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The Effect of Spacing in Dual Wheel Arrangements on Surface Load Support and Soil Compaction

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ABSTRACT

This research explores the possible benefits to be derived from interactions between wheels, for supporting a greater proportion of applied loads in the shallower soil layers. This creates possibilities for reducing the risk of deep soil compaction. Previous research indicated that different interaction modes occurred under simulated wheel arrangements, being mostly dependent upon the spacing between them. Hence, field experiments were arranged to investigate a range of spacings between dual wheels in practical situations. Two field conditions were prepared providing loose and firm surface layers. Dry bulk density, penetration resistance, wheel sinkage and contact area were measured under each arrangement. A clear link was identified between results previously obtained in soil bin tests and those in the field, confirming that spacing has a major effect on the potential benefits. As wheel spacing decreased the interaction increased, inducing a greater resistance in the soil surface layers to carry higher loads. The optimum range of appropriate spacings and interaction modes identified in the laboratory tests was found to be applicable in the field.

Keywords: Compaction, Load support, Wheels, Wheel spacing.

INTRODUCTION

New mechanisation methods associated with increasing weight and size of machinery have the potential to cause undesirable deep soil compaction below the normal tillage operation depth. Farmers need, therefore, to use deep tillage implements such as subsoilers to alleviate compaction, although their technical knowledge is limited and it is an expensive operation (Adam and Erbach, 1995). Numerous factors have been identified by researchers as the main causes of deep compaction, including axle load, wheel shape and contact pressure (Abu-Hamed *et al*., 2000; Olsen, 1994; Soane *et al*., 1980). It has been noted that load is a dominant factor in causing deep soil compaction (Smith and Dickson, 1990). Loads are transferred to the soil by wheels and the stress distribution is directly dependent on wheel design, shape and arrangement (Abu-Hamed, 2000).

It was shown that some benefits can be achieved through the interaction of tillage tools (Spoor and Godwin, 1978). There have also been many investigations on wheel and tyre interactions indicating some interaction benefits, but none of them investigated the soil movement pattern and interaction behaviour.

McLeod *et al*. (1966) found less compaction occurred under low pressure and dual tyres compared with single tyres. It was also reported that pressure from a conventional wheel-type tractor is greater than a tractor with dual rear wheels (Reaves and Cooper, 1960; Brixius and Zoz, 1976).

Kinney *et al*. (1992) identified soil strain under three tractor configurations: a tractor

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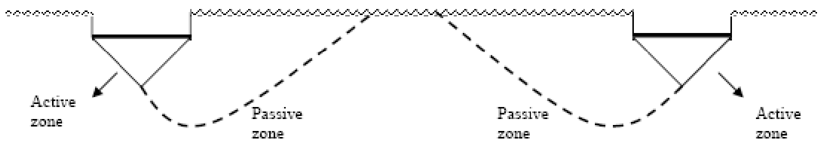
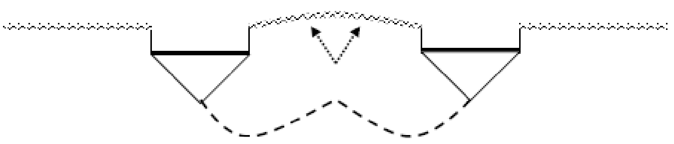
with a single rear wheel, with a dual rear wheel and with a steel track. They concluded that the tractor with a single rear wheel produced more strain in the 100 to 440 mm soil layer than did equal-mass tractors with dual rear wheels or with steel tracks. Gee-Clough (1979) experimented with dual rigid wheels in sand at a range of spacings from zero to three wheel widths. It was noted that the coefficient of rolling resistance decreased as separation increased and, at a separation 3 times larger than wheel width, was 12% less than zero separation. It was also reported that the wheels were not acting independently of each other even at a 3 wheel width separation although, in practice, the allowable separation will be less than this. Hakansson and Petelkau (1994) noted that the more widely spaced the wheels the less the interaction. It was concluded that, to avoid deep soil compaction, heavy vehicles should have many wheels spaced widely apart.

Recent laboratory studies identified different interaction modes occurring between the failure zones under simulated wheel arrangements at different spacings (Javadi, 2002; Javadi and Spoor, 2004). The wheels were simulated using flat footings which were forced into the soil and effectively took the form of a dual wheel system. The soil failure modes identified in these studies depended on spacing are summarised below.

