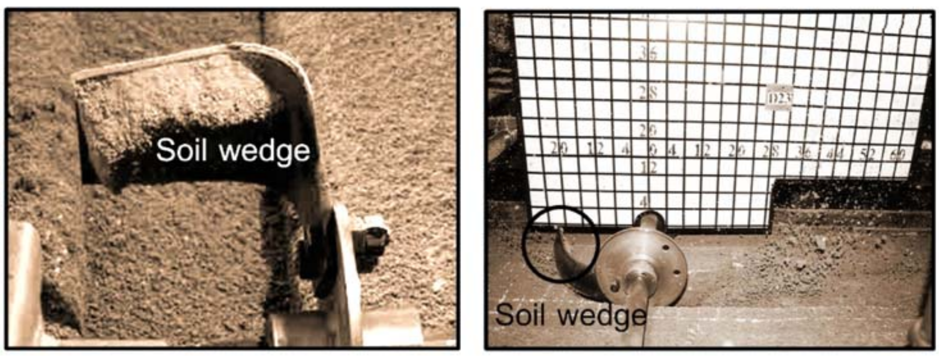


Figure 5 Tilling processes of the rotary blades



a. European L-shaped blade b. European C-shaped blade

Figure 6 A soil wedge on the scoop surface

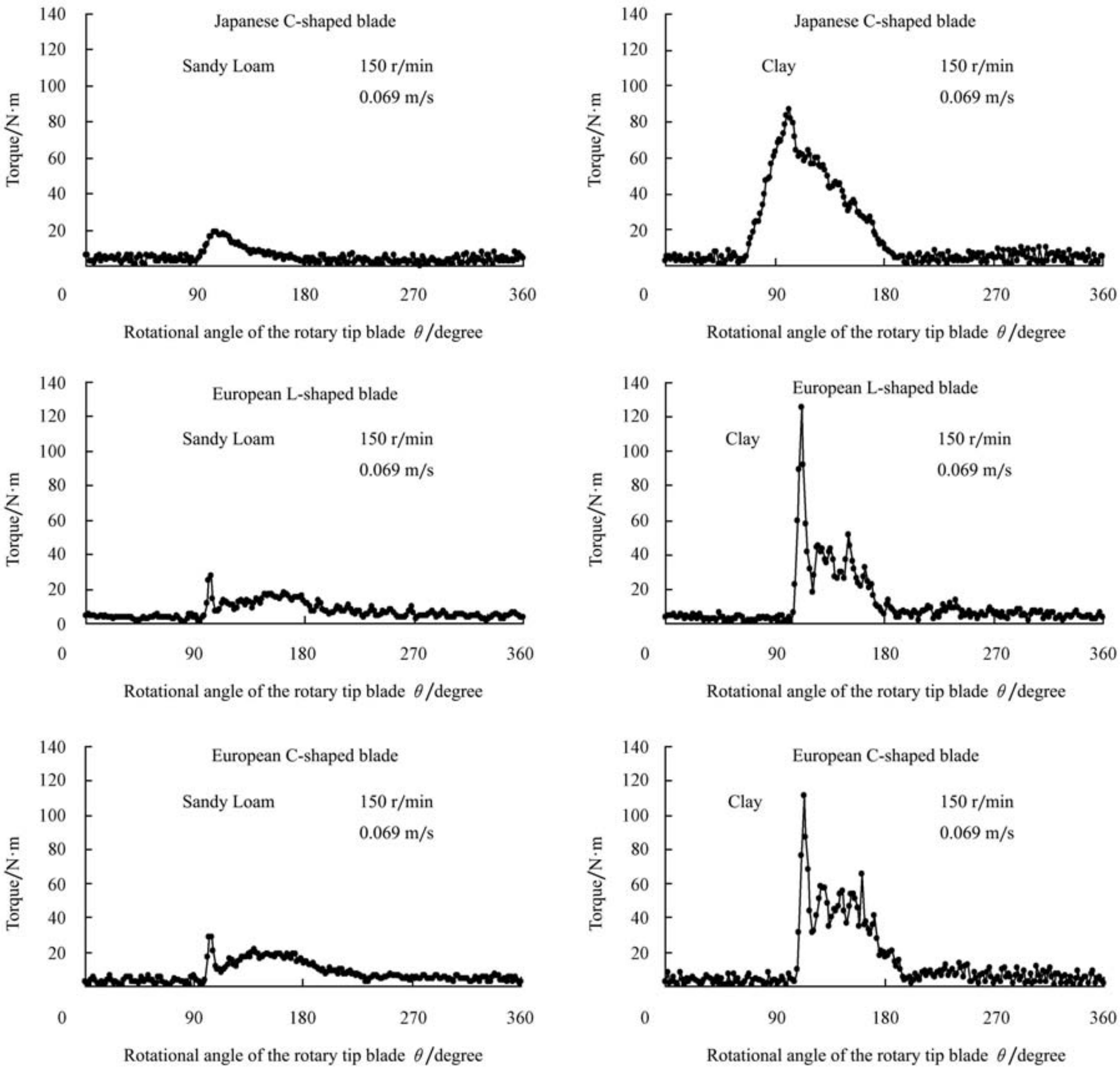


Figure 7 Characteristics of torque curve

Makanga, Salokhe and Gee-Clough (1997) and Kataoka and Shibusawa (2002) explained that it was the phenomenon of reaction forces between soil and tillage tool that related to soil failure pattern. Subsequently, the tilled soil in the second quadrant was still held on the scoop surface of these rotary blades in the third quadrant. This soil was shattered and then thrown backwards. Noticeably, in the 3rd and the 4th quadrants, the torque acting on the rotary shaft of both European blades was slightly higher than for the Japanese C-shaped blade. Due to the adhesion of a soil wedge on these European blades, the increasing inertia force might have caused an increase in the torque.

Figure 8 shows the characteristics of torque acting on the rotary shaft at various forward speeds and rotational speeds in clay soil. The results show that the torque increased with an increase of the forward speed. The reason is that as the forward speed increased, the volume of soil slice cut also increased and thus so did the torque required. The characteristics of torque depended on the shape of the blades which induced different cutting methods. For the Japanese C-shaped blade (Figure 9a), almost the straight blade was the first to start tilling the soil. Thus its torque rose to the maximum value before tine tip touched the soil. Evidently for both European blades (Figures 9b and 9c) the curvature between the straight blade and blade tip (smaller compared to Japanese blade) was the first portion which began to till into the soil mass at the soil surface level. This caused a sudden rise in the characteristic of torque. Finally, the distinctly different size of the blade portions of these blades determined their torque characteristics.

