Soil Reactions on the Cage Wheels with Staggered Echelons of Half-width Lugs and Perfect Chevron Lugs in Wet Clay Soil

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Abstract

This study aimed at investigating the performance of cage wheels with staggered echelons of half-width lugs. Effect of free sinkage on two lug arrangements was studied. The experiments were carried out in a soil bin filled with clay soil at 51% average soil moisture content (dry basis) and 140 kN average soil cone index. All tests were conducted at a forward speed of 0.87 m/s (3.13 km/h) common for two wheel tractors. The results showed that soil reacts differently to the different lug arrangements. The pull forces on cage wheel with perfect chevron arrangement were lower than that with staggered echelons of half-width lugs at 24^o and 30^o lug spacings around the periphery. The lift force of cage wheel with perfect chevron arrangement was lower than that with staggered echelons of half-width lugs at 24^o and 30^o spacing around the periphery. The sinkage of cage wheel with perfect chevron lug arrangement was lower than cage wheel with staggered echelons of half-width lugs at 24^o and 30^o spacing around the periphery. The results showed that the lug arrangements significantly affected the pull and lift forces on cage wheels. The tractive power curve can be represented by a polynomial function. The power reached maximum value at 15% wheel slip and then it decreases further with increase of wheel slip. The perfect chevron arrangement provided lesser sinkage and lower traction, while the staggered echelons of half-width lugs at 30^o spacing around the periphery give optimum traction during wet land cultivation.

Keywords: Wet clay soil; cage wheel; staggered echelons of half-width lugs; perfect chevron arrangement; sinkage.

Introduction

In paddy fields, open flat-lugged cage wheels are more popular compared to rubber tires due to their higher traction and floatation. The open flat-lugged cage wheels are also inexpensive, easy to fabricate, and can be made wider than a conventional tire. However, compared to the axle power, the traction performance of the open flat-lugged cage wheels is still low (Hossain, 1981). Salokhe (1986) stated that a good traction device should be able to deliver power close to that supplied to its axle.

A study on the effect of the design parameters of cage wheel in soil bin showed that wheel with 680 mm diameter, 16 lugs and 220 mm lug width gave optimum dynamic performance (Nakashima and Tanaka, 1986). The thrust efficiency of the lug was maximum at 30% slip in the case of a wheel with 12 lugs. These scholars also studied the effect of lug angle on the soil reaction in clay loam in a soil bin and found that the average lift of a lug increased when the lug angle became large but the average thrust decreased. The thrust was maximum when the wheel slip was 28.8%.

Jayasundera (1980) tested a pair of cage wheel with a diameter of 93 cm and a width of 38 cm fitted to a 12.5 kW four-wheel (two-wheel drive) tractor in a flooded, puddled field. He found that the 30° lug spacing with 12 lugs gave the highest power transmission. The performance of movable and fixed lug wheels was investigated by Hermawan et al. (1998). The results showed that sinkage, wheel slip and driving torque of the lug wheels fluctuated periodically with the rotation angle. The periodic fluctuations corresponded to the angular lug spacing.

There are two configurations which have the potential of reducing the resulting side forces on a cage wheel viz. straight and staggered chevron arrangements similar to a rubber tire. The small lug opening may result in fewer variations and the right-half/left-half staggered lugs may result in smaller side force (Watyotha and Salokhe, 2001a & b).

The performance of cage wheels with lug arrangement similar to rubber tire (staggered echelons of half-width lugs) was studied by Watyotha and Salokhe (2001a & b). In their study, the cage wheels with staggered echelons of half-width lugs at 15^{o} angle of staggered echelon at 24^{o} and 30^{o} lug spacing gave superior performance compared to other combinations including conventional cage wheel. This is an evidence that the lug opening, end of lug clearance and lug overlapping values will change if the lug spacing and angle of staggered echelons are changed. In their study, however, the lug sinkage was kept constant which is unlikely situation in the real life working of the cage wheels in the field.

This study, therefore, aimed at investigating the performance of free sinking cage wheels with perfect chevron arrangement of lugs or staggered echelons of half-width lugs without lug opening and compare it with the performance of cage wheels with staggered echelons of half-width lugs with lug opening.

Materials and Methods

The cage wheels with staggered echelons of half-width lugs with and without lug opening were studied (Figs. 1 and 2). Fig. 1 shows the schematic of cage wheel with definition of various terminology used. Fig. 2 shows the actual cage wheels tested. Both cage wheels, namely the one with staggered echelons of half-width lugs and the perfect chevron arrangement of lugs are newly developed and, therefore, they have distinct characteristics with the commercial models currently available in market. The former type is a modification of the model designed by Watyotha and Salokhe (2001a & b), while the latter is newly developed. The lugs of the cage wheels used in this study were the staggered echelons of half-width lugs with 24^{o} and 30^{o} lug spacings around periphery, as well as without lug opening (perfect chevron configuration) at 30^{o} lug spacing around periphery (Fig. 1b). Table 1 presents the specifications of the cage wheels. The more details of terminologies used to describe specification of cage wheels are given by Watyotha and Salokhe (2001a & b).

The experiments were carried out in a soil bin with of size 18 m X 2 m on which a hydrostatic driven remote controlled carriage was mounted. The soil bin was filled with clay soil with 51% average soil moisture content (dry basis) and 140 kN average soil cone index.

The special set up to test the free sinking of the cage wheels consisted of a fixed and movable frame designed to support the test wheel mounted on the soil bin carriage (Figs. 3 and 4). The total weight of the frame was about 1.4 kN, half the weight of a commonly used power tiller in Asia, since only one wheel was used for testing. The characteristic of the two orthogonal force components (pull and lift forces) exerted by the cage wheels were obtained using an octagonal ring transducer. The torque was measured by a load cell mounted on the wheel shaft. The sinkage was measured by the displacement transducer. Data obtained were amplified and recorded via a digital dynamic strain amplifier. All transducers were calibrated prior to the tests. The test wheel was rotated by a hydraulic motor through sprocket and chain arrangement. A hydraulic pump powered by the PTO drive of carriage was used to drive the hydraulic motor.

The soil was prepared using a rotary tiller. Water was sprayed uniformly between rotavating passes to achieve the desired soil moisture. The scraper blade was used to level the soil until the desired level and cone index values were achieved. The test wheel was free to penetrate into the soil, thus the lug sinkage fluctuated depending on the vertical (normal) and drawbar load.

The definitions of sketch of lugs and cage wheel parameters as presented in Fig.1 are as follows:

- Lug angle is defined as the angle from the lug face to a radial line drawn from the center to the tip of lug.
- Lug spacing is defined as the angle between two radial lines of the adjacent lugs (around the periphery).
- Angle of staggered echelon is defined as the angle made by lug with the axis of wheel.
- Lug opening is a distance from the end tip of a lug to the end tip of the following lug.
- Lug overlapping is a distance between the end tip of the adjacent lugs.
- End-of-lug-clearance is a distance between the trailing tip of a lug and the end tip of the lug that follows.

To calculate the tractive power, following formula was used.

$$D_p = \frac{[P \times V]}{1000} \qquad \ldots(1)$$

where, D_p is tractive power (kW),
V is the actual forward speed (with load) (m/s), and
P is the pull generated (N).