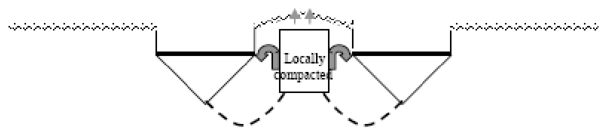
- *Failure mode 0*: No interaction between the two lateral passive failure zones occurred and each plate acted independently (see *Figure* 1a*)*.
- *Failure mode 1*: As spacing decreased the lateral passive failure zones from both footings now overlapped and interacted, inducing some local upward soil movement in the central area (see *Figure* 1b).
- *Failure mode 2*: By further spacing reduction a central local compacted soil zone



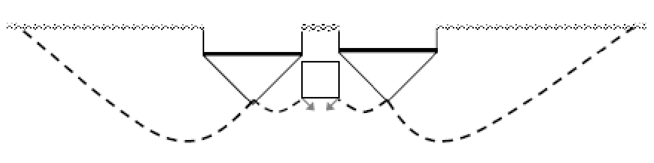
(a) Mode 0



(b) Mode 1



(c) Mode 2



(d) Mode 3

Figure 1. Failure zones sketch and interaction modes under dual arrangements (after Javadi, 2002).

developed between the footings, with soil moving upwards around its edges (see *Figure* 1c).

- *Failure mode 3*: In this mode, there was little or no soil movement at the sides of the compacted soil zone, and the zone itself remained fairly static (see *Figure* 1d).

The laboratory studies showed that a greater proportion of load could be supported in the shallower soil layers when the locally compacted zone was generated, thus reducing the risk of deep soil compaction. The aim of this research was to validate this hypothesis under field conditions in order to identify the trend between the data of disturbed soil in the soil bin and undisturbed soil in the field.

MATERIALS AND METHODS

The investigation was performed in Khuzestan Province, in the Dezful area of Iran, longitude 48.25′, latitude 32.26′ and altitude 82 m above sea level. The average annual rainfall is 350 mm and the common soil textures are clay-loam and silty-clay-loam.

Two different soil surfaces, one loose and the other firm, were prepared for this research. The loose field was prepared using a moldboard plough at working depth of a 200 mm, followed by two passes with an offset disc harrow 1.4-m in width. In the firm field a land leveler followed the disc harrowings. The fields were divided into four 40×30 m^2 plots and tests were performed in completely randomized block designs with three replications.

Two model 3140 John Deere tractors were selected to provide the required range of spacings between the rear wheels. New rear tyres were fitted to ensure the same conditions on both tractors, particularly at lug height. The wheels of each tractor were adjusted to maximize the distance between the rear wheels and minimize that between the front wheels, in order to avoid interaction between the front and rear wheels. The tractors were driven side- by- side at the same constant forward speed and a travel line was marked with chalk for drivers to keep the required distance apart.

Four different spacings between the wheels were investigated providing a varied range of possible interactions. The spacing measured was that between the outside of the rear tyres on each tractor. This was equivalent to the inside spacing in dual wheel arrangements. A single tyre was also tested carrying twice the load of one wheel on the dual arrangement. On the other hand, the load was equal to lalf the load on each side of dual wheel tractor. The load was applied using extra weights as well as mounted implements. The factors of forward speed, moisture content and soil texture were kept the same in order to identify only the influence of the wheel spacings.

The treatments were dual wheels at a wide range of spacing in relation to wheel width (425 mm) and representing different modes identified in previous research. Therefore, the arramnements were considered to be generally larger than wheel width (500 mm), 0.8 of wheal width (350 mm), 0.5 (200 mm) and the closest possible to wheal width (50 mm) as follows.

I) Dual wheels with 50mm spacing (S=50mm).
II) Dual wheels with 200mm spacing (S=200mm).

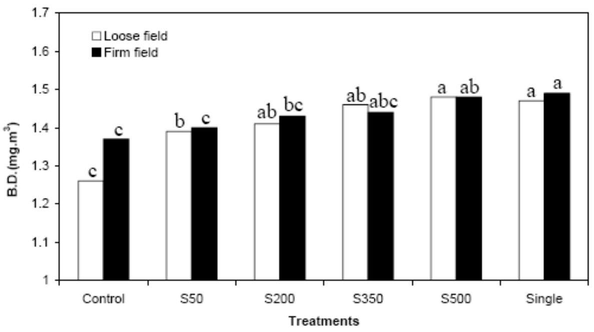
Table1. Moisture content in both fields, before and after operations.