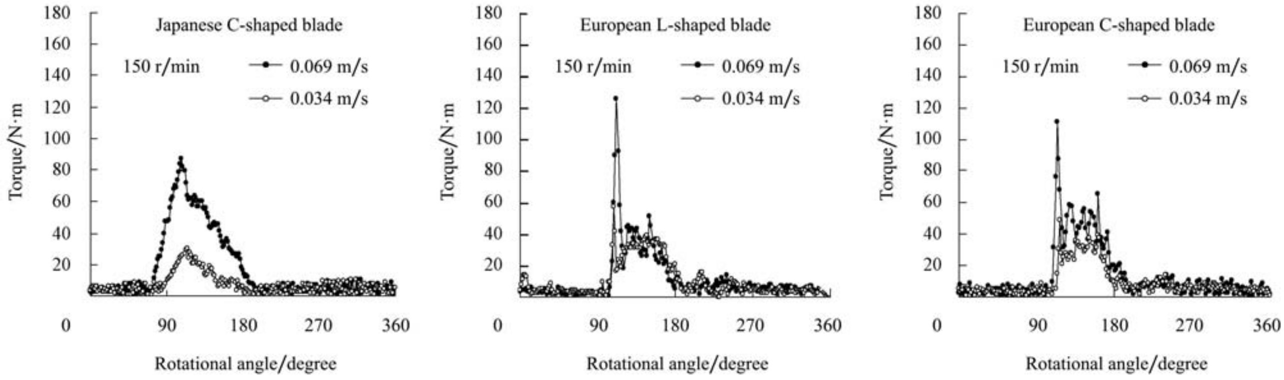


Figure 8 Torque obtained at 12 cm tilling depth, and 9.81 kN/m^3 soil specific weight in clay condition for different rotary blades