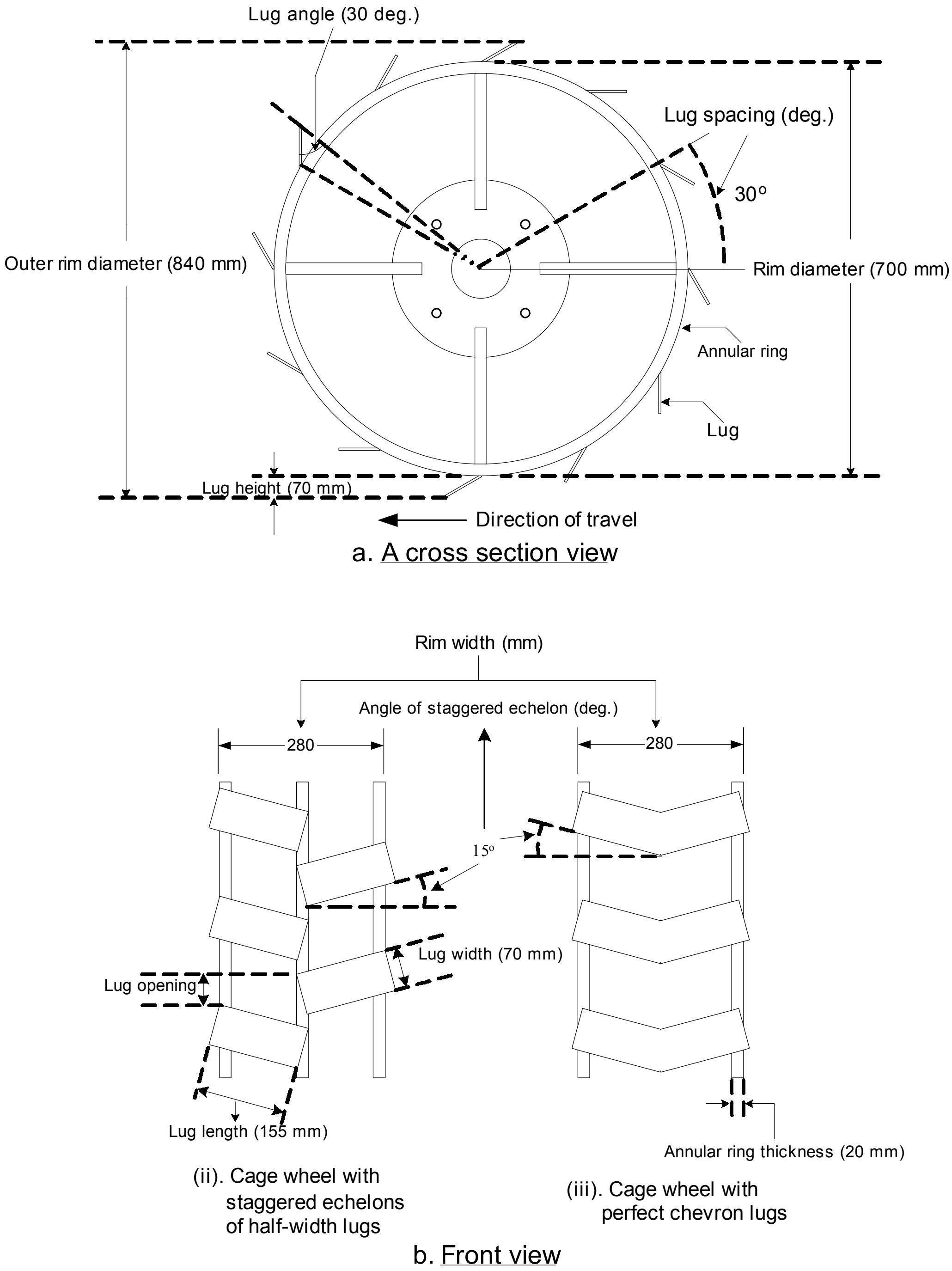
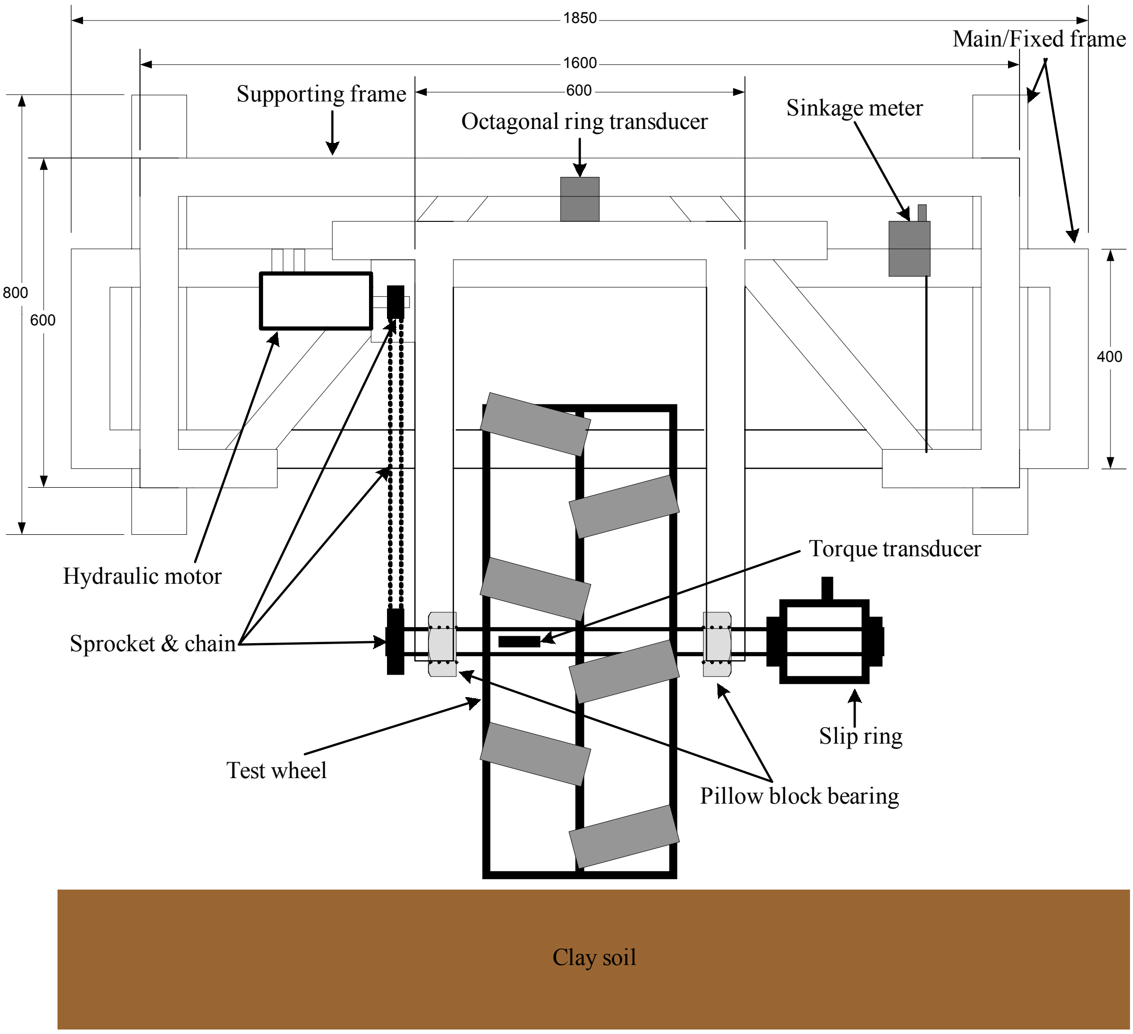


Fig.1: Sketch of the cage wheel (see Fig. 2 for actual wheels)

(a) (b)

Fig. 2: Cage wheels tested (a-with staggered echelons of half-width lugs; b-with perfect chevron lugs)