	Before operation				After operation			
Depth(mm)	0 - 300		300 - 600		0 - 300		300 - 600	
Condition	Loose	Firm	Loose	Firm	Loose	Firm	Loose	Firm
mc(%) (mean)	13.53	11.13	18.79	17.60	14.27	12.70	19.50	17.62

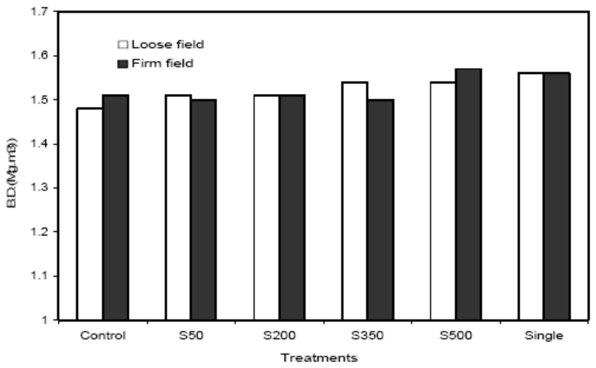
III) Dual wheels with 350mm spacing (S=350mm).
IV) Dual wheels with 500mm spacing (S=500mm).
V) Single tyre carrying the same load.

The tyre inflation pressure was adjusted to 137.9 kPa or 1.38 bar, which was the factory recommended pressure for ploughing operations with an 18.4-34 tyre size. The axle load was measured using a 50 kN load cell model TC-21K made by Tokyo Sokki Kenkyujo Company. The measured loads were 15.7 kN on each of the dual wheels and 31.3 kN on the single wheel. Soil dry bulk density, penetration resistance, wheel sinkage and contact area was measured under each treatment to assess soil movement and compaction which are explained below. The moisture content in different depth levels before and after operation is given in Table1.

a) 0-150 mm depth



b)150-300 mm depth



c)300 -600 mm depth

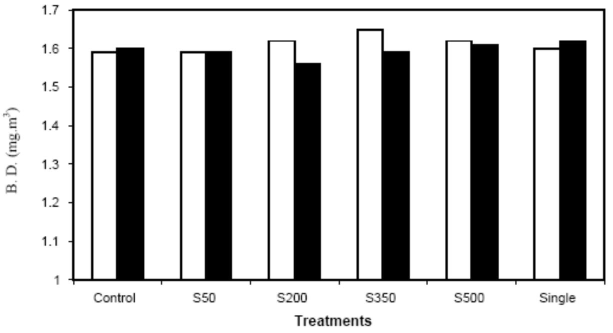


Figure 2. Bulk density (Mg/m^3 in both loose and firm fields).
S50=50 mm spacing; S200=200 mm spacing; S350=350 mm spacing; S500=500 mm spacing
Similar letter on each column shows no significant difference with 95% cinfidence.

RESULTS AND DISCUSSION

Bulk Density

The soil bulk density was measured in the rut within three depth ranges of 0-150, 150-300 and 300-600 mm with reference to the original soil surface for each arrangement. The technique was to take undisturbed soil in a small ring with enough replications. Figure 2 shows the results under both loose and firm field conditions. Comparing the unwheeled condition (control) in both the firm and loose fields showed that the density in the firm field was higher than in the loose one, mostly in the surface layer, and the depth range 0-150 mm, a common situation following land planing operations.

All the wheel arrangements increased the density in the 0-150 mm depth range in both the loose and firm fields (compare the control with the others in Figure 2-a). The results in the loose field, however, indicated a greater increase than in the firm field. Density differences were also significant between the small spacings (50 and 200 mm) and large spacings (350 and 500 mm). This was considered to be due to interaction between the failure zones and mode changes based on a previous study described in the litrature review (Figure 1). The dual wheels with wide spacing performed individually without interaction or with very weak interaction imposing more stress in the rut, compared with small spacings with dense interaction.

The results from an analysis of variance, given in Tables 2 and 3, showed that there was a significant difference between arrangements in the loose field, but not between the treatments in the firm field. A Duncan grouping was therefore performed and indicated that the difference was between the dual wheel at the largest spacing (500 mm) and the smallest spacing (50 mm). The analysis also showed that there was a significant B.D. difference between the single tyre and the closest spaced dual wheel, both carrying the same overall load.

The analysis of variances were also noted and there was significant difference between three depth levels. It was shown that the interaction effect of depths and arrangements was significant in the loose field. However, no significant difference was found between the arrangements in the 150-300 and 300-600 mm depth ranges in both fields, indicating most of the interaction effects occurred in the 0-150 mm depth range. The results

Table 2. ANOVA test for bulk density in the loose field.

