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DETERMINATION OF THE SUPER-ELLIPTIC SHAPE OF TIRE-SOIL CONTACT AREA USING IMAGE PROCESSING METHOD

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ABSTRACT. The present study is aimed at determination of the super-elliptic shape of tire-soil contact area using image processing method. Contact area has a substantial role on determination of soil compaction and tractive parameters of agricultural tractors. A very well-known model in this realm is to describe the contact area with superellipse geometry. A soil bin testing facility equipped with a single-wheel tester was utilized to conduct the needed experiments. The experiments were carried out at three levels of wheel load, three levels of tire inflation pressure with three replicates in a completely randomized block design. Corresponding images were taken for each of the experiments and the images were processed accordingly. The contact length and width were determined using imdistline command in MATLAB commercial software. This experiment was conducted at three levels of wheel load (2, 3, and 4 *kN*), and three levels of tire inflation pressure (100, 200, and 300 *kPa*) with three replications. The aforementioned parameters were applied consequently in the superellipse model and the contact area was computed. The obtained results disclosed that increase of wheel load increases the contact area. Contradictory, increment of tire inflation pressure reduces the formed contact area. Additionally, the potential of contact area determination with the proposed model was compared with that of actual values, which denoted coefficient of determination equal to 0.96, which shows the promising ability of the proposed model and the appropriateness of describing contact area with superellipse geometry.

Key words: Contact area; Image processing; Soil; Superellipse; Tire.

INTRODUCTION

It is well recognized that the contact area is a key parameter in evaluating physical, environmental loads such as soil and subsoil compaction, owing to the bulk of soil being subjected to the soil stresses. Moreover, the performance of off-road machines is strictly dependent on how much is the area of tire-ground

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contact and also how is the tire engaged by the soil profile. Contact area of run-off-road vehicle tires with the terrain is of substantial subjects that has been a dynamic field of studying interest for many years, particularly for those of driving tires owing to the non-uniform distribution of the wheel load and stresses on the at the soil-tire interface. A correct insight into the qualitative and quantitative condition of soil-tire contact area would also lead to a better understanding of the stress propagation into the different soil layers and also computing the anticipated amount of tractive parameters. It is recognized that the quality of soil-tire engagement is directly influenced by the amount of contact area. Additionally, the net traction of driving wheels (as a preferred parameter) and also the rolling resistance are direct functions of contact area. However, the investigation of contact area determination has always been a problematic issue to be achieved. This challenge simultaneously attributes to the stochastic behavior of wheel dynamics and also to the elastic-plastic characteristic of the soil medium. Various methodologies of analytical and empirical have been practiced to achieve the outperforming representation.

The analytical models are formulated utilizing elasticity and plasticity approaches (Roşca *et al.,* 2014). Elasticity models are constructed on account of the classical mechanical contact concept to estimate deformations and stresses (using approaches such as that of Boussinesq's), while plasticity based models consider the material (soil) failure theories (Roşca *et al.,* 2014). Upadhyaya *et al.* (1990) stated that analytical models fail to describe the interaction between tire and soil preferably because of the inconsistent physical properties of the medium and the material. Thus far, many algorithms and approaches have been employed for calculating the contact area of tires on farmland occasionally being customized for local interests. Reviewing the shape of the contact area, Grecenko (1995) recommended multiplying the length and the width of the contact area by a coefficient, c, varying between 0.8 and 0.9. Special consideration should be given that the contact area in this manner is yielded elliptical in shape and not the rudimentary shapes of circular or rectangular. Hallonborg (1996) proposed an extensively acceptable super ellipse model to describe the geometry of tire-terrain contact (Keller, 2005; Keller *et al.,* 2007; Taghavifar and Mardani, 2013 a), with half-axes, *a* and *b*, as well as a positive variable exponent to determine the shape of the ellipse. However, the accurate measurement of contact length and width is still standing as an unsolved issue which has to be overcome. Diserens (2009) calculated the contact areas in the field on 19 sites, from soft to hard surfaces, using 24 different trailer tires, with varying loads and inflation pressures. The obtained results, contrary to expectations revealed that with low levels of load, reducing inflation pressure can also reduce the contact area. Schjønning *et al.,* (2008) measured the distribution of vertical stress in the contact area for two radial-ply agricultural trailer tires loaded with about 60 *kN* on a sandy soil at a water content slightly less than field capacity under the effect of three different inflation pressures (50, 100 and 240 *kPa*) in a randomized block design with three replications. Furthermore, the proposed model (named FRIDA) that described the tire footprint by a superellipse and the stress distribution by a combined exponential (perpendicular to the driving direction) and power-law (along the driving direction) function. Since the periphery of the contact area particularly for driving lugged tires, when viewed, has some indents and projections, Taghavifar and Mardani (2013a, b) adopted the potential of a functional image processing technique to precisely separate the actual borders of the contact area from the soil medium.