Front view

Fig. 3: Sketch of the cage wheel test set up

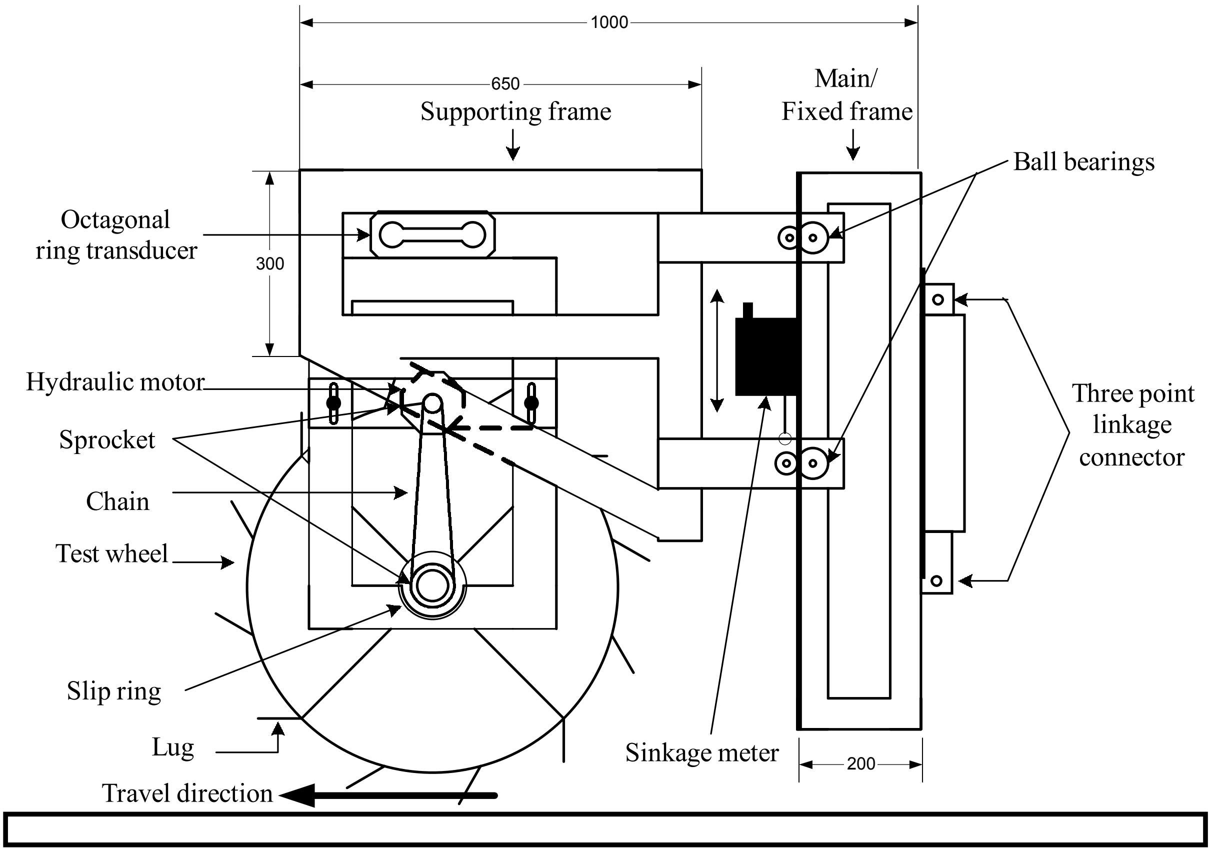


Fig. 4: Sketch of cage wheel test setup with free sinkage system

Table 1: Specifications of the cage wheels

Specifications	Dimensions
Outer rim diameter	700 mm
Rim width	280 mm
Annular ring thickness	20 mm
Outer diameter of wheel (Rim diameter + Width of lug)	840 mm
Lug spacing around the periphery	24°, 30°
Lug angle	30°
Lug length (at 15° angle of staggered echelon):	
- Staggered echelons of half-width lugs at 24° and 30° lug spacings	155 mm
- Perfect chevron arrangement	(2 x 155) mm
Lug number:	
- Staggered echelons of half-width lugs at 24° lug spacing	30 pieces
- Staggered echelons of half-width lugs at 30° lug spacing	24 pieces
- Perfect chevron arrangement	12 pieces

All tests were conducted at 20 rev/min rotational speed of the wheel equivalent to a forward speed of 0.87 m/s (3.13 km/h) common for hand tractors (Watyotha and Salokhe, 2001a & b). The wheel slip was changed from 10% to 15%, 25%, 35%, and 50%. The forward speed of the carriage at desired slip was calculated. The values of forward speed of the carriage at the desired slip of the wheel are given in Table 2.

Table 2: Desired slip and corresponding speed of the carriage and the test wheel

Slip (%)	Rotating speed of the test wheel (m/s)	Forward speed of the carriage (m/s)
10	0.87	0.78
15	0.87	0.74
25	0.87	0.65
35	0.87	0.57
50	0.87	0.44

The experiments were replicated three times. Analysis of variance was conducted and Least Significant Difference (LSD) tool was used to test the level of significance.

Results and Discussion

Figs. 5 to 7 show the characteristics of the measured pull and lift forces of the cage wheels with staggered echelons of half-width lugs and perfect chevron arrangement. The figures show the simultaneous cyclic variations of the pull and lift forces with the wheel rotation angle. The corresponding period was approximately equal to the angular lug spacings on each wheel. The pull forces were higher than the lift force at all wheel slips and lug spacings. The peak values of pull and lift forces were achieved at different wheel rotation angle depending on lug spacings. For cage wheel with staggered echelons of half-width lugs, as the number of lugs on the wheel were twice than that on the normal cage wheel for the same lug spacing, the peak values of forces were reached at every rotation of wheel equal to half of lug spacing. At 24^o and 30^o lug spacing, the peak values were achieved at about every 12^o and 15^o rotations respectively. On the other hand, for cage wheel with perfect chevron arrangement, the peak values were attained every 30^o of wheel rotation which corresponded to the spacing of lugs on the wheel. The characteristics of fluctuations of the forces in this study were inline with those obtained by Watyotha and Salokhe (2001a). In this case, the values of forces were slightly higher than reported in a study by Watyotha and Salokhe (2001a). This might be caused by the free sinking system such that the test wheel can move up and down depending on the soil condition. These findings were also consistent with the calculated pull and lift forces of freely sinking cage wheel studied by Wang et al. (1993 & 1995). The effect of wheel slip on the forces was similar to that observed by Salokhe et al. (1994). As the wheel slip increased, the pull and lift forces on the succeeding and preceding lugs increased at all lug spacing. This was true for the range of slip values used in this study.

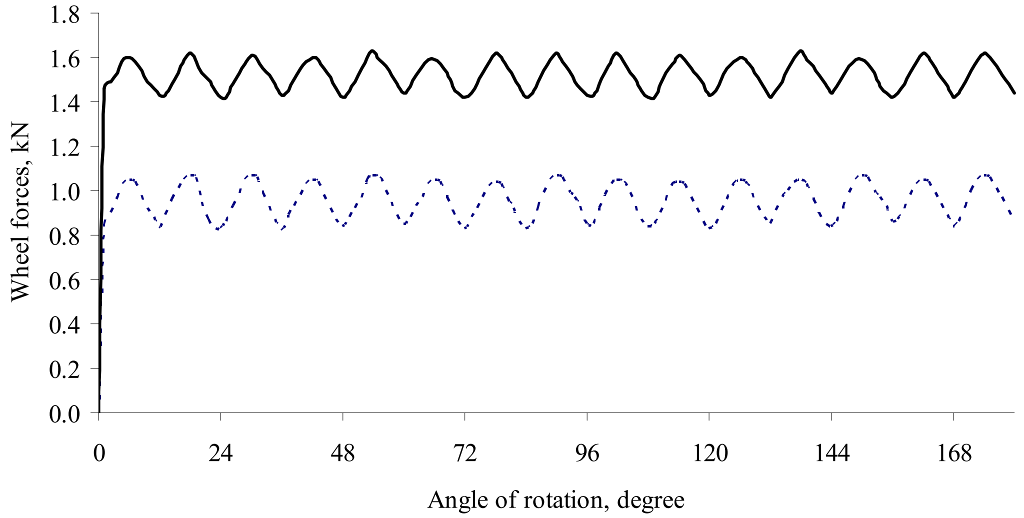


Fig. 5: Forces on the cage wheel with right-half/left-half staggered lugs with lug opening at 15° angle of staggered echelon, 30° lug angle, 24° lug spacing at 15% slip (- - - - lift force; ▬▬▬ pull force)

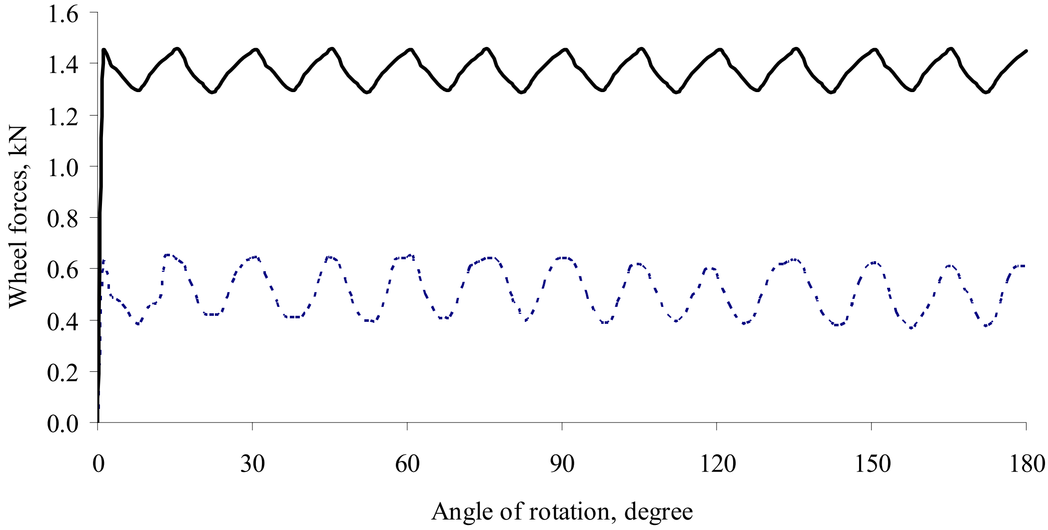


Fig. 6: Forces on the cage wheel with right-half/left-half staggered lugs with lug opening at 15° angle of staggered echelon, 30° lug angle, 30° lug spacing at 15% slip (- - - - lift force; ▬▬▬ pull force)