Source	Df	SS	F value	Pr > F
Arrangements	5	0.067	7.60	0.0001**
Depth	2	0.341	97.13	0.0001**
Arran. * depth	10	0.040	2.28	0.0388*
Replications	2	0.0068	1.96	0.1585
Error	31	0.0544		
Total	50	0.4963		

$R^2 = 0.89$ C. V. = 2.78

Table 3. ANOVA test for bulk density in the firm field.

Source	Df	SS	F value	Pr > F
Arrangements	5	0.02334	2.41	0.0665
Depth	2	0.1698	43.76	0.0001**
Arran. * depth	10	0.01506	0.78	0.6502
Replications	2	0.00034	0.09	0.9168
Error	24	0.04656		
Total	43	0.2881		

$R^2 = 0.84$ C. V. = 2.91

showed that there was a step increase (about %10) in density above the 200-mm spacing (350 and 500 mm) in the loose field for two depth levels of 0-150 and 150-300 mm. This step occurred a little later in the firm field, above the 350-mm spacing (500 mm) at similar depth levels, due to the different soil condition. It is suggested that some change in failure mode could have occurred between the wheels at those steps.

Penetration Resistance

The penetration resistances were measured before and after the operations using a SP1000 model penetrometer. A 30° cone with 12.83-mm base diameter was used in this experiment. The resistance after the tests was measured both within and between the wheelings for each treatment. For the 50 and 200 mm wheel spacings, three positions were monitored, under the outer wheel, in between and under the inner wheel. These positions were increased to five at the wider spacings of 350 and 500 mm, giving three measurements in between. Figure 3 shows the measurement pattern.

Figure 3. The number and position of measurements under different spacings.

The penetration resistance was only recorded in the 0-200 mm depth range, due to resistances below that depth exceeding the 50 kN force limit. Moreover, the 0-200 mm range was, deep enough for the purposes of the experiment, since the interaction mostly occurred within that range.

The results at a 50 mm spacing, showed that the resistance between the wheels was slightly higher than that under the wheels (see the 50 mm spacing in Figure 4), confirming a stronger interaction than that identified previously occurring in the middle (mode 3). The difference was clearer in the loose field than in the firm.

The resistances in and between the wheelings were almost the same at the 200mm spacing (see 200 mm spacing in Figure 4), confirming that the failure planes met each other in the middle. This was identified as mode 2 of interaction.

The results at 350 and 500 mm spacings indicated that the values in between were less than those in the wheelings (see Figure 4). This was considered to be due to weak interaction and upward soil movement in the middle (mode 1 and mode 0).

The results in the deeper soil layers (150 mm and below) showed that differences between the values reached a minimum at both 350 and 500 mm spacings. This was thought to be due to upward movement being prevented due to the surcharge effect in the centre. The results in the firm field showed a similar trend to those in the loose field (see Figure 5). The results at the 150 mm depth in the firm field have not been presented due to the unavailability of the record for all arrangements.

It can be generally concluded that the resistances in the central area between the wheels were higher with the smaller spacing than with the larger, thus there was a potential for supporting more of the load in the upper soil layers. Comparing the resistances at the largest spacing (500 mm) with the values before the operation, revealed that there was no significant difference between the middle values. This was particularly clear in the shallower layer (0-100 mm depth) where there was no surcharge to affect the movement.