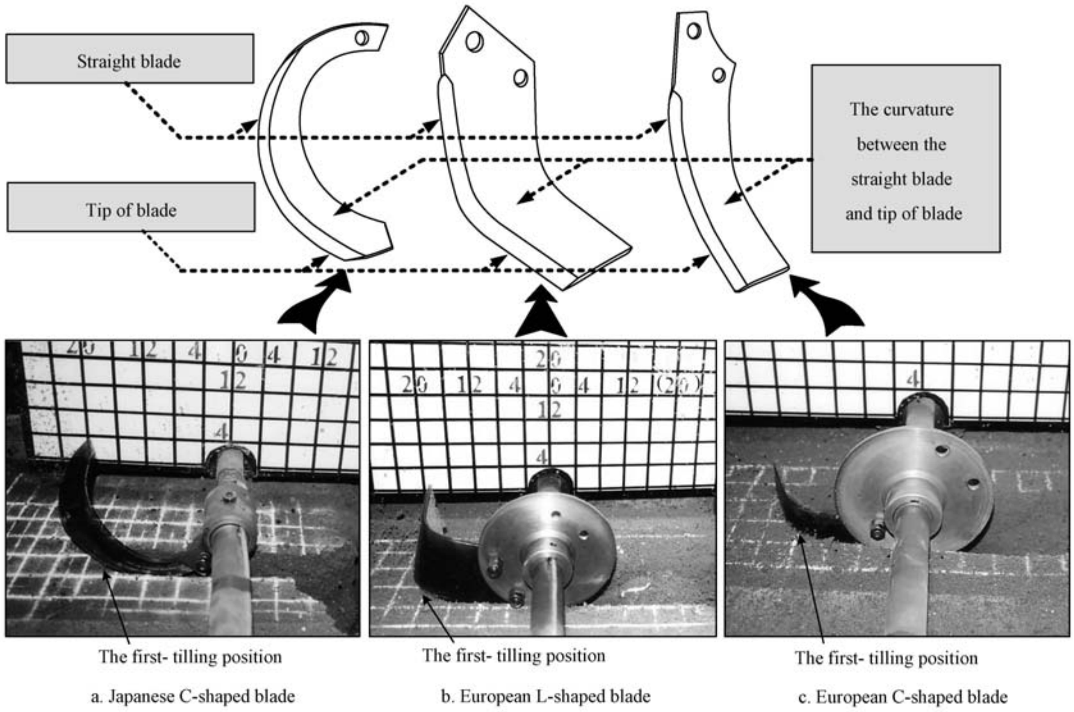


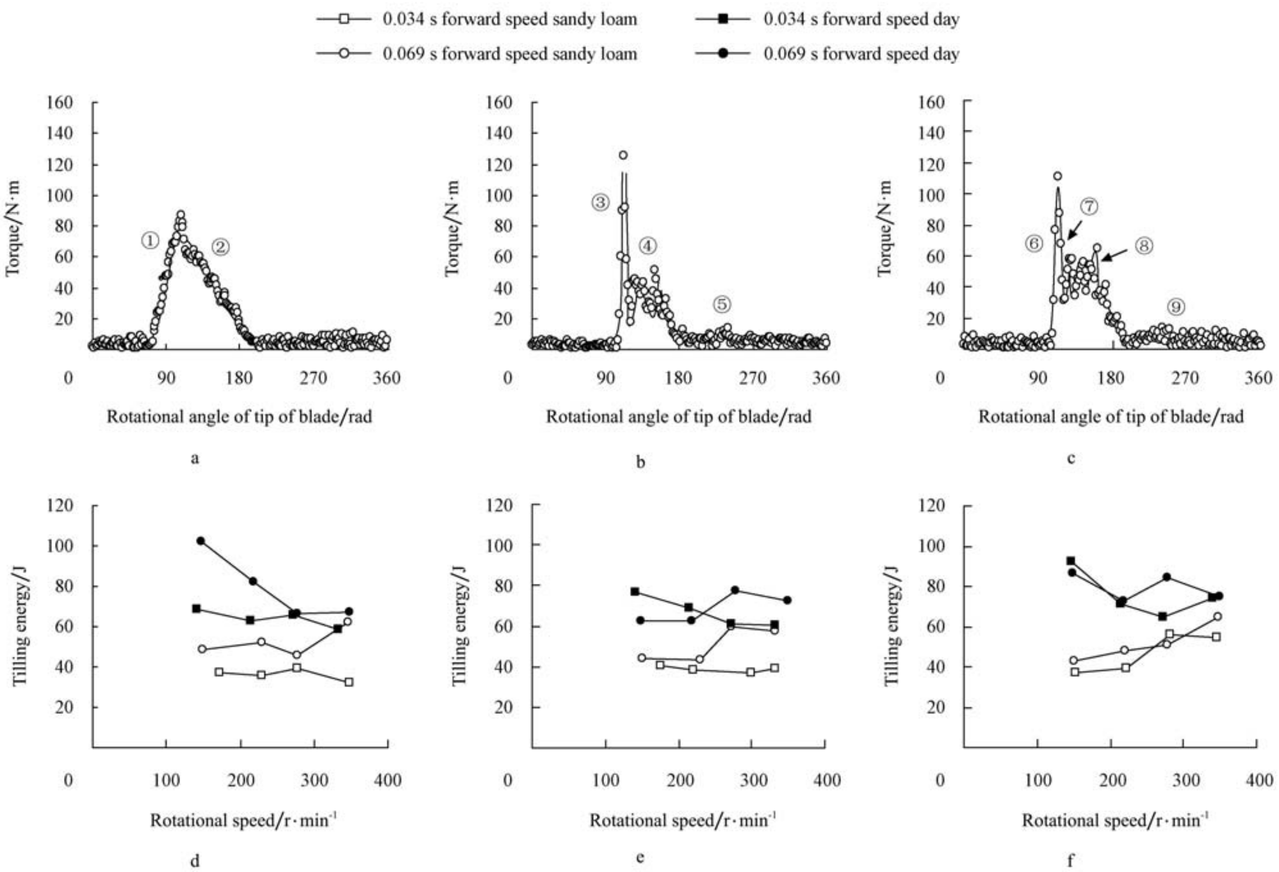
Figure 9 First-tilling position

3.3 Tilling energy and specific tilling energy

Polynomial regressions were used to express the relationship between torque and rotational angle of blade tips as shown in Figure 10. The tilling energy per tillage around is a summation of the integrated torque functions. Figure 10 shows the tilling energy of blades at different forward and rotational speeds in both soils. Although the relationship between the tilling energy and forward and rotational speeds did not show any trend, these results distinctly showed the effect of soil type. Since the size of clay particles was less than 0.002 mm causing compact arrangement, the contact area between the soil particles in clay soil was more than in sandy loam soil. Therefore, the energy requirement in clay soil was higher than in sandy loam soil.