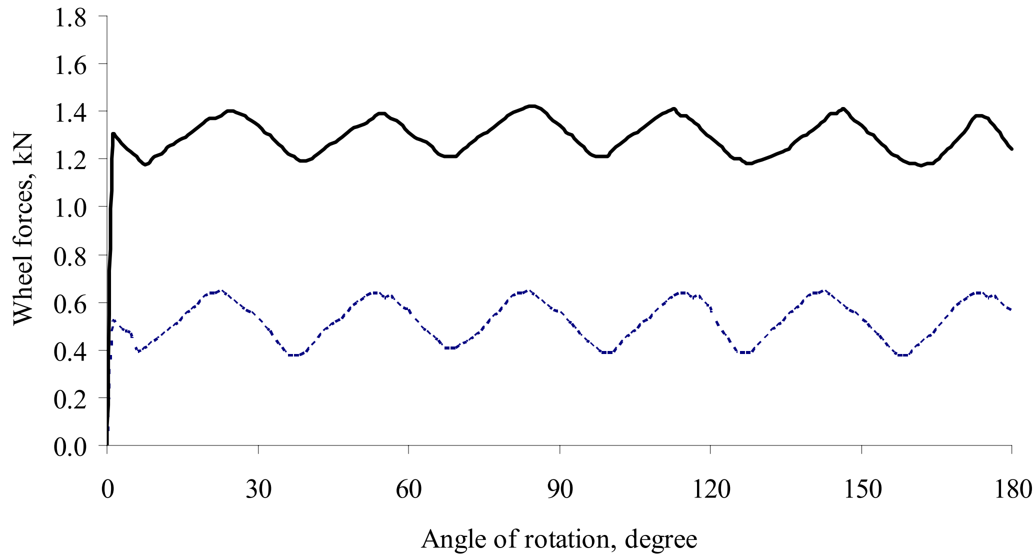


Fig. 7: Forces on the cage wheel with perfect chevron arrangement at 15° angle of staggered echelon, 30° lug angle, 30° lug spacing at 15% slip (- - - - lift force; ——— pull force)

Tables 3 to 5 present the data recorded and calculated from the experiment.

Table 3: Performance parameters of the cage wheel with staggered echelons with half-width lugs at 24° lug spacing at various wheel slips

Wheel slip (%)	Actual forward speed (m/s)	Pull force (N)	Lift force (N)	Sinkage (cm)	Pull per unit sinkage (N/cm)	Lift per unit sinkage (N/cm)	Tractive power (kW)
10	0.78	800	1033	11.6	69	89	0.62
15	0.74	1480	948	16.7	89	57	1.10
25	0.65	1504	1012	17.0	88	60	0.98
35	0.57	1534	1056	20.7	74	51	0.87
50	0.44	1634	1908	21.7	75	88	0.72

Table 4: Performance parameters of the cage wheel with staggered echelons with half-width lugs at 30° lug spacing at various wheel slips

Wheel slip (%)	Actual forward speed (m/s)	Pull force (N)	Lift force (N)	Sinkage (cm)	Pull per unit sinkage (N/cm)	Lift per unit sinkage (N/cm)	Tractive power (kW)
10	0.78	809	830	11.1	73	75	0.63
15	0.74	1350	517	13.7	99	38	1.00
25	0.65	1462	708	17.0	86	42	0.95
35	0.57	1503	1049	17.3	87	61	0.86
50	0.44	1504	1152	18.7	81	62	0.66

Table 5: Performance parameters of the cage wheel with perfect chevron arrangement at various wheel slips

Wheel slip (%)	Actual forward speed (m/s)	Pull force (N)	Lift force (N)	Sinkage (cm)	Pull per unit sinkage (N/cm)	Lift per unit sinkage (N/cm)	Tractive power (kW)
10	0.78	673	607	10.5	64	58	0.525
15	0.74	1265	498	12.0	105	42	0.936
25	0.65	1098	508	13.0	84	39	0.714
35	0.57	985	574	14.3	69	40	0.561
50	0.44	974	1131	15.3	64	74	0.429

Pull forces

The pull forces of cage wheels with different lug arrangements at various slips are shown in Fig. 8 and Tables 3 to 5. While initially, the pull forces of all cage wheels increased sharply up to 15% wheel slip, the pull of cage wheel with staggered echelons of half-width lugs at 24^{o} and 30^{o} lug spacing was almost unchanged after 15% wheel slip. In contrast, the pull forces of cage wheel with perfect chevron configuration decreased beyond the 15% up to 50% wheel slip. The statistical analysis showed that wheel slip significantly affected the pull (Table 6). The peak values of pull were achieved at 50% slip for cage wheel with right-half/left-half staggered lugs at 24^{o} or 30^{o} lug spacings. On the contrary, the cage wheel with perfect chevron arrangement attained the peak value of pull force at 15% slip. This was because the wheel could not penetrate well into the soil and therefore the wheel was sliding on the soil which declined the value of the pull force. An increase in the pull due to increase in slip resulted in a more horizontal soil compression and shearing. At all wheel slips, the highest value of pull was given by the cage wheel with staggered echelons of half-width lugs with a lug opening of 24^{o}. The cage wheel with perfect chevron arrangement gave the lowest pull. This was because the total number of lugs and shorter lug length, as the cage wheel with staggered echelons of half-width lugs, would require more pull force for rotating the wheel. However, the longer lug length as on the cage wheel with perfect chevron configuration can reduce the pull, since the number of lugs was less than the cage wheel with staggered echelons of half-width lugs.

In this experiment, the analysis of variance showed a significant difference between the mean pull force obtained by the cage wheel with staggered echelons of half-width lugs both at 24^{o} and 30^{o} lug spacing and perfect chevron arrangement at 30^{o} lug spacing at all slips. The effect of lug spacing on the pull was (Fig. 7) observed to follow a similar behavior as observed in the study by Watyotha and Salokhe (2001a) who reported that the pull increased significantly as the lug spacing decreased. At all wheel slips, the pull forces of the cage wheel with perfect chevron arrangement were significantly lower than that of a cage wheel with staggered echelons of half-width lugs at 24^{o} and 30^{o} lug spacing (Table 7).

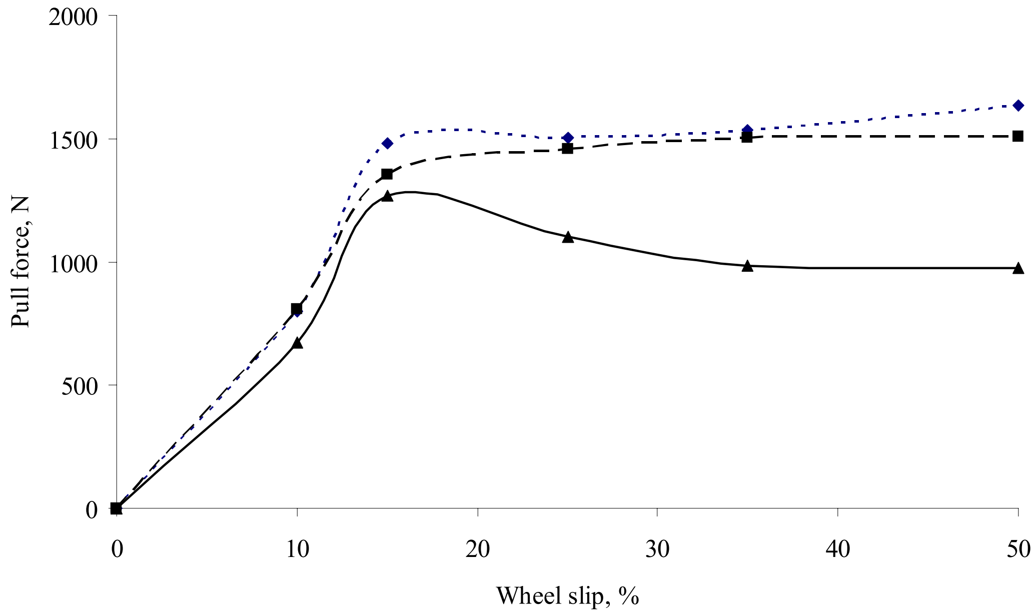


Fig. 8: Pull forces on the cage wheels at varying wheel slips (right-half/left-half staggered lugs with 24^o lug spacing; right-half/left-half staggered lugs with 30^o lug spacing; perfect chevron arrangement at 30^o lug spacing)

Table 6: Analysis of variance of pull force for all cage wheels tested at various wheel slips

Wheel slip (%)		Sum of squares	d.f.	Mean square	F-value	Significance
10	Between groups	33867	2	16933	14.243	0.005*
	Within groups	7133	6	1189		
	Total	41000	8			
15	Between groups	69067	2	34533	23.194	0.002*
	Within groups	8933	6	1489		
	Total	78000	8			
25	Between groups	294156	2	147078	43.977	0.000*
	Within groups	20067	6	3344		
	Total	314222	8			
35	Between groups	573800	2	286900	22.240	0.002*
	Within groups	77400	6	12900		
	Total	651200	8			
50	Between groups	728156	2	364078	26.511	0.001*
	Within groups	824000	6	13733		
	Total	810556	8			

- * The difference is highly significant.
- d.f. is degree of freedom.