The current study centers on the closeness of the soil-tire contact area of a driving wheel with that of superellipse shaped model proposed by Hallonborg (1996), that is widely affirmed by the numerous researchers in this context. In this regard, the concept of obtaining the contact length and width utilizing image processing technique and computing the contact area on account of superellipse model seems to be more accurate prediction of the contact area. Additionally, it is ideal to cross-validate the predicting ability of super ellipse model with those of contact area values obtained by discretely obtained image processing method.

MATERIALS AND METHODS

Theoretical basis

The periphery of the contact area may be better modeled by a superellipse which, in an orthogonal coordinate system with center at the origin, is given as following:

$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1 \quad (1),$$

where the exponent *n*, is a positive real number that determines the shape, and parameters *a* and *b* determine the length of half the major axes and thus, the proportions of the surface.

Therefore, *y* is yielded as given by:

$$y = b.\left(1 - \frac{x^n}{a}\right)^{\frac{1}{n}} \quad (2)$$

At a sample *x* range of between 0 and 0.6 and *a*=*b*=1, the output y is schematically obtained as *Fig. 1*.

The aforementioned description was presented to shed light on some major principles of superellipse shape and the effect of the exponent *n*. The area of one quadrant is given as (Hallonborg, 1996):

$$A = b\int_0^a \left(1 - \frac{x^n}{a^n}\right)^{\frac{1}{n}} dx = kab \quad (3),$$

where *k* is a constant that is a function of *n* which can be found by numerical integration. As proposed by Keller (2005), the parameter *n* was yielded as following:

$$n = 2.1(a.b)^2 + 2 \quad (4),$$

where *n* is dimensionless and the width of the tire *b*, and length of contact *a* are in *m*. It is noteworthy that for *n*=2, the curve is a pure ellipse whereas it grows towards a rectangle as $n \rightarrow \infty$.

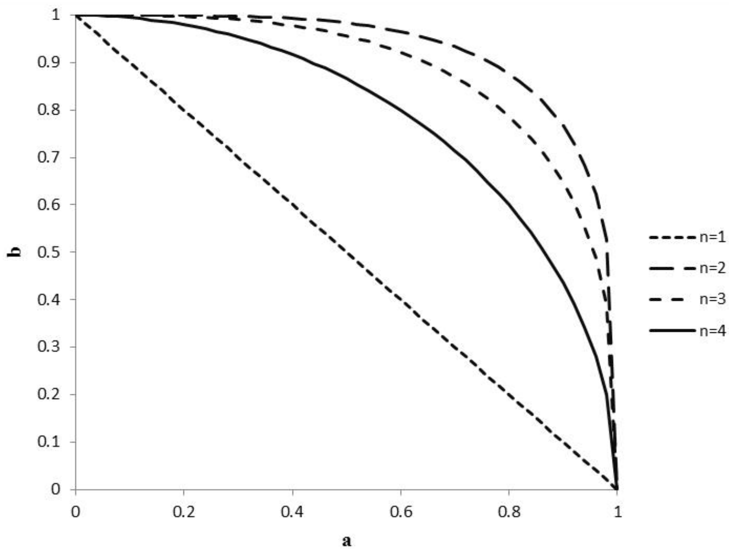


Figure 1 - The shape of the curve in the first quadrant when *a*=*b*=1 and *n*=1, 2, 3 and 4 in order from the origin of coordinates

