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Development of a Simplified Dynamic Testing Device for Turfed Sports Surfaces

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ABSTRACT

The response of natural turf surfaces to loading changes with the force and loading rate applied. Quantification of surface behaviour to athlete loading is complicated by the lack of devices that replicate forces, stresses and loading rates of athletes that can be specifically used on natural turf. To address this issue, a vertical dynamic impact testing device, the DST, was developed. The DST consists of a compressed air driven ram which vertically impacts a studded test foot onto the surface using data from biomechanical studies. The vertical dynamic stress of athlete foot strike during running is replicated, using peak force and mean boot contact area data. The ram pressure is adjustable to allow variation of the stress applied upon impact, potentially replicating a range of athlete-surface interactions.

Initial laboratory testing indicated that the device was sensitive to changes in soil condition due to variations in impact data. Total penetration time and distance, and surface energy absorption were all significantly greater in prepared ‘soft’ soil treatments ($p<0.05$). Loading rate in the first 50 ms after impact was significantly greater in the ‘hardest’ soil treatment ($p<0.05$). Future research work will determine *in-situ* behaviour of actual playing surfaces, compare device loading rates to those of athletes, and assess surfaces to a range of stresses.

Key words: Natural turf, dynamic soil strength, test device, athlete-surface interaction

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1. INTRODUCTION

Natural turf sports field surfaces are used extensively for winter sports such as football and rugby. The mechanical behaviour of these surfaces is important for both the prevention of injuries and to aid athlete performance. Dissipation of impacting energy and reduction of loads returned to athletes is regarded as important to prevent injuries [1], while stiffness and energy return from sports surfaces allows athletes to perform athletic movements more efficiently [2].

Understanding of athlete loading of natural turf surfaces requires further research [3], to determine how these surfaces provide impact absorption and how they behave during and following unloading in terms of energy return and surface wear. Quantifying the mechanical response of natural turf surfaces to impact is complicated by stress-strain behaviour being dependent upon the magnitude and loading rate of the stress applied [3]. The ability of mechanical devices to replicate the forces, stresses and loading rates of athletes is therefore vital to understand the behaviour of this surface type in the human sport context.

Previous research has identified a lack of sports surface testing devices that replicate loading and boundary conditions of athlete-surface interaction [1, 4, 5], with fewer devices suitable for use on natural turf than synthetic turf sports surfaces. Vertical impact loading of athletes is replicated by the Artificial Athlete Berlin (and similar devices) but testing of natural turf surfaces with these devices has not been reported in the literature reviewed, although the Artificial Athlete Berlin has been used in benchmarking natural turf in the development of synthetic turf. This could be due to the availability of such devices for natural turf research or issues related to large plastic deformations in natural turf [3] which are not experienced in the testing of elastomeric or synthetic turf surfaces. The Clegg Impact Soil Tester (CIST) is the most commonly used vertical impact device for natural turf sports field surfaces, and quantifies peak deceleration of a falling mass onto the surface under performance quality standards [6]. While it is lightweight and portable, the device does not represent contact times, rate of loading or peak forces of athletes [5]. The lack of biomechanically valid, vertical impact devices specifically for use *in-situ* on natural turf has restricted comparisons between artificial and natural turf sports field surfaces. To address these issues, a mechanical vertical testing device was developed to investigate the effects of dynamic impact stresses simulated on natural turf surfaces.

2. METHODOLOGY

2.1 The Dynamic Surface Tester Device

2.1.1 Design and Operation

The Dynamic Surface Tester (DST) device consists of a compressed-air driven ram (VG040/0100 Numatics Inc., Skelmersdale, UK) of 100 mm stroke length that impacts a studded cylindrical test foot vertically onto the surface. Pressure-controlled testing is created with the pneumatic system, allowing ram pressure to be adjustable (0.2-0.7 MPa) to vary the velocity (1.10-1.34 m s^{-1}) and force (0.26-0.82 kN) of the test foot upon impact. The test foot is an aluminium cylinder (41 mm diameter, 38 mm height, 1320 mm^2 surface area), which allows a single stud to be positioned in the centre of the foot. The stud is interchangeable, with a British Standard 15 mm length aluminium rugby stud [7] selected for this research due to its low wear characteristics.