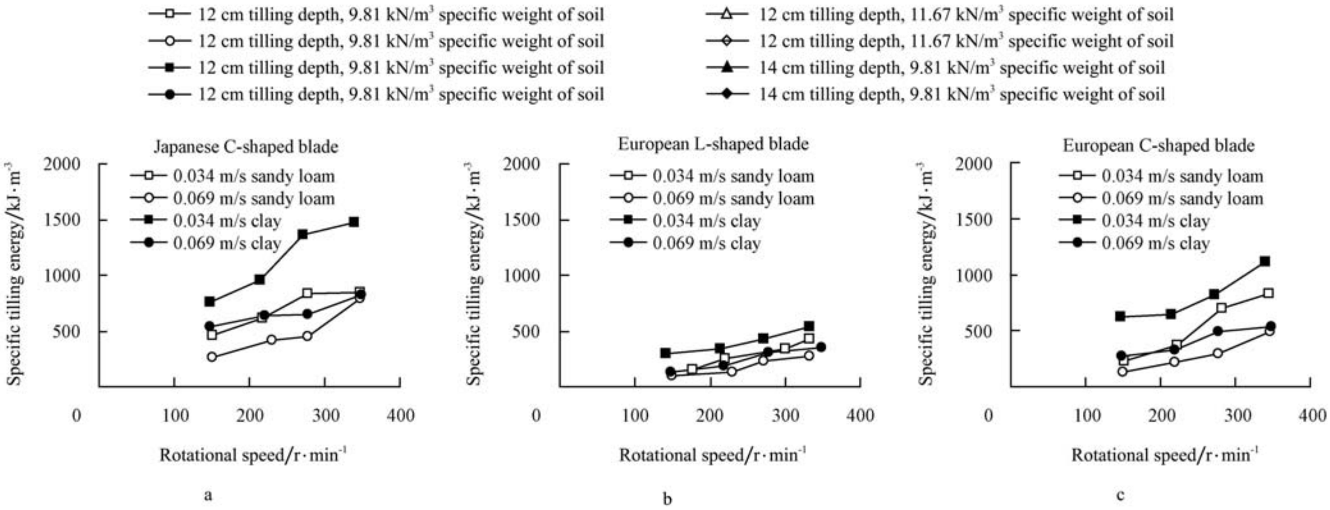
The specific tilling energy requirement for all experiments is plotted in Figures 11a to 11f, which show tilling energy per unit volume of the soil tilled by the blade in a single rotation. Figures 11a and 11d illustrate the effect of the specific weight of soil on the specific tilling energy of Japanese C-shaped blade at 12 cm tilling depth in sandy loam soil. The specific tilling energy of the Japanese C-shaped blade at 11.67 kN/m^3 specific weight of soil was 2.6%–11.3% more than at 9.81 kN/m^3 specific weight of soil. The effect of the tilling depth on the specific tilling energy in clay soil can be observed from Figs.11a to 11f. These figures show that the specific tilling energy of the Japanese C-shaped, the

European L-shaped and the European C-shaped blades at 14 cm tilling depth (Figs.11d to 11f) were 0.5%–13.3%, 3.5%–22.6%, and 4.3%–25% more than at 12 cm tilling depth (Figs.11a to 11c) respectively. The specific tilling energy of the Japanese C-shaped blade was higher than both European blades. The specific tilling energy for the European L-shaped blade was the least compared to the other blades. Experiments in sandy loam soil indicated that the average specific tilling energy requirement of the Japanese C-shaped blade was about 2.0–4.0 and 1.0–1.9 times higher than the European L-shaped and European C-shaped blades respectively. The specific tilling energy requirement of the Japanese C-shaped blade was about 2.8–2.9 times and 1.4–1.6 times higher than the European L-shaped and the European C-shaped blades in clay soil respectively.