Table 7: Multiple comparisons of mean pull force at different slips by using LSD analysis

Slip	Type of wheel (A)	Type of wheel (B)	Mean difference (A-B)	Standard error	Significance	95% Confidence interval Lower bound	95% Confidence interval Upper bound
10%	1	2	-6.67	28.15	0.821	-75.55	62.22
	1	3	126.67*	28.15	0.004	57.78	195.55
	2	3	133.33*	28.15	0.003	64.45	202.22
15%	1	2	126.67*	31.51	0.007	49.58	203.76
	1	3	213.33*	31.51	0.001	136.24	290.42
	2	3	86.67*	31.51	0.033	9.58	163.76
25%	1	2	43.33*	47.22	0.394	-72.21	158.87
	1	3	403.33*	47.22	0.000	287.79	518.87
	2	3	360.00*	47.22	0.000	244.46	475.54
35%	1	2	30.00	92.74	0.757	-196.92	256.92
	1	3	550.00*	92.74	0.001	323.08	776.92
	2	3	520.00*	92.74	0.001	293.08	746.92
50%	1	2	126.67	95.69	0.234	-107.47	360.80
	1	3	656.67*	95.69	0.000	422.53	890.80
	2	3	530.00*	95.695	0.001	295.87	764.13

* The mean difference is significant at the .05 level.

Note for type of wheel:

(A) *is a first wheel compared with* (B) a *second wheel*;

(A-B) *is the mean difference between first and second wheel performance*;

1: *Cage wheel with staggered echelons of half-width lugs at 24^o lug spacing & 30^o lug angle*

2: *Cage wheel with staggered echelons of half-width lugs at 30^o lug spacing & 30^o lug angle*

3: *Cage wheel with perfect chevron arrangement at 30^o lug spacing & 30^o lug angle*

Lift forces

Fig. 9 shows the mean lift forces at various wheel slips for different types of lug arrangements. It was observed that initially the lift forces tend to decrease from 10% up to 15% wheel slip and then starts to increase as the slip increased. This trend continued up to 50% slip for all cage wheels. For cage wheel with staggered echelons of half-width lugs, at all wheel slips, as the lug spacing increased from 24^o to 30^o the lift forces decreased significantly due to the decrease of wheel weight caused by the benefit of decreasing in number of lugs. The result of analysis of variance showed that the wheel slip affected lift forces significantly (Table 8). Table 9 presents multiple comparison analysis by using LSD. The lift forces of cage wheel with perfect chevron arrangement were lower compared to the cage wheels with staggered echelons of half-width lugs at 24^o and 30^o lug spacing (Tables 3 to 5 and 9). The less number of lugs on the cage wheel would result a lower value of lift forces useful for higher floatation.

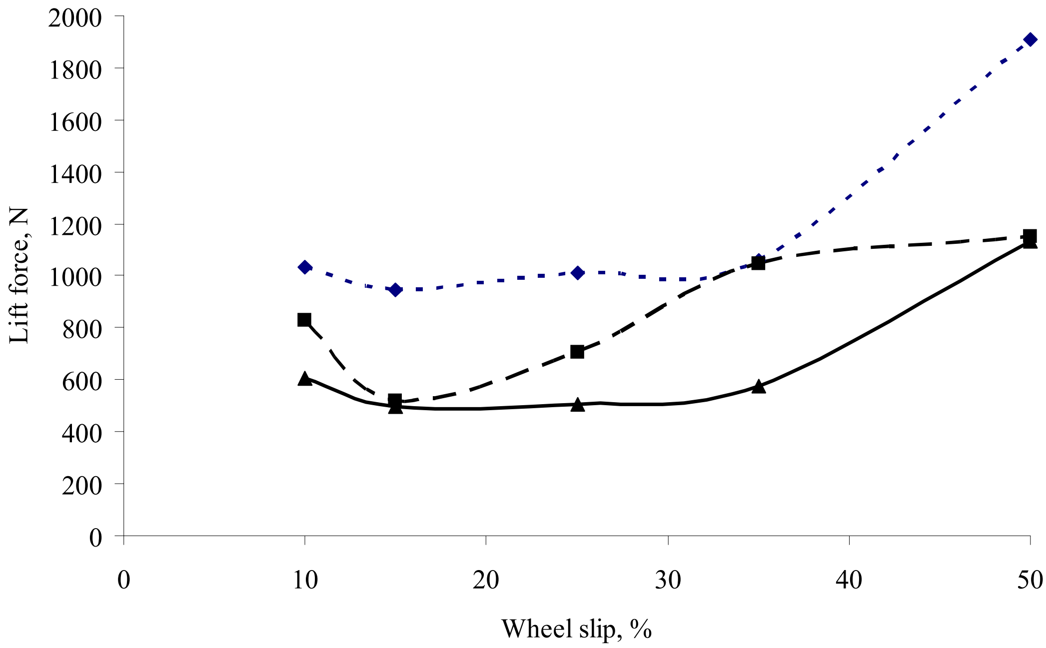


Fig. 9: Lift forces on cage wheels at varying wheel slip (right-half/left-half staggered lugs with 24° lug spacing; right-half/left-half staggered lugs with 30° lug spacing; perfect chevron arrangement at 30° lug spacing)

Table 8: Analysis of variance of lift force for all cage wheels tested at various slips

Wheel slip (%)		Sum of squares	d.f.	Mean square	F-value	Significance
10	Between groups	273267	2	136633	114.925	0.000*
	Within groups	7133	6	1189		
	Total	280400	8			
15	Between groups	385089	2	192544	13.964	0.006*
	Within groups	82733	6	13789		
	Total	467822	8			
25	Between groups	385356	2	19268	27.053	0.001*
	Within groups	42733	6	7122		
	Total	428089	8			

35	Between groups	457756	2	228878	10.127	0.012*
	Within groups	135600	6	22600		
	Total	593356	8			
50	Between groups	1170867	2	585433	19.675	0.002*
	Within groups	178533	6	29756		
	Total	1349400	8			

- * The difference is highly significant.
- d.f. is degree of freedom.

Table 9: Multiple comparisons of mean lift force at different slips by using LSD analysis

Slip	Type of wheel		Mean difference (A-B)	Standard error	Significance	95% Confidence interval	
	(A)	(B)				Lower bound	Upper bound
10%	1	2	203.33*	28.153	0.000	134.45	272.22
	1	3	426.67*	28.153	0.000	357.78	495.55
	2	3	223.33*	28.153	0.000	154.45	292.22
15%	1	2	426.67*	95.878	0.004	192.06	661.27
	1	3	450.00*	95.878	0.003	215.39	684.61
	2	3	23.33	95.878	0.816	-211.27	257.94
25%	1	2	303.33*	68.907	0.005	134.72	471.94
	1	3	503.33*	68.907	0.000	334.72	671.94
	2	3	200.00*	68.907	0.027	31.39	368.61
35%	1	2	10.00	122.746	0.938	-290.35	310.35
	1	3	483.33*	122.746	0.008	182.98	783.68
	2	3	473.33*	122.746	0.008	172.98	773.68
50%	1	2	756.67*	140.844	0.002	412.03	1101.30
	1	3	773.33*	140.844	0.002	428.70	1117.97
	2	3	16.67	140.844	0.910	-327.97	361.30

* The mean difference is significant at the .05 level.

Note for type of wheel:

(A) *is a first wheel compared with* (B) a *second wheel*;

(A-B) *is the mean difference between first and second wheel performance*;

1: *Cage wheel with staggered echelons of half-width lugs at 24^o lug spacing & 30^o lug angle*

2: *Cage wheel with staggered echelons of half-width lugs at 30^o lug spacing & 30^o lug angle*

3: *Cage wheel with perfect chevron arrangement at 30^o lug spacing & 30^o lug angle*

Effect of slip on sinkage

Sinkage is used as a criterion of floatation performance of cage wheel. Fig. 10 presents the effect of wheel slip on sinkage. All cage wheels showed that the sinkage increased as the wheel slip increased. The statistical analysis showed that at 15%, 25%, 35% and 50% wheel slips, the sinkage values of all cage wheels were affected (Table10). LSD analysis indicated that the sinkage values are significantly different at all wheel slips, except at 25% slip, where no significantly difference between sinkage for the cage wheel with right-half/left-half staggered lugs at 24^o lug spacing and cage wheel with right-half/left-half staggered lugs at 30^o lug spacing was observed. The results showed that the sinkage of cage wheel with perfect chevron arrangement was lower than that with right-half/left-half staggered lugs at 24^o and 30^o lug spacings (Table 11). The perfect chevron arrangement had the lowest sinkages among the other cage wheels tested. These values were 10.5 cm, 12 cm, 13 cm, 14 cm and 15 cm at 10%, 15%, 25%, 35% and 50% wheel slips respectively. In terms of sinkage produced, cage wheel with perfect chevron arrangement provided higher floatation resulting in lower sinkage desirable in wet land cultivation.