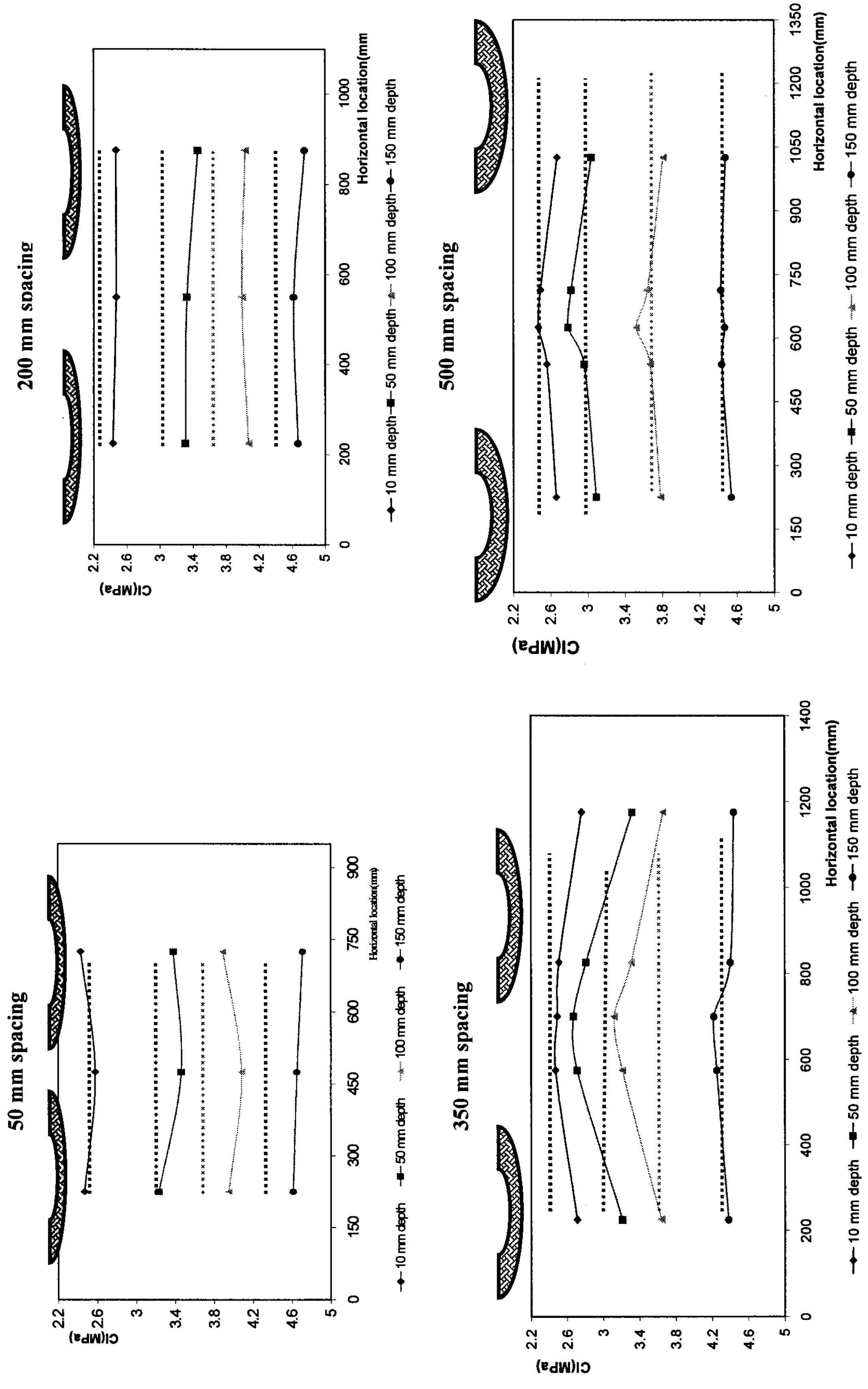


Figure 4. The penetration resistance under dual arrangements in the loose field.