Soil water content (volumetric) is recorded as a first stage measurement using an impedance sensor (ML2x, Delta-T Devices Ltd., Cambridge, UK). At rest the foot is positioned 35 mm above the surface (Figure 1a), and passes through an aperture in a steel base plate during operation, causing a direct impact with the surface. The test foot continues to penetrate into the surface until the ground reaction force is equal to the impacting force of the test foot, at which point the device stops moving (Figure 1b). Maximum surface penetration is limited to 46 mm by ram stroke length. The foot retracts to its original position (Figure 1a) at the end of each test. Data collected with the DST is stored on a logger and transferred to a PC for processing through a numerical computing script (MatLab 7.1, Mathworks, Natick, MA, USA). The device and air cylinder fit onto a sack-barrow to allow for portability.

An Entran ELHS force transducer (Entran, Lexington, KY., USA) measures the force acting on the test foot (1 kN range, 0.5 % combined non-linearity and hysteresis), and a linear encoder (rack and pinion single turn 20 kΩ potentiometer; precision ± 0.2 mm) measures positional data during impact and penetration, at a frequency of 533 Hz. Time measurements are based on a crystal-controlled 10 ms timing pulse from the data logger controller. Impact speed is calculated by the maximum change in distance between two time points (1.875 ms) before impact with the surface.

Total energy absorption of the surface is determined by calculating the integral of the work done by the test foot during penetration (W) during each timestep (Equation 1).

$$W = \int_{0}^{z\,\max} F\,dz \qquad (1)$$

Where *zmax* is the maximum depth of penetration, *F* is the ground reaction force acting on the test foot, and *dz* is the vertical displacement interval in each logging cycle.

Loading rate in the first 50 milliseconds of impact (dFz_{50}, kN s^{-1}) is calculated by:

$$\mathrm{dFz}_{50} = \frac{\Delta \mathrm{F}}{50} \tag{2}$$

Where ΔF is the difference in force between t = 50 ms and t = 0 ms (i.e. initial impact).

2.1.2 Biomechanical Validation

The DST device was developed to simulate the peak vertical dynamic stress of the loading phase during athlete foot-surface contact when running (Figure 2). Previous research [8, 9] showed that when subjects ran on natural turf surfaces in a laboratory at 3.83 m s^{-1}, they had a mean external boot contact area of 3800 mm^2, exerting a mean peak vertical force of 2.12 kN (B, Figure 2) and vertical stress of 0.56 MPa during foot contact. This value of mean stress is replicated by the smaller footprint (1320 mm^2) of the DST device using an impacting force of 0.74 kN.

The aluminium test foot on the device was selected to increase durability during use, and therefore repeatability in surface testing, instead of selection of boot-specific materials. The effect of the stud on the test foot during impact is considered minimal in terms of decelerating the test foot on soft surfaces, but may be used as an indicator of reduced comfort for athletes on harder surfaces where complete stud penetration is not possible. The range of impact velocities provided by the device (1.10-1.34 m s^{-1}) is comparable to vertical touchdown velocities (1.10 m s^{-1}) recorded when athletes ran at 4 m s^{-1} [10].

2.2 Soil Characterisation and Experimental Design

Validation experiments were performed with the DST in the Soil Dynamics Laboratory at Cranfield University. The soil used was a sandy loam texture (66 % sand, 17 % silt, 17 % clay), as per [11]. Integrated excavation and consolidation machinery which provide uniform soil conditions [12, 13] were used to prepare four different soil only (no grass, no organic matter) treatments. The variation in the soil treatments was created by manipulating soil dry bulk density and water content, and quantified using core sampling for dry density [14] and a soil water content impedance probe (type ML2x, Delta-T Devices Ltd., Cambridge, UK) respectively. The deceleration (multiples of the acceleration due to gravity, g) of a 2.25 kg CIST, (SD Instrumentation Ltd., Bath, UK), dropped three times from 0.45 m vertically onto the test surface, was used to determine soil hardness in each treatment (Table 1). Undrained soil shear strength (Cu) was measured with a 19 mm shear vane (Pilcon DR 2149 Pilcon Engineering Ltd, Basingstoke, UK) and reported as per [15].