On the other hand, increasing the lug spacing from 24^o to 30^o decreased the sinkage significantly at all wheel slips, except at 25% wheel slip, since the decrease of lug numbers could reduce the weight as well as vertical forces on the cage wheel (Tables 3 to 5).

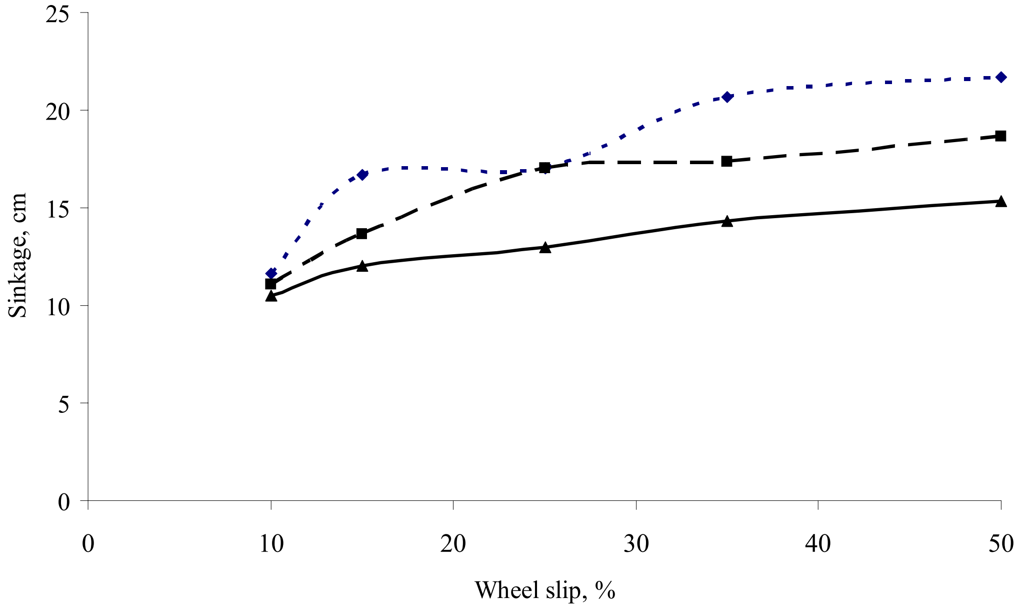


Fig. 10: Sinkage of the cage wheels at varying wheel slip (- -◆ - right-half/left-half staggered lugs with 24^o lug spacing; - ■ - right-half/left-half staggered lugs with 30^o lug spacing; —▲— perfect chevron arrangement at 30^o lug spacing)

Table 10: Analysis of variance of sinkage for all cage wheels tested at various slips

Wheel slip (%)	Sum of squares	d.f.	Mean square	F-value	Significance

10	Between groups	1.88	2	0.941	12.568	0.007*
	Within groups	0.45	6	0.075		
	Total	2.33	8			
15	Between groups	33.56	2	16.778	75.500	0.000*
	Within groups	1.33	6	0.222		
	Total	34.89	8			
25	Between groups	32.00	2	16.000	48.000	0.000*
	Within groups	2.00	6	0.333		
	Total	34.00	8			
35	Between groups	60.22	2	30.111	90.333	0.000*
	Within groups	2.00	6	0.333		
	Total	62.22	8			
50	Between groups	60.22	2	30.111	22.583	0.002*
	Within groups	8.00	6	1.333		
	Total	68.22	8			

- *The difference is highly significant.
- d.f. is degree of freedom.

Table 11: Multiple comparisons of sinkage at different slips by using LSD analysis

Slip	Type of wheel		Mean difference (A-B)	Standard error	Significance	95% Confidence interval	
	(A)	(B)				Lower bound	Upper bound
10%	1	2	0.57*	0.22	0.043	0.0233	1.1167
	1	3	1.12*	0.22	0.002	0.5733	1.6667
	2	3	0.55*	0.22	0.049	0.0033	1.0967
15%	1	2	3.00*	0.38	0.000	2.0582	3.9418
	1	3	4.67*	0.38	0.000	3.7248	5.6085
	2	3	1.67*	0.38	0.005	0.7248	2.6085
25%	1	2	0.00	0.47	1.000	-1.1535	1.1535
	1	3	4.00*	0.47	0.000	2.8465	5.1535
	2	3	4.00*	0.47	0.000	2.8465	5.1535
35%	1	2	3.33*	0.47	0.000	2.1798	4.4868
	1	3	6.33*	0.47	0.000	5.1798	7.4868
	2	3	3.00*	0.47	0.001	1.8465	4.1535
50%	1	2	3.00*	0.94	0.019	0.6930	5.3070
	1	3	6.33*	0.94	0.001	4.0264	8.6403
	2	3	3.33*	0.94	0.012	1.0264	5.6403

* The mean difference is significant at the .05 level.

Note for type of wheel:

(A) *is a first wheel compared with* (B) a *second wheel*;

(A-B) *is the mean difference between first and second wheel performance*;

1: *Cage wheel with staggered echelons of half-width lugs at 24^o lug spacing & 30^o lug angle*

2: *Cage wheel with staggered echelons of half-width lugs at 30^o lug spacing & 30^o lug angle*

3: *Cage wheel with perfect chevron arrangement at 30^o lug spacing & 30^o lug angle*

Pull and lift forces per unit wheel sinkage

The values of pull per unit wheel sinkage for different wheels at various slips are shown in Fig. 10. The peak pull per unit sinkage of all cage wheels tested was reached at 15% slip. After 15% wheel slip, the pull per unit sinkage of all cage wheels tended to decrease up to 25% slip, and then remain unchanged over 35% wheel slip. The analysis of variance showed that wheel slips significantly affected the pull force per unit sinkage at 15% and 35% wheel slips (Table 12). The LSD analysis showed (Table 13) that for cage wheel with right-half/left-half staggered lugs at 24^o lug spacing, the pull force per unit sinkage was about 10 N/cm and 12 N/cm, lower than that with right-half/left-half staggered lugs at 30^o lug spacing with 15% and 35% wheel slips respectively. These differences were statistically significant. However, at 10%, 25% and 50% slips, the values of pull force per unit sinkage were not significantly different. If compared to the cage wheel with perfect chevron arrangement, the values of pull force per unit sinkage of cage wheel with staggered echelons of half-width lugs with 24^o lug spacing were 5 N/cm, 3 N/cm, 6 N/cm and 12 N/cm higher at 10%, 25%, 35% and 50% wheel slips respectively. The difference was not statistically different. In contrast, at 15% wheel slip the value of pull force per unit sinkage is significantly different. The values of pull force per unit sinkage of the cage wheel with staggered echelons of half-width lugs with 30^o lug spacing were about 9 N/cm, 1 N/cm, 18 N/cm and 17 N/cm higher than that with perfect chevron arrangement at 10%, 25%, 35% and 50% wheel slips respectively. LSD analysis showed that the difference was not significant at 10%, 25% and 50% wheel slips. However, at 15% wheel slip, the value of pull force per unit sinkage of cage wheel with staggered echelons of half-width lugs at 30^o lug spacing was about 6 N/cm lower than that with perfect chevron arrangement.

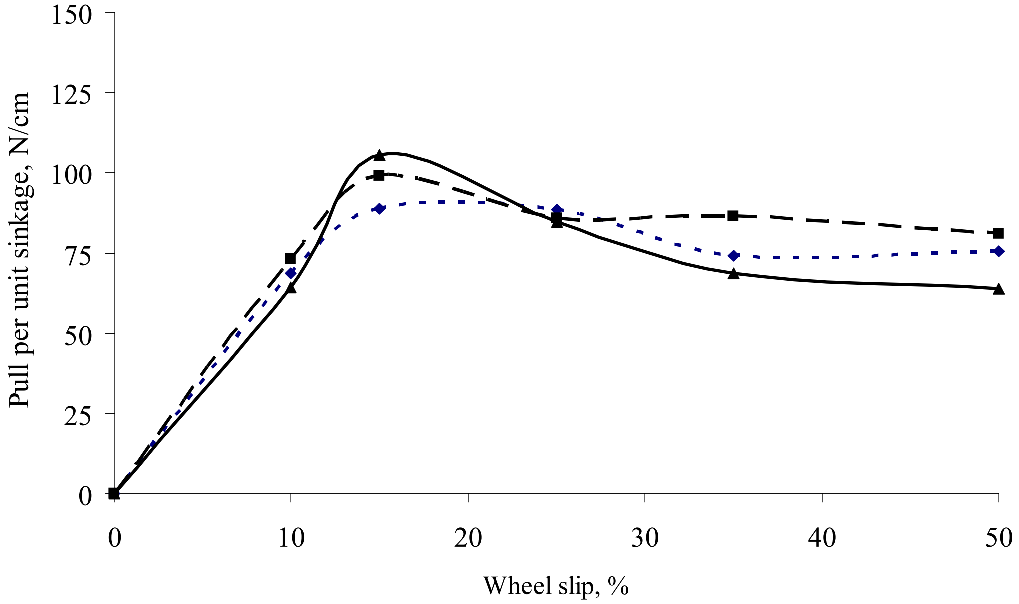


Fig. 11: Pull force per unit of sinkage of cage wheel at varying wheel slip (right-half/left-half staggered lugs with 24^o lug spacing; right-half/left-half staggered lugs with 30^o lug spacing; perfect chevron arrangement at 30^o lug spacing)