▪▪▪▪▪▪ Data before operation ——— Data after operation

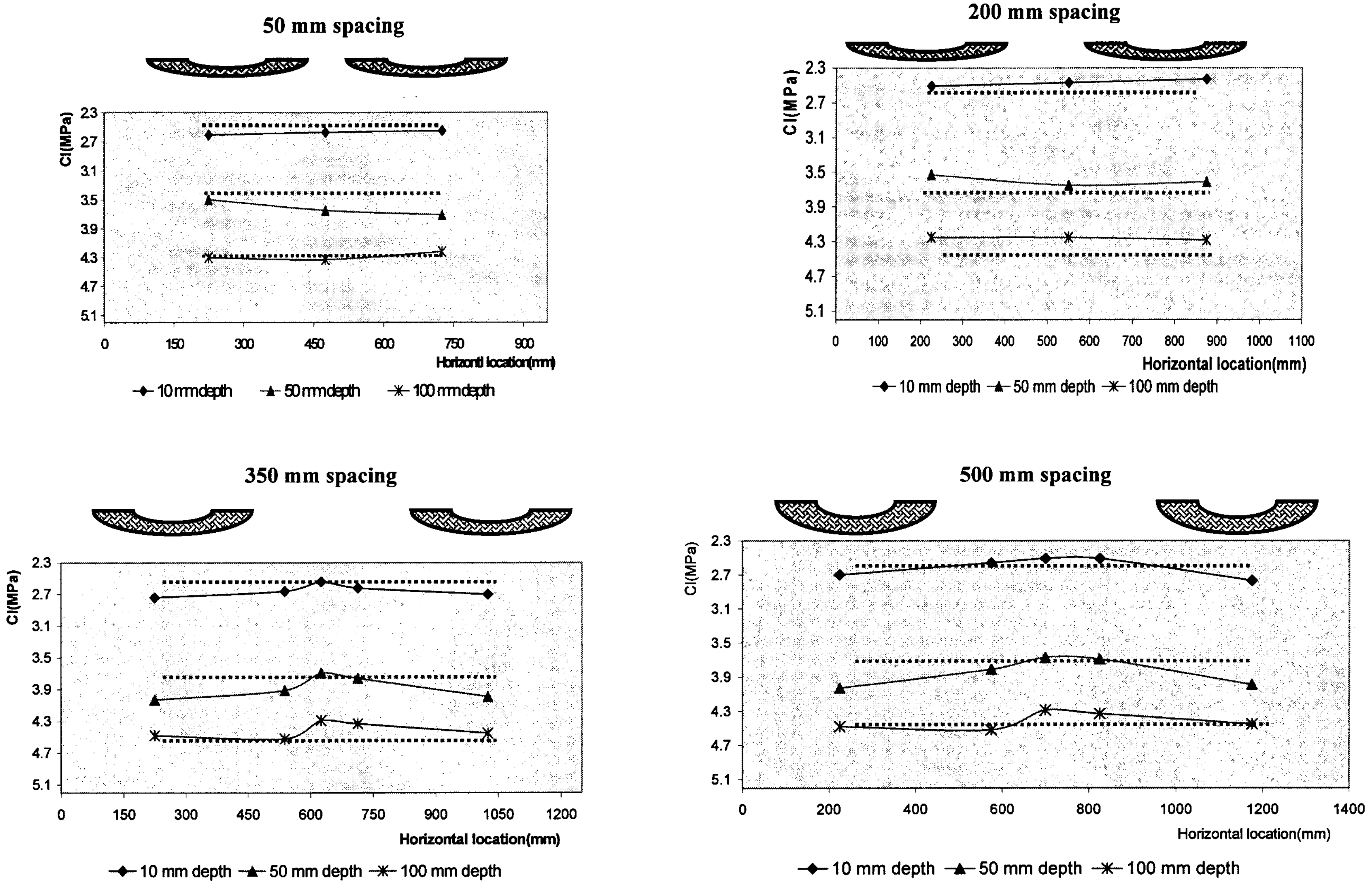


Figure 5. The penetration resistance under dual arrangements in the firm fie

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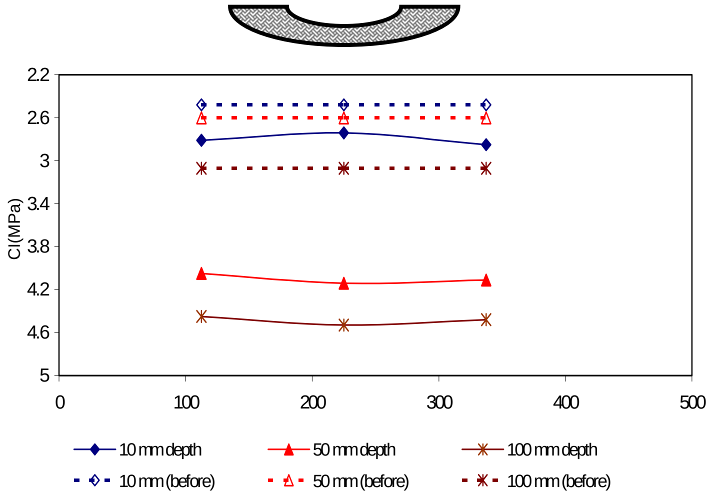


Figure 6. The penetration resistance under a single tyre in the loose field.