Each treatment was split into six plots of size 400 mm x 2200 mm and a randomised block design was used. Three replications of soil dry bulk density, volumetric moisture content and rebound hardness were collected per plot (n = 18), with five replications of DST impacts performed per plot (n = 30). The operating pressure on the DST device was set at 0.6 MPa, resulting in an impact force of 0.79 kN ± 0.03

(impact stress of 0.6 MPa) on a reference 15 mm thick styrene butadiene rubber (SBR) shockpad over concrete.

Total penetration distance, total penetration time, total surface energy absorption and dFz_{50} as measured by the DST were used to assess the variation in the soil treatments. All treatments were analysed for differences with one-way ANOVA and Fisher LSD ($p<0.05$) to determine *post-hoc* differences. Pearson correlation coefficient analysis was performed to assess linear relationships on mean treatment data of the soil characterising variables (Table 1) and the DST impact variables. All statistical analysis was performed using Statistica 9 (Statsoft Inc., Tulsa, OK., USA).

3. RESULTS AND DISCUSSION

Mean force-time histories for DST impact in each treatment are illustrated in Figure 3. Lower dry density soil treatments (3 and 4) took longer to bring the DST test foot to rest, and exhibited greater force readings than the harder dry density treatments at end of penetration. This suggests that there is a time-dependence in the generation of force through the pneumatic system.

Significant differences ($p<0.05$) were found among the soil treatments for penetration distance, penetration time, surface energy absorption data and loading rate (Figure 4). The more loosely packed, lower density soil treatments (Treatments 3 and 4) allowed significantly greater penetration distance (Figure 4a), penetration time (Figure 4b) and surface energy absorption (Figure 4c) due to lower shear strength of the soil (Table 1). This is due to an increase in soil shear strength and resilient modulus with soil dry density [3, 17, 18]. Shear strength (Cu) was linearly correlated with these parameters ($r = -0.93$ to -0.97; Table 2). Soil hardness as measured by the CIST was also linearly correlated with these parameters (r = -0.85 to -0.98; Table 2) and with shear strength (Cu, r = 0.93; Table 2).

These initial data support the potential of the device as a tool to assess dynamic strength of natural surfaces. Data from *in-situ* surfaces is required for further validation of the device, and will allow assessment of a variety of physical surface conditions, including the effects of turfgrass. Strong correlation coefficients between penetration distance, penetration time and energy absorption are expected due to the inter-dependency of these parameters.

Rate of loading was only significantly greater in Treatment 2 ($p<0.05$). Rate of loading is an important variable for assessing sports surfaces for athlete interaction [16], and is not currently performed by other mechanical devices. Although described as dynamic, the data from these initial experiments indicate the DST device loaded the surface 7 times more slowly than subjects in the previous study [8] (10.3 kN s^{-1} compared to 75.8 kN s^{-1}), and this aspect will be considered further in future work. The DST can be considered a simplification of athlete-surface interaction by the adoption of mean contact area to produce stress data, and modelling vertical aspects only. However, it provides a further step towards understanding player-surface interaction on natural turf due to the lack of biomechanically valid vertical impact devices evident for use *in-situ* on this surface type.

Replicating the dynamic stress an athlete imparts onto a surface, through the development of a mechanical device, allows increased understanding of surface behaviour in response to athlete impacts (e.g. surface deformation), and the extent of the energy absorption an athlete may receive. The stud on the test foot allows stud/test foot penetration ratios to be investigated, and replicates more closely the boundary conditions of athlete-surface impacts [19]. The function of the DST device measures maximum surface deformation when loaded, important for energy dissipation when athletes impact the surface. The behaviour of the surface during unloading is not determined with the current device configuration but should also be considered, as viscous and elastic properties are important for surface durability and player performance [3].