Note: ①–⑨ Curves of the torque functions in each range of rotational angle

Figure 10 Torque functions for tilling energy calculation (a, b, and c) and tilling energy at 12 cm tilling depth, and 9.81 kN/m^3 specific weight of soil (d, e, and f)



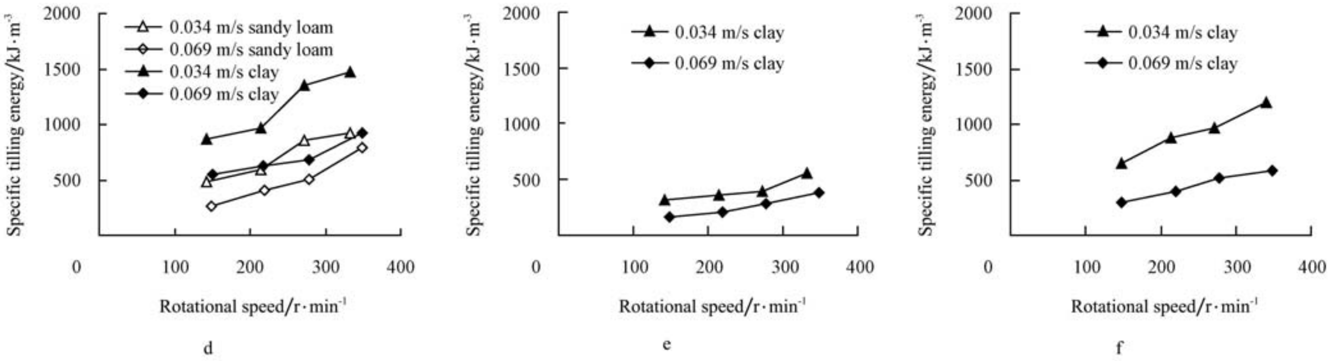
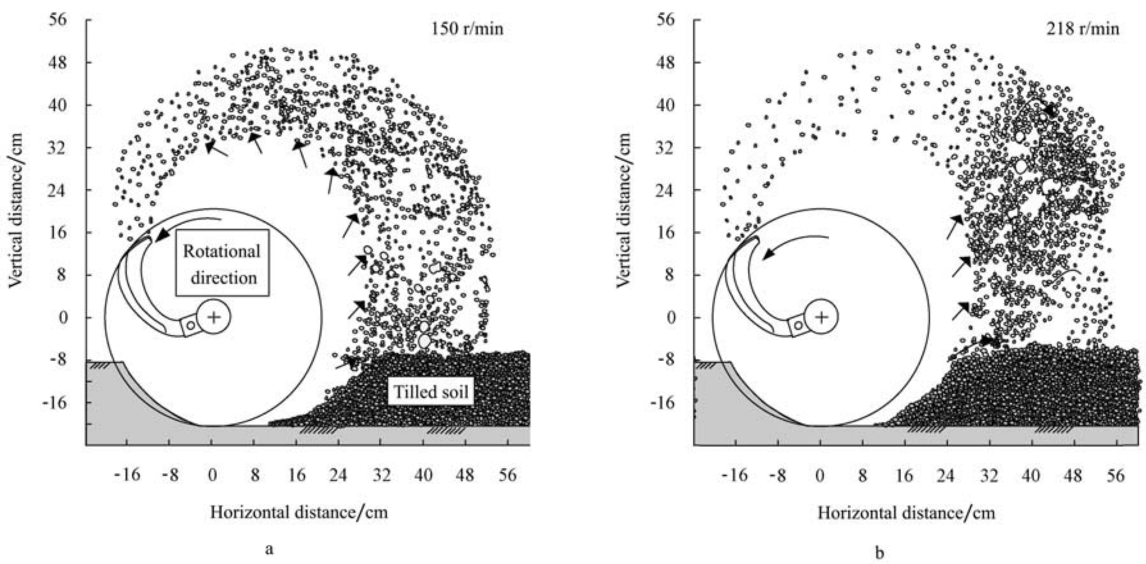