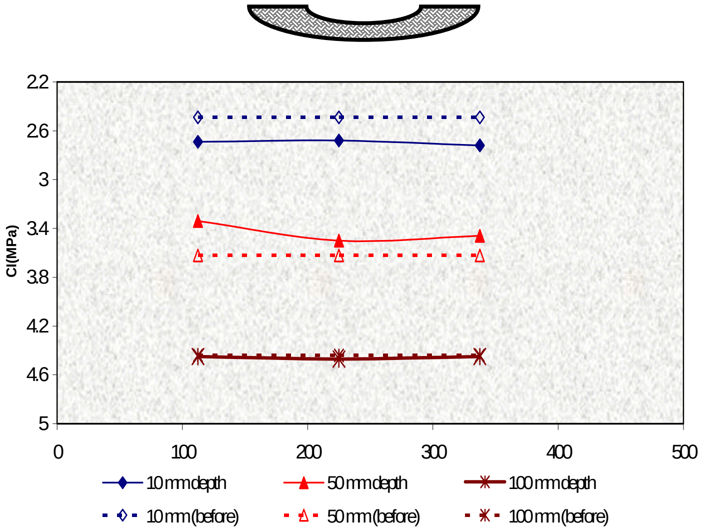
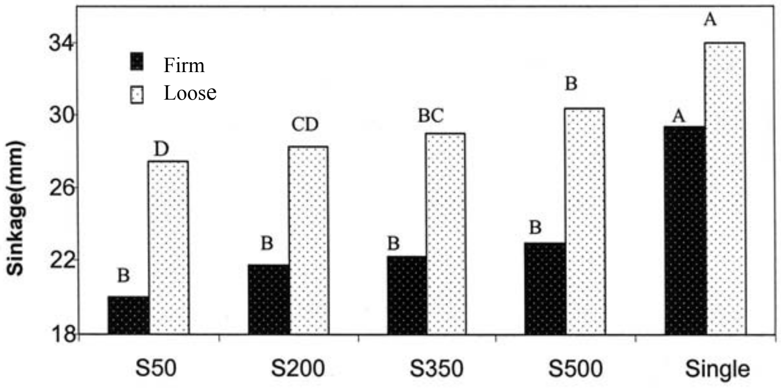


Figure 7. The penetration resistance under a single tyre in the firm field.

The single tyre test result indicated that the penetration resistance in the wheelings was higher when compared with the dual wheels, particularly at the small spacing in both fields (see Figures 6 and 7). The values of density before operation are also showed in the those figures revealing the changes after operation under a single tyre.

Wheel Sinkage

The sinkage of the wheels was measured as a mean across the rut under each arrangement with reference to a standard datum. The values were measured and the wheel sinkage results indicated that there were differences between the dual arrangements at different spacings, with higher sinkages being generated in the loose field than in the



*Similar capital letter on each column shows no significant difference with 99% confidence.

Figure 8. Whell sinkage comparison in both loose and firm fields.

firm one (see Figure 8).

The results analysis of variance given in Tables 4 and 5 showed that there was a significant difference between the treatments in both field conditions. The mean comparison using a Duncan grouping revealed that the difference between the largest spacing (500 mm) and the smallest spacing (50 mm) was very significant under both conditions. The difference between 350 mm and 50 mm spacings was significant in the loose field.

The analysis also showed that there was a very significant difference between the single tyre and all the dual arrangements under both field conditions.

Contact Area

The tyre contact area was measured on a concrete surface under both the dual wheel (one of them) and single wheel arrangements. The areas were determined to be 0.1794 and 0.2384 m^2 under the dual (one wheel) and single wheels respectively at the same inflation pressure. With loads of 15.73 and 31.36 kN on one dual and the single tyre respectively, the respective stresses applied to the soil were 132 and 88 kPa. Thus the stress induced in the soil under the single wheel was approximately 1.5 times

Table 4. ANOVA test for wheel sinkage in the loose field.

Source	df	SS	F value	Pr > F
Arrangements	4	444.88	22.86	0.0001**
Plot	3	23.9	1.64	0.1882
Error	72	350.225		
Total	79	819		

$R^2 = 0.57$ C.V. = 7.41

Table 5. ANOVA test for wheel sinkage in the firm field.

Source	df	SS	F value	Pr > F
Arrangements	4	866.825	11.16	0.0001**
Plot	3	32.65	0.56	0.6429
Error	72	1398.48		
Total	79	2297.95		

$R^2 = 0.39$ C.V. = 18.77

greater than under each tyre of the dual arrangement.

CONCLUSION

The test results confirmed that the different interaction modes between the failure zones, identified in the small-scale tests, also occurred in the field. The spacing between the dual wheels, through its influence on the nature and mode of the soil interaction, has a major effect on potential benefits in terms of reducing deep compaction.

The results of bulk density, penetration resistance and wheel sinkage measurements indicated that there were some differences between the large and small wheel spacings. The benefit of using the optimum spacing between the dual wheels increased the potential of supporting load within the surface layer. This is likely to reduce the risk of inducing stresses into deeper soil layer.