Data collection

The required experiments were planned out to be carried out inside a soil bin of 23×2×1*m* of length, width and depth, respectively, while a single-wheel tester was mounted on a carriage (Taghavifar and Mardani, 2013 b). A three-phase electromotor of 22 *kW* was adopted to travel the carriage equipped with the single-wheel tester using chaining system. A Bongshin Model DBBP load cell with the capacity of 2000 *kg*, sensitivity of 0.1 *kg* and frequency of 50 *Hz* was located vertically between a power bolt and the wheel-tester chassis. There were also four S-shape Bongshin Model DBBP load cells with 200 *kg* capacity horizontally situated at places in parallel pattern between the carriage and the single-wheel tester. These transducers were then interfaced to data acquisition system including Bongshin digital indicator BS7220 model connected to a port of RS232 Data Logger. The system set up is shown in *Fig. 2*. The soil bin was filled with clay-loam soil as the predominant soil texture in Urmia, Iran. Tine, leveler and harrow were adopted to reverse soil bed to initial condition prior to each test run. Soil constituents and its properties are defined in *Table 1*.

Table 1 - Soil constituents and its measured properties

Item	Value
Sand (%)	34.3
Silt (%)	22.2
Clay (%)	43.5
Bulk density (kg/m^3)	2360
Frictional angle ( )	32
Cone Index (*kPa*)	700

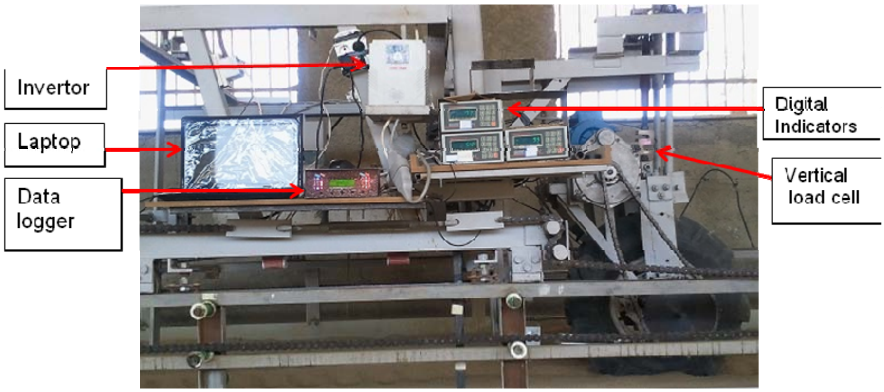


Figure 2 - The soil bin testing facility and the experimental data collecting devices

This experiment was conducted at three levels of wheel load (2, 3, and 4 *kN*), and three levels of tire inflation pressure (100, 200, and 300 *kPa*) with three replications. The soil constituents and specifications are tabulated in *Table 1*. During the experiments, the tire was treated by a desired level of wheel load under a definite amount of inflation pressure. The periphery of the contact section was poured by a white powder. The wheel was then unloaded and the tire footprint was recorded at eat treatment by taking images. The image processing method was applied to compute the contact area.

Image analysis

A new method was performed to calculate contact pressure in this study by application of image processing method. A white color powder was used at soil-tire interface for each treatment and the images were taken simultaneously. A Panasonic LUMIX DMC TZ25 camera was used for this purpose at a constant distance while a 4×4 cm index was used for calibration. The images were taken in RGB environment, where illumination is combined with color that a small change in color space could change the color of image remarkably. Therefore, it is necessary to use a space that color and illumination are separated. Using *s* (saturation) component in HSV color space and *b* component in LAB space, a preferred separation of tire track and background was achieved. First, the components were normalized in the range between 0 and 1. For improving the separation, the Gamma transform was applied as following:

$$x_1 = (s + v) \qquad (5)$$

$$x_2 = x_1^{\alpha} \qquad (6),$$

where α=2 was found as an optimal degree for separations. Furthermore, dilation was performed with structural elements equivalent to *ball*. Otsu method was applied to achieve the desired thresholding level and the binary images were obtained. Structural element closing was also used for deletion of noise effects on the images. Subsequently, connected components which had pixels lower than a definite level were removed and the connected region was filled. A sample of the taken and processed images is shown in *Fig. 3*. Wheel load at each treatment divided by contact area, yielded the corresponding contact pressure value.

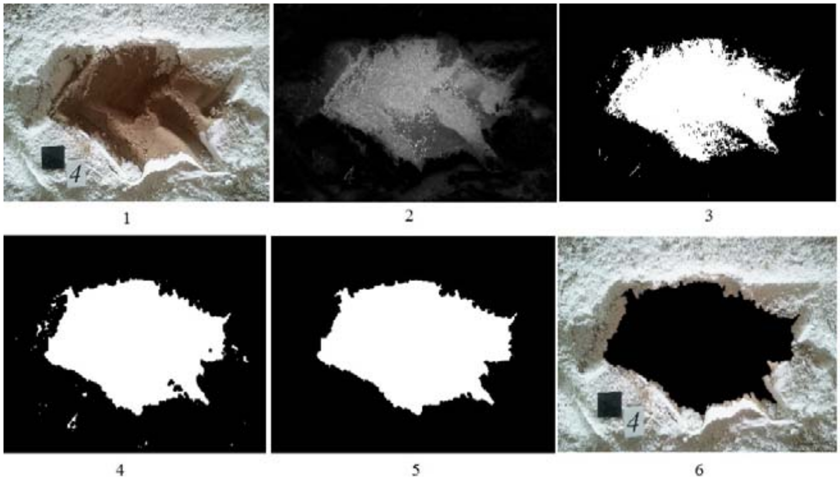
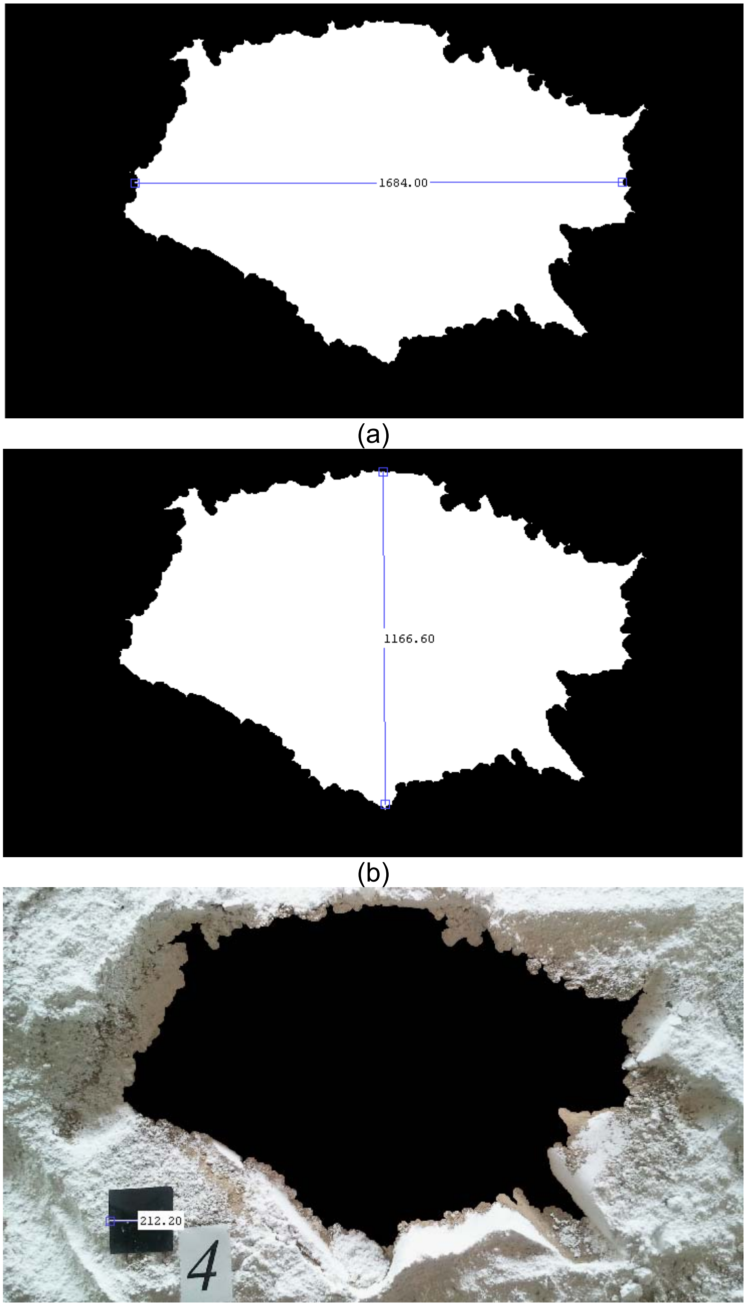