The non-linear stress-strain behaviour of sports surfaces requires new testing devices to possess the ability to vary the impacting forces and stresses imparted onto the surface [5]. The DST device possesses this capability in terms of variable ram pressure and interchangeable test feet and studs of different dimensions, and future research will be directed towards assessing surface behaviour to a range of vertical stresses which replicate a range of athlete masses or biomechanical movements.

4. IMPLICATIONS

A new variable-force dynamic testing device for use on natural turf surfaces has been developed, which replicates the vertical stress of an athlete when running. This device can be used to increase understanding of the behaviour of sports surfaces under athlete loading and the energy dissipation athletes encounter.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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Tables

Table 1. Mean soil characterisation data for each treatment (n = 18 for each parameter; ± standard error): dry density (ρ_d), water content (θ_v), hardness (2.25 kg Clegg Impact Soil Tester, third drop) and. undrained soil shear strength (Cu).

Soil Treatment	ρ_d (g cm^{-3})	θ_v (% vol.)	Hardness (g)	Cu (kPa)
1	1.56 ± 0.01	23.1 ± 0.43	105 ± 7.59	83 ± 4.32
2	1.50 ± 0.02	17.2 ± 0.38	165 ± 4.36	96 ± 4.74
3	1.37 ± 0.01	13.1 ± 0.51	59 ± 3.50	20 ± 1.01
4	1.34 ± 0.01	16.7 ± 0.36	65 ± 0.97	27 ± 1.18

Table 2. Pearson correlation coefficient (r) of mean treatment data for soil characterisation properties as outlined in Table 1, soil hardness determined by the 2.25 kg Clegg Impact Soil Tester, and DST impact variables penetration distance, penetration time, energy absorption and loading rate at 50 ms (dFz_{50})

	Soil hardness (CIST)	Penetration distance	Penetration time	Energy absorption	dFz_{50}
Dry density (ρ_d)	0.71	-0.77	-0.97	-0.94	0.32
Water content (θ_v)	0.36	-0.36	-0.66	-0.59	-0.09
Cu	0.93	-0.93	-0.97	-0.96	0.65
Rebound hardness (CIST)		-0.98	-0.85	-0.88	0.89
Penetration distance			0.90	0.93	-0.85
Penetration time				>0.99	-0.54
Energy absorption					-0.60