Figure 11 Specific tilling energy per tilling round

Very few researchers have explained the influence of the shape of a rotary blade on its torque characteristic and the specific tilling energy used in the tilling process. In this work, an interesting observation was noted. The shape of the rotary blade and its blade holding mechanism are important factors that affect its torque characteristic. The straight blade especially determined the initial slope of tillage torque before it reached the maximum. Moreover, even though tilling width of both European blades was wider than the Japanese C-shaped blade, their tilling energies were not associated with the tilling width of the blades. This is difficult to explain since the reaction forces of each test blade were affected by the complex shape of these blades. However, the wider tilling width of the European blades might have caused cyclicity of the torque due to the soil volume handled by these blades.

3.4 Throwing patterns of different rotary blade shapes

The soil throwing patterns of the three rotary blades are shown in Figure 12. The positions of soil clods thrown were determined by the method explained earlier. In addition, the soil movements were observed by video replays. In case of the Japanese C-shaped blade, four different throwing patterns as a function of rotational speed were identified. The first pattern (Figure 12a) appeared when the blade was tilling at 150 r/min rotational speed. Some part of the tilled soil was thrown into the furrow and the remainder was thrown behind and around the rotary shaft. At 218 r/min rotational speed, most of the soil clods cut by the blade were thrown in the air and dropped behind the rotary shaft as shown in Figure 12b. The third and the fourth patterns appeared for the tests at 278 and 348 r/min rotational speeds respectively. These two throwing patterns showed almost similar soil movements (Figures 12c and 12d). All of the soil cut by the rotary blade was thrown and dropped to the furrow bottom behind the rotary shaft.