Figure 3 - The procedure of image analysis from the taken image to the binary image: 1) Original image; 2) Separation of tire track and background using Gamma Transform; 3) Dilation with structural elements; 4) Thresholding; 5) Binary image; 6) Colored image with the calibration index

RESULTS AND DISCUSSION

The command of imdistline was applied to all of the processed images to determine the length and width of contact on account of the corresponding pixels. Additionally, the predetermined length of the calibration object (Black square shaped paper with the dimensions of 4×4 cm) was calculated by the imdistline for each of the treatment images. *Fig. 4* shows this process for a sample treatment (i.e. number 4), which is under the wheel load of 2 *kN* and tire inflation pressure of 200 *kPa*. The contact length, contact width and the length of the calibration object are illustrated in terms of pixels. For instance, the product of the multiplication of contact length by 4 (dimension of the calibration object), divided by the length of calibration object in terms of pixels would yield the contact length (i.e. (1684×4) / 212.2, which is equal to 31.74 *cm*). This procedure was developed for all of the experiment cases. Knowing the contact length and contact width and considering Eq. 4, the exponent value, n, was determined. In the case of treatment number 4, the amount of exponent n was yielded equal to 2.01. The amount of contact area was then computed by Eq. 3.



(c)

Figure 4 - Determination of a) contact length; b) contact width; c) calibration object dimension using imdistline command

The obtained results are further revealed by *Fig. 5*, which is dedicated to the obtained results by the coupled method of image processing method and superellipse model. As it is appreciated from *Fig. 5*, it is deducible that the increment of the wheel load led to the increased contact area. This is justified in a manner that the increased wheel load is an attempt to push the tire into the soil profile with greater intensity. A resistive force is applied against the penetration direction to the wheel that brings about the more distributed area of the tire that leads to the increment of contact area. However, the increased tire inflation pressure results in the reduced contact area. The increased tire inflation pressure causes the creation of bulging effect of the tire that increases the stiffness of the tire. The more stiffened tire is more resistive against deflection when subjected to a wheel load. Therefore, the contact area reduces with respect to the increased tire inflation pressure. Similar results in the literature are in compliance with the results of the present investigation (Komandi, 1976; Taghavifar and Mardani, 2013 a; Schjønning *et al.,* 2008).