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Figures

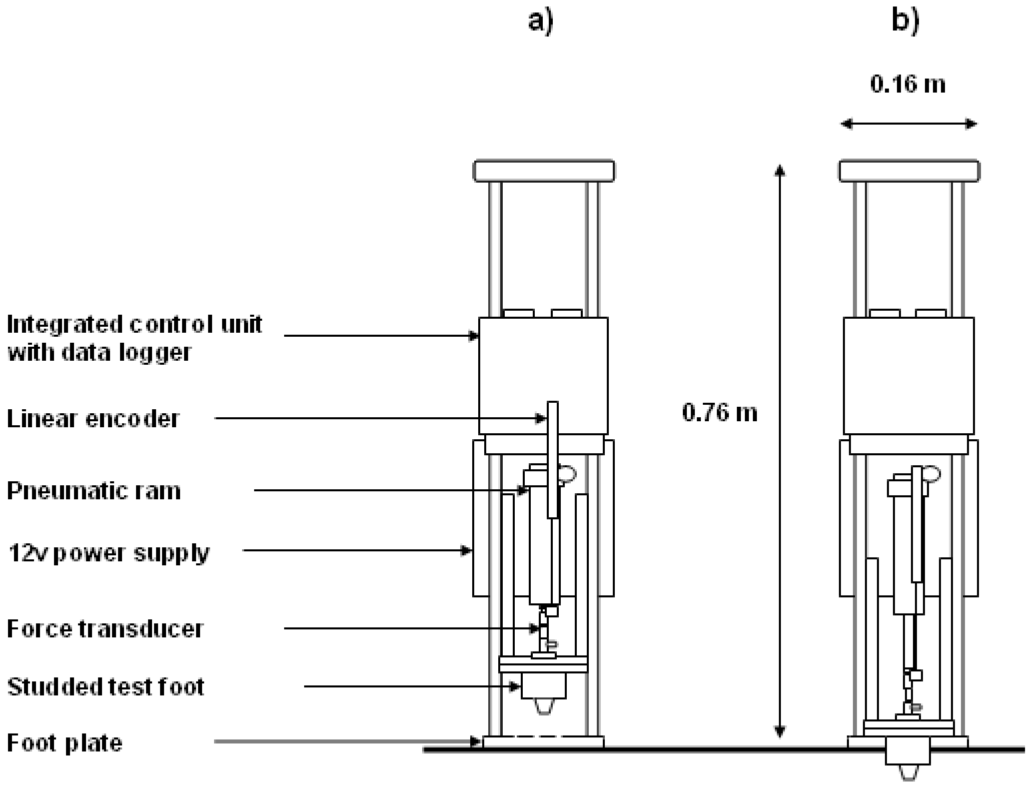

Figure 1. A schematic diagram outlining operation of the Dynamic Surface Tester device. a) device at rest; b) at the end of penetration phase of measurement. Not drawn to scale.