The results of penetration resistance proved that the values changed when spacing was increased from 50 to 500 mm. Soil resistance between the wheels at the smallest spacing was found to be higher than at the largest, confirming that more of the load was being supported in the surface soil layers.

Significant differences in wheel sinkage occurred between the largest and smallest dual wheel spacings and between all the dual arrangements and the single wheel.

The stress transmitted to the soil under the single tyre was found to be 1.5 times greater than that under the dual arrangements.

The link between the laboratory tests and the field experiments allowed estimates to be made of the optimum range of spacings for practical situations. In a typical soil with an angle of soil internal friction of 20-30 degrees, two beneficial interaction modes would occur with spacings (S) in relation to wheel width (W), as follows.

Failure mode 2: $0.75\ W < S < 1.50\ W$.
Failure mode 3: $0.40\ W < S < 0.75\ W$.

(where S is the spacing between wheels and W is wheel width)

It can be concluded, therefore, that the spacing between dual wheels should not exceed 1.5 nor be less than 0.4 times wheel width to realise the benefit. An appropriate spacing for supporting more loads in the surface layer and reducing deep soil compaction, would be 0.75 times the wheel width, covering both modes 2 and 3 of interaction.

It may also be concluded that using two or three narrow tyres at appropriate spacings, would be preferable for deep compaction reduction than a single wide tyre.

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بررسی اثر فاصله تایرهای دوبل بر روی تحمل بار و تراکم خاک

ا. جوادی و گ. اسپور

چکیده

در این تحقیق امکان استفاده از مزیت همپوشانی بین مناطق گسیختگی تحت تایرهای دوبل به‌منظور تحمل بخشی از بار وارده در قسمت‌های سطحی خاک مورد بررسی قرار گرفت. تحقیقات قبلی نشان داد همپوشانی‌های مختلفی بین محدوده شکست و گسیختگی خاک تحت تایرهای شبیه‌سازی شده صورت گرفته که بستگی مستقیم به فاصله بین تایرها داشت. تحقیق حاضر این امکان در شرایط واقعی مزرعه‌ای با فواصلی مختلف بین تایرهای دوبل را مورد بررسی قرار داد. تحمل بخشی از بار در لایه‌های سطحی خاک می‌تواند منجر به کاهش ریسک ایجاد تراکم عمقی خاک گردد. لذا دو نوع مزرعه با شرایط خاک سطحی متفاوت آماده شد بدین ترتیب که در مزرعه اول با عملیات خاک‌ورزی اولیه و ثانویه سطح خاک سست و در مزرعه دوم با عملیات نهایی تسطیح، سطح سفت‌تری تهیه گردید. اثرفاصله بین تایرهای دوبل در قالب ۴ تیمار با فواصل ۵۰ تا ۵۰۰ میلی متر مورد بررسی قرار گرفت. همچنین یک تایر تکی با بار مشابه تایرهای دوبل مورد آزمون و مقایسه قرار گرفت. پارامترهای جرم مخصوص ظاهری (بر مبنای خشک)، مقاومت به نفوذ خاک با استفاده از شاخص مخروطی (CI)، نشست تایرها و فشار سطح تماس تایرها نیز برای هر یک از تیمارها تعیین گردید. نتایج و تحلیل پارامترها در مزرعه وجود مدهای مختلف همپوشانی بین مناطق گسیختگی را تایید نمود و نشان داد که ارتباط قابل قبولی بین نتایج حاصله در شرایط آزمایشگاهی و مزرعه‌ای وجود دارد. لذا کاربرد تایرهای دوبل در فاصله بهینه با بهره‌گیری از مزیت همپوشانی بین محدوده های گسیختگی قابل توصیه می باشد. بدین ترتیب که با کاهش فاصله بین تایرها تا

حد مشخصی، میزان همپوشانی افزایش می‌یابد و نتیجتاً مقاومت بیشتری در لایه سطحی خاک برای تحمل بار وارده ایجاد و باعث ممانعت از انتقال بار و جابجایی در لایه‌های عمقی خاک می‌گردد. فاصله بهینه بین تایرها برای ایجاد همپوشانی مؤثر که پیشتر به‌صورت تئوری و در شرایط آزمایشگاه تعیین شده بود قابل کاربرد در شرایط مزرعه ای تشخیص داده و قابل توصیه و عمل می‌باشد. این فاصله برای خاکی با زاویه اصطکاک داخلی ۲۰ تا ۳۰ درجه معمولی حدودا" ۰/۷۵ عرض تایر تشخیص داده شد.