Table 12: Analysis of variance of pull force per unit sinkage for all cage wheels tested at various slips

Wheel slip (%)		Sum of squares	d.f.	Mean square	F-value	Significance
10	Between groups	120.0	2	60.0	2.772	0.140
	Within groups	129.9	6	21.6		
	Total	249.9	8			
15	Between groups	425.8	2	212.9	11.148	0.010*
	Within groups	114.6	6	19.1		
	Total	540.4	8			
25	Between groups	20.3	2	10.2	.412	0.680
	Within groups	147.9	6	24.6		
	Total	168.2	8			
35	Between groups	502.1	2	251.1	9.608	0.013*
	Within groups	156.8	6	26.1		
	Total	658.9	8			
50	Between groups	475.4	2	237.7	2.742	0.143
	Within groups	520.2	6	86.7		
	Total	995.6	8			

- *The difference is highly significant.
- d.f is degree of freedom.

Table 13: Multiple comparisons of mean pull force per unit sinkage at different slips by using LSD analysis

Slip	Type of wheel		Mean difference (A-B)	Standard error	Significance	95% Confidence interval	
	(A)	(B)				Lower bound	Upper bound
10%	1	2	-4.22	3.80	0.310	-13.5122	5.0788
	1	3	4.72	3.80	0.260	-4.5722	14.0188
	2	3	8.94	3.80	0.057	-0.3555	18.2355
15%	1	2	-10.30*	3.57	0.028	-19.0307	-1.5693
	1	3	-16.70*	3.57	0.003	-25.4274	-7.9660
	2	3	-6.40	3.57	0.123	-15.1274	2.3340
25%	1	2	2.55	4.05	0.552	-7.3650	12.4717
	1	3	3.57	4.05	0.412	-6.3483	13.4883
	2	3	1.02	4.05	0.810	-8.9017	10.9350
35%	1	2	-12.31*	4.17	0.026	-22.5266	-2.1001
	1	3	5.56	4.17	0.231	-4.6499	15.7766
	2	3	17.88*	4.17	0.005	7.6634	28.0899
50%	1	2	-5.35	7.60	0.508	-23.9527	13.2527
	1	3	12.03	7.60	0.165	-6.5727	30.6327
	2	3	17.38	7.60	0.062	-1.2227	35.9827

* The mean difference is significant at the .05 level.

Note for type of wheel:

(A) *is a first wheel compared with* (B) a *second wheel*;
(A-B) *is the mean difference between first and second wheel performance*;
1: *Cage wheel with staggered echelons of half-width lugs at 24^o lug spacing & 30^o lug angle*
2: *Cage wheel with staggered echelons of half-width lugs at 30^o lug spacing & 30^o lug angle*
3: *Cage wheel with perfect chevron arrangement at 30^o lug spacing & 30^o lug angle*

Fig. 12 presents the lift force per unit sinkage of cage wheels tested at various wheel slips. The analysis of variance shows that the wheel slips significantly affect the values of lift force per unit sinkage at 10% and 25% wheel slips, and did not show significantly effects at 15%, 35% and 50% wheel slips (Table 14). The LSD analysis (Table 15) showed that comparison of cage wheel with staggered echelons of half-width lugs with 24^o lug spacing, the values of lift force per unit sinkage were significantly higher compared to cage wheel with staggered echelons of half-width lugs with 30^o lug spacing at all wheel slips, except at 35% wheel slip, in which the value of lift force per unit sinkage of cage wheel with staggered echelons of half-width lugs with 24^o lug spacing was slightly lower compared to cage wheel with staggered echelons of half-width lugs with 30^o lug spacing. For cage wheel with perfect chevron arrangement, the values of lift force per unit sinkage were significantly lower at 10% and 25% wheel slips compared to that with staggered echelons of half-width lugs. The values of lift force per unit sinkage of cage wheel with perfect chevron arrangement were significantly lower at 10% and 35% wheel slips, and slightly lower at 25% wheel slip compared to that with staggered echelons of half-width lugs with 30^o lug spacing. However, at 15% and 50% wheel slips, the values of lift force per unit sinkage of cage wheel with perfect chevron arrangement were slightly higher than that with staggered echelons of half-width lugs with 30^o lug spacing. The cage wheel with staggered echelons of half-width lugs with 24^o lug spacing gave highest value of the lift force per unit wheel sinkage at all wheel slips, except at 35% slip.
While the cage wheel with staggered echelons of half-width lugs with 24^o lug spacing give the highest values among the other cage wheels tested i.e. 89 N/cm and 57 N/cm, 59 N/cm, 51 N/cm and 88 N/cm at 10%, 15%, 25%, 35% and 50% wheel slips respectively, the cage wheel with perfect chevron arrangement gave the lowest values of 58 N/cm, 39 N/cm and 40 N/cm at 10%, 25% and 35% wheel slips respectively (Fig. 12). In this study, the values of lift force per unit sinkage were also used as the criterion of floatation performance. It is revealed that the higher the lift force per unit sinkage, the better the floatation performance of cage wheel. In contrast with the results of sinkages obtained in this study, the cage wheel with perfect chevron arrangement gave the lowest values. This is because the wheel can not penetrate well into the soil due to its lugs arrangement resulting in decreased pull forces.

The higher the value of pull force per unit sinkage and the higher the value of lift force per unit sinkage, the cage wheel performs better in terms of traction and floatation (Table 3 to 5).

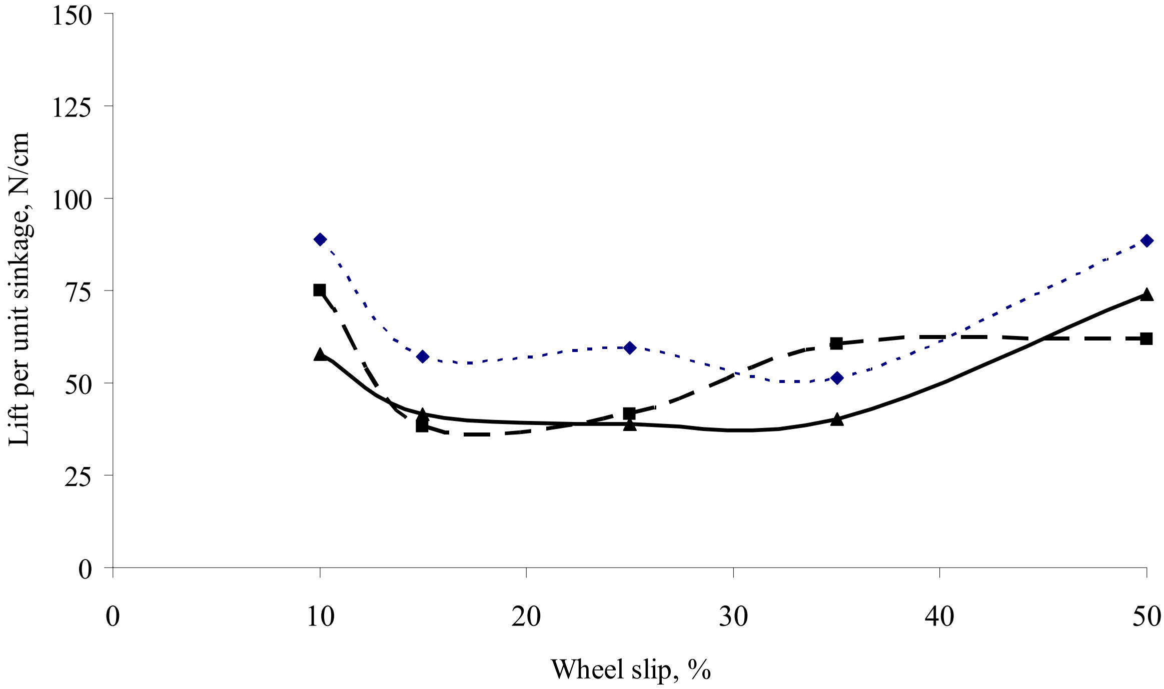


Fig. 12: Lift force per unit of sinkage of cage wheel at varying wheel slips (right-half/left-half staggered lugs with 24° lug spacing; right-half/left-half staggered lugs with 30° lug spacing; perfect chevron arrangement at 30° lug spacing)

Table 14: Analysis of variance of lift force per unit sinkage for all cage wheels tested at various slips

Wheel slip (%)		Sum of squares	d.f.	Mean square	F-value	Significance
10	Between groups	1453.84	2	726.92	133.022	0.000*
	Within groups	32.79	6	5.47		
	Total	1486.63	8			
15	Between groups	608.69	2	304.35	3.684	0.090
	Within groups	495.66	6	82.61		
	Total	1104.35	8			
25	Between groups	750.66	2	375.33	17.261	0.003*
	Within groups	130.46	6	21.74		
	Total	881.12	8			
35	Between groups	611.89	2	305.95	3.563	0.095
	Within groups	515.16	6	85.85		
	Total	1127.05	8			

50	Between groups	1069.28	2	534.64	3.290	0.108
	Within groups	974.93	6	162.49		
	Total	2044.21	8			

- *The difference is highly significant.
- d.f. is degree of freedom.