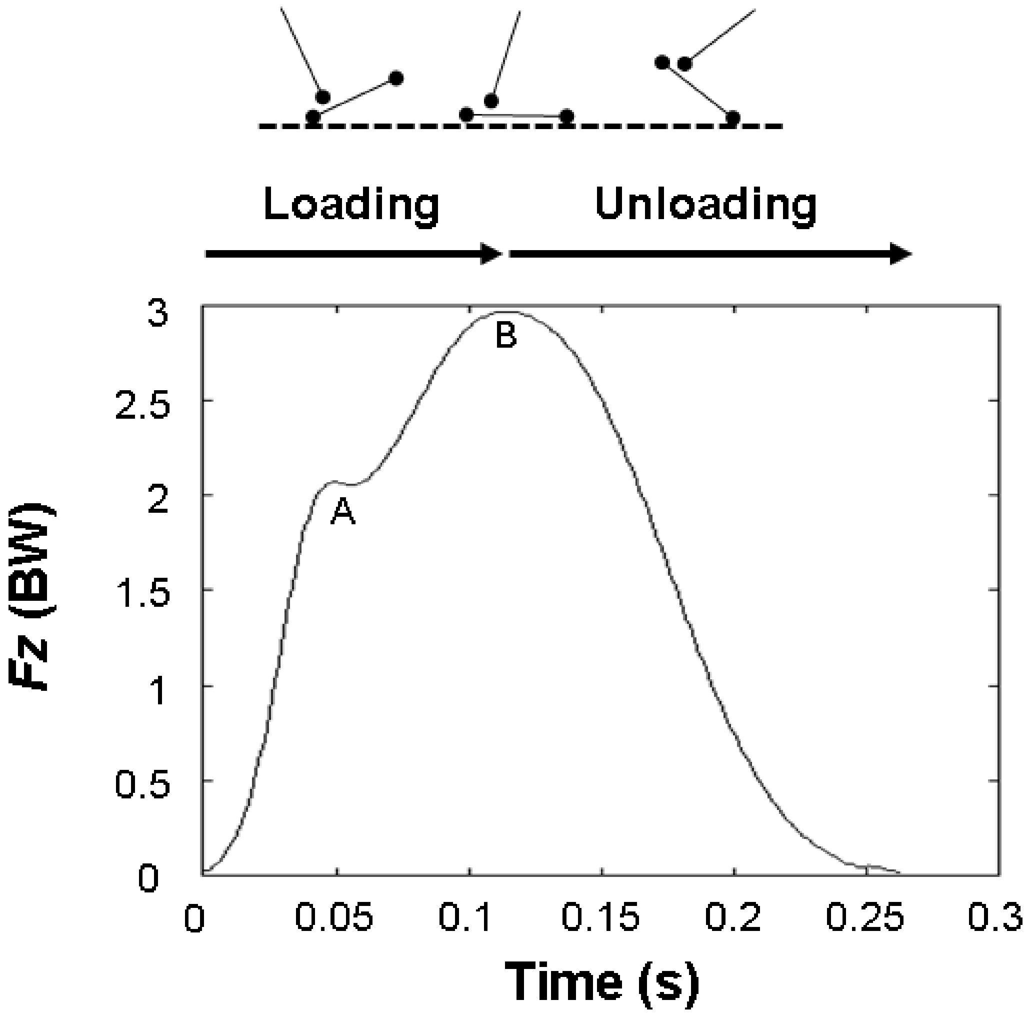

Figure 2. A typical vertical force-time history (in terms of body weight, BW) for a heel-toe running foot strike (adapted from [3]). Loading and unloading phases, and foot contact angles are indicated. A represents peak vertical impact force and B peak vertical active force.