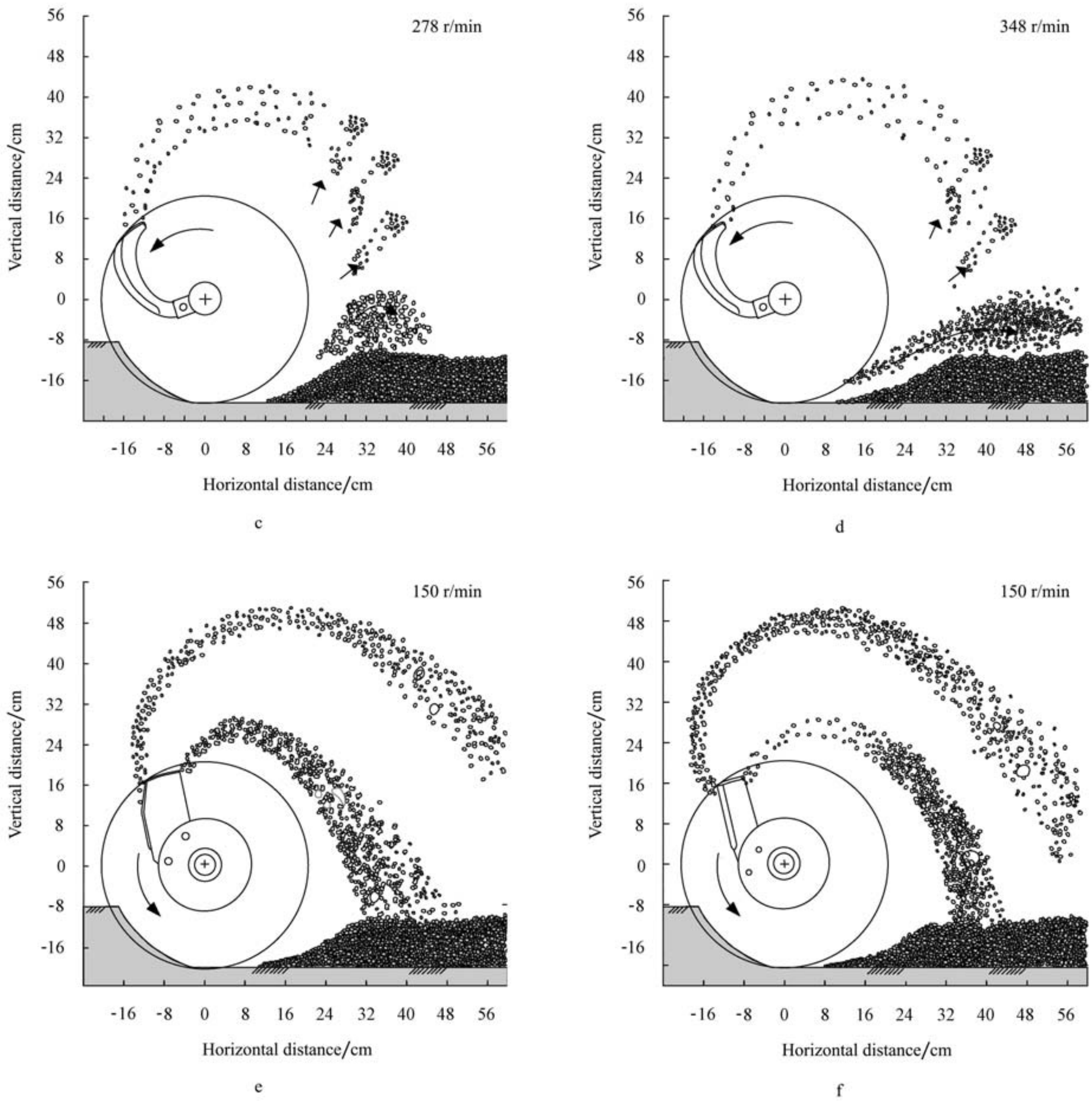


Figure 12 Soil throwing patterns of rotary blades: Japanese C-shaped blade (a, b, c, and), European L-shaped blade (e) and European C-shaped blade (f)

For both European blades, the soil throwing patterns were similar, but were distinctly different from the throwing patterns of the Japanese C-shaped blade. Evidently, there were two streams of soil movement, the upper and lower as shown in Figures 12e and 12f. The upper and lower streams were the movement of the soil clods released around the rotary shaft from the front and the rear parts of the blade scoop surface respectively. The reason for the soil clods thrown from the front of the scoop surface was the appearance of a soil wedge on the scoop surface. It caused the soil clods to slide on the scoop surface from the front to the rear altering the trajectory of backward throwing.

4 Conclusions

The results in these experiments showed that the torque characteristics of the Japanese C-shaped blade, the European L-shaped blade and the European C-shaped blade during tilling were different. The varying torque was related to the blade tip positions of each rotary blade. The shape of the rotary blade influenced its torque characteristic. The Japanese C-shaped blade's maximum torque was the lowest and its torque increased less steeply when compared with both European rotary blades in all experimental conditions. The edge curve of the straight blade determined the torque rise. For the

European blades, the torque suddenly increased. Furthermore, the cyclicity in torque at a later stage of the European rotary blades was related to a soil wedge adhering on the scoop surface of the blades.

The specific tilling energies of all blades increased with the rotational speed. When the depth and the soil specific weight increased, the specific tilling energy also increased. The specific tilling energy decreased when the forward speed increased. The specific tilling energies in clay soil were more than in sandy loam soil. The specific tilling energy of the Japanese C-shaped blade was higher than the European L-shaped and the European C-shaped blades in sandy loam soil about 2.0–4.0 times and 1.0–1.9 times, respectively. Also, the specific tilling energy of the Japanese C-shaped blade was higher than the European L-shaped and European C-shaped blades in clay soil about 2.8–2.9 times and 1.4–1.6 times, respectively. So, the specific tilling energy per a round of cutting of the European L-shaped blade was the least compared to other blades. For the Japanese C-shaped blade, the rotational speed influenced its soil throwing pattern. For the two European rotary blades, the tilled soil throwing had an almost similar pattern that was different from the soil throwing pattern of the Japanese C-shaped blade.

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