Table 15: Multiple comparisons of mean lift force per unit sinkage at different slips by using LSD analysis

Slip	Type of wheel		Mean difference	Standard	Significance	95% Confidence interval	
	(A)	(B)	(A-B)	error		Lower bound	Upper bound
	1	2	13.74*	1.909	0.000	9.0663	18.4071
10%	1	3	31.06*	1.909	0.000	26.3929	35.7337
	2	3	17.33*	1.909	0.000	12.6563	21.9971
	1	2	18.83*	7.421	0.044	0.6711	36.9889
15%	1	3	15.61	7.421	0.080	-2.5456	33.7722
	2	3	-3.22	7.421	0.680	-21.3756	14.9422
	1	2	17.84*	3.807	0.003	8.5271	27.1596
25%	1	3	20.61*	3.807	0.002	11.2904	29.9229
	2	3	2.76	3.807	0.495	-6.5529	12.0796
	1	2	-9.18	7.566	0.271	-27.6892	9.3359
35%	1	3	10.99	7.566	0.196	-7.5192	29.5059
	2	3	20.17*	7.566	0.037	1.6574	38.6826
	1	2	26.67*	10.408	0.043	1.2059	52.1407
50%	1	3	14.36	10.408	0.217	-11.1107	39.8241
	2	3	-12.32	10.408	0.281	-37.7841	13.1507

* The mean difference is significant at the .05 level.

Note for type of wheel:

(B) *is a first wheel compared with* (B) a *second wheel*;

(A-B) *is the mean difference between first and second wheel performance*;

1: *Cage wheel with staggered echelons of half-width lugs at 24° lug spacing & 30° lug angle*

2: *Cage wheel with staggered echelons of half-width lugs at 30° lug spacing & 30° lug angle*

3: *Cage wheel with perfect chevron arrangement at 30° lug spacing & 30° lug angle*

Tractive power

The curve of tractive power versus wheel slip for different cage wheels is shown in Fig. 13. The analysis of variance showed that wheel slip significantly affected the tractive power (Table 16).

Considering that the slip must occur to provide the pull (Gee-Clough, 1991), so the tractive power depend on wheel slip and the calculated mean power can very well be fitted to a polynomial function of the form:

$$P_o = As - Bs^2 \qquad (1)$$

where P_o is the power delivered in kW; s is wheel slip in %; A and B are constants.

The values of coefficients A and B, and the regression analysis showed a high correlation (Table 17). The increase of wheel slip led to a decrease of tractive power. At 15% slip the tractive power reached maximum value and then it decreased with further increase of wheel slip.

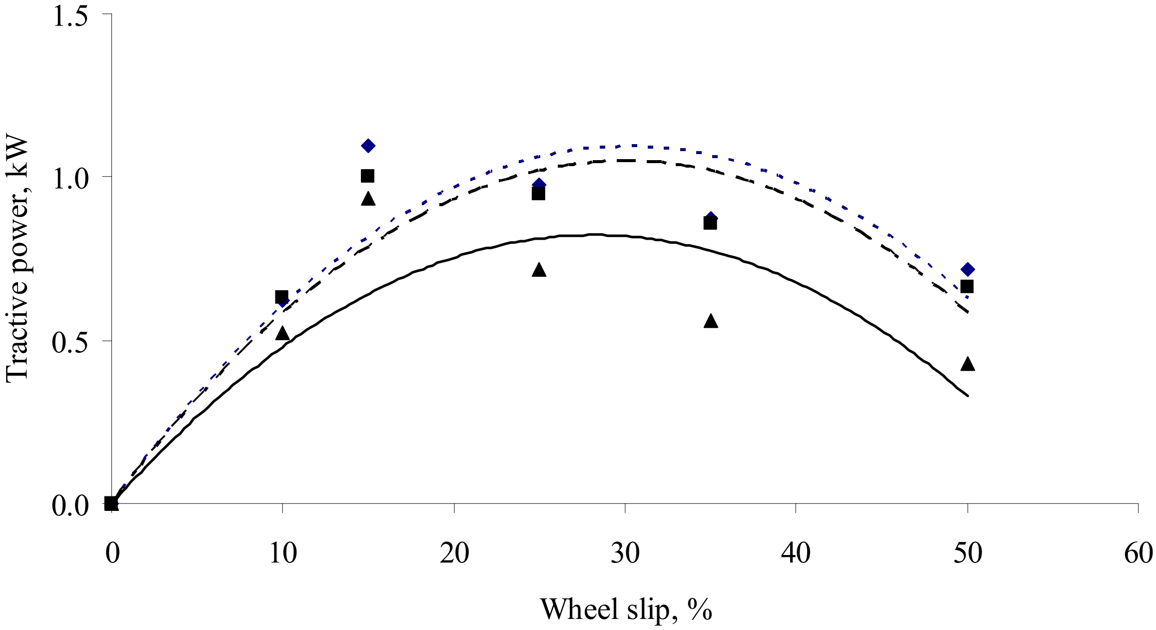


Fig. 13: Tractive power of cage wheel at varying wheel slip (right-half/left-half staggered lugs with 24° lug spacing; right-half/left-half staggered lugs with 30° lug spacing; perfect chevron arrangement at 30° lug spacing)

Table 16: Analysis of variance of tractive power for all cage wheels tested at various slips

Wheel slip (%)		Sum of squares	d.f.	Mean square	F-value	Significance
10	Between groups	0.021	2	0.011	15.302	0.004*
	Within groups	0.004	6	0.001		
	Total	0.026	8			
15	Between groups	0.041	2	0.020	33.934	0.001*
	Within groups	0.004	6	0.001		
	Total	0.045	8			
25	Between groups	0.128	2	0.064	20.284	0.002*

	Within groups	0.019	6	0.003		
	Total	0.147	8			
35	Between groups	0.209	2	0.104	23.390	0.001*
	Within groups	0.027	6	0.004		
	Total	0.235	8			
50	Between groups	0.132	2	0.066	14.808	0.005*
	Within groups	0.027	6	0.004		
	Total	0.158	8			

- *The difference is highly significant.
- d.f is degree of freedom.

Table 17: Results of regression analysis of tractive power versus wheel slip for different cage wheels

Type of cage wheel	Constant *A*	Constant *B*	R^2*	*SEE***
Cage wheel with staggered echelons of half-width lugs at 24° lug spacing	0.0656	0.00109	0.84	0.20
Cage wheel with staggered echelons of half-width lugs at 30° lug spacing	0.0637	0.00107	0.88	0.16
Cage wheel with perfect chevron arrangement at 30° lug spacing	0.0505	0.00091	0.72	0.21

* R^2, coefficient of determination
**SEE*, Standard Error of Estimation

Conclusions

This study showed that for cage wheels with staggered echelons of half-width lugs and perfect chevron arrangement, the lug forces fluctuated periodically with the wheel rotation. The corresponding frequency was approximately equal to the angular lug spacings. The wheel slips affect the wheel forces directly. Concerning the force per unit sinkage, the higher the value of pull force per unit sinkage and the higher the value of lift force per unit sinkage, the cage wheel performed better in terms of traction and floatation. While the cage wheel with staggered echelons of half-width lugs at 24° lug spacing gave the highest pull and the deepest sinkages, the cage wheel with perfect chevron arrangement experienced the least sinkage and pull compared to cage wheels with other two lug arrangements. The study revealed that cage wheel with staggered echelons of half-width lugs at 30° lug spacing performed better compared to the other cage wheels tested. This cage wheel can provide higher pull force and reduced wheel sinkage, and can be recommended for working in wet paddy fields.

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