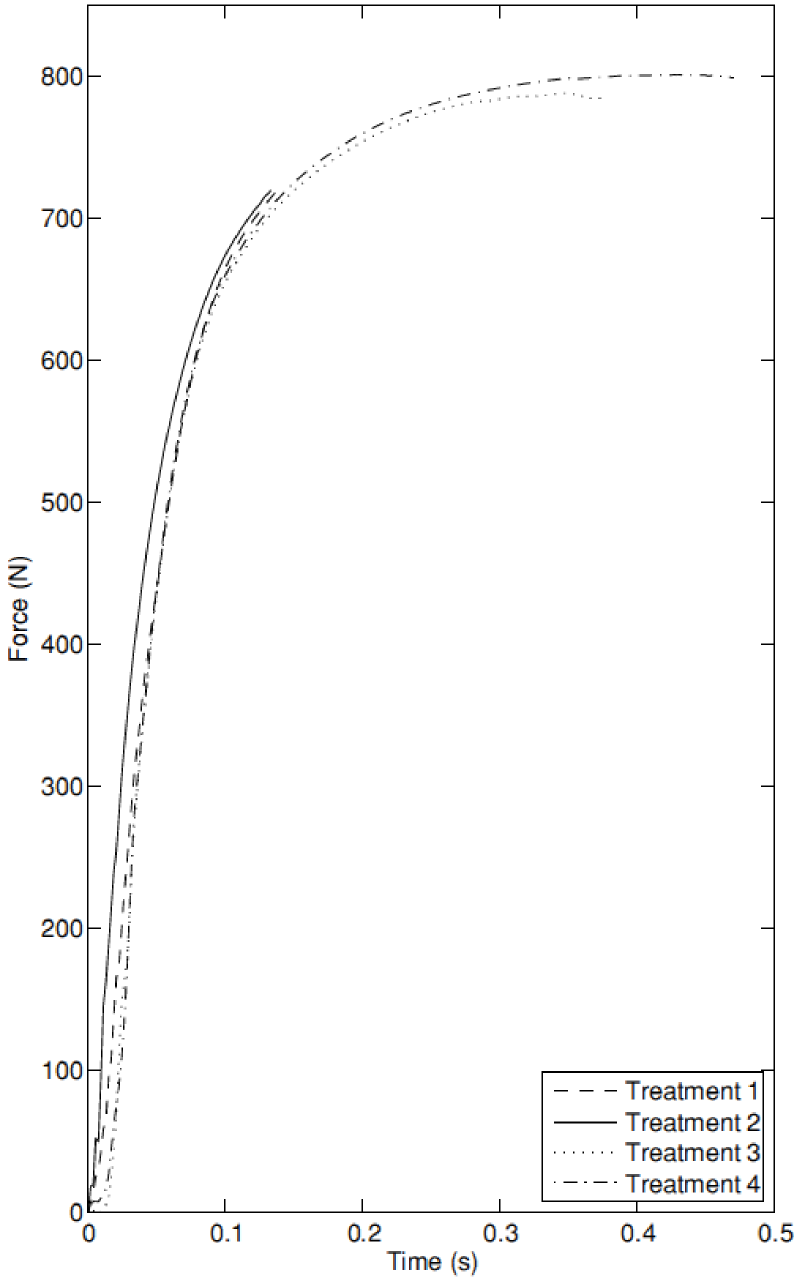

Figure 3. Force-time histories depicting mean ground reaction force for each soil treatment as measured with the DST device (n = 30 for each treatment).

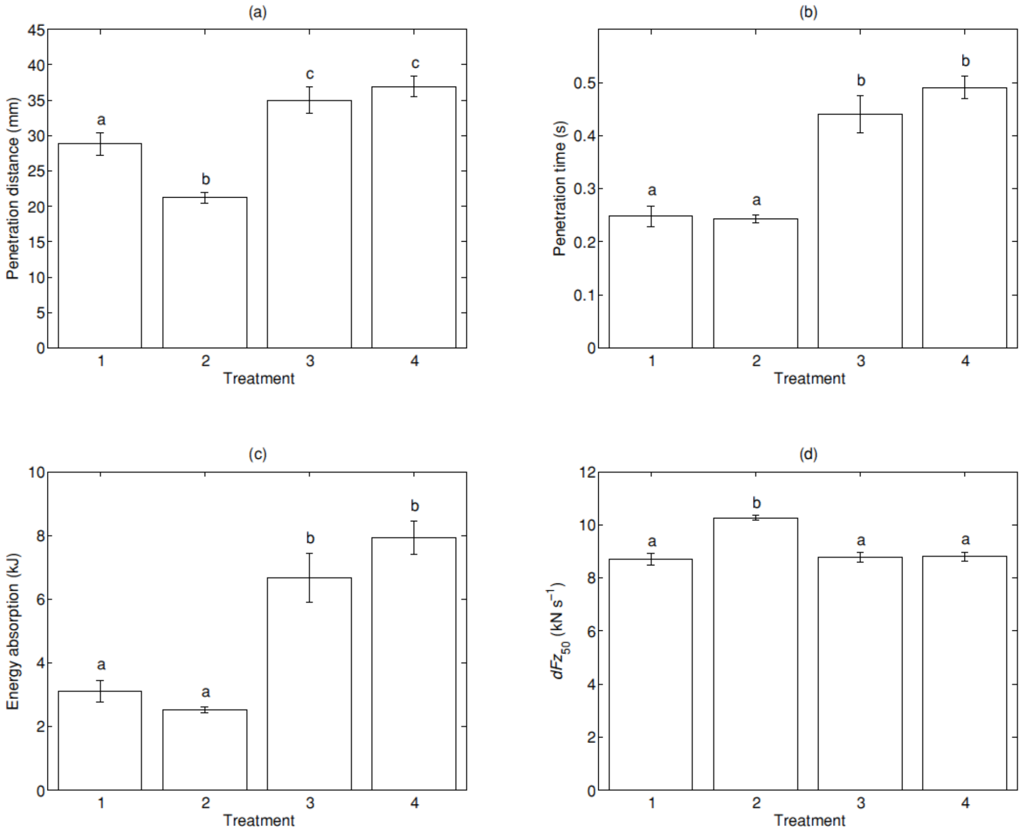

Figure 4. The response of soil treatments 1-4 to impact as measured using the DST device a) mean total penetration distance; b) mean total penetration time; c) mean total surface energy absorption; d) loading rate during the first 50 ms of impact. Letters indicate homogenous groups tested with Fisher LSD (p<0.05), whiskers represent standard error (n = 30 for each treatment)

Appendix One

List of Notation

dFz_{50}	Vertical loading rate in the first 50 ms of impact
dz	Vertical displacement
Fz	Vertical force