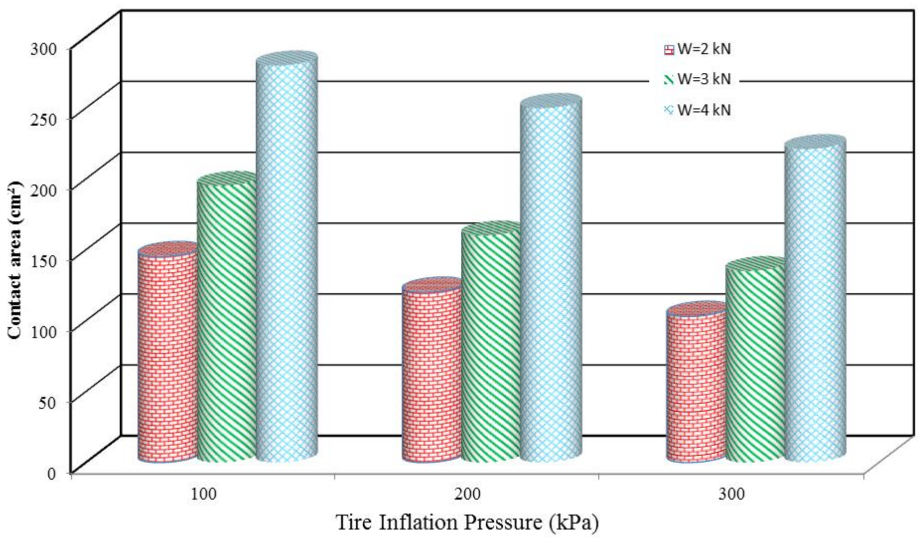


Figure 5 - Contact area with respect to the tire inflation pressure under different levels of wheel load

A comparison was developed also between the discrete image processing method and the coupled method of image processing method and the superellipse model. The obtained results are shown in *Fig. 6*, that shows the scatter plot of the obtained results around the best fitting line of $y = ax + b$. In this manner, a is the representative of the slope of the line, that a equal to 1 is preferred as well as b closer to 0. The coefficient of determination for this comparative trend was obtained at 0.9695, which is a promising value. The findings additionally indicate that superellipse is an appropriate method for the description of the contact area at different exponent numbers.

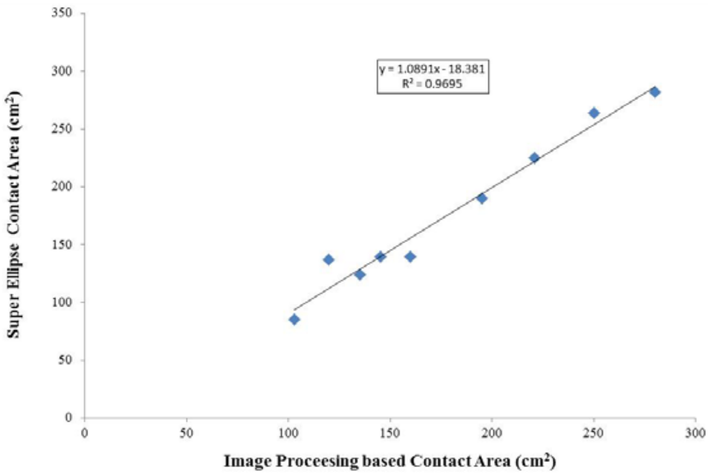


Figure 6 - The scatter plot of superellipse contact area versus image processing based contact area

CONCLUSIONS

The present study is aimed at determination of the super-elliptic shape of tire-soil contact area using image processing method. Contact area has a substantial role on determination of soil compaction and tractive parameters of agricultural tractors. A very well-known model in this realm is to describe the contact area with super ellipse geometry. A soil bin testing facility equipped with a single-wheel tester was utilized to conduct the needed experiments. The experiments were carried out at three levels of wheel load, three levels of tire inflation pressure with three replicates in a completely randomized block design. Corresponding images were taken for each of the experiments and the images were processed accordingly. The contact length and width were determined using imdistline command in MATLAB commercial software. The aforementioned parameters were applied consequently in the superellipse model and the contact area was computed. The obtained results disclosed that increase of wheel load increases the contact area. Contradictory, increment of tire inflation pressure reduces the formed contact area. Additionally, the potential of contact area determination with the proposed model was compared with that of actual values, which denoted coefficient of determination equal to 0.96, which shows the promising ability of the proposed model and the appropriateness of describing contact area with superellipse geometry.

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