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Force transmitted below the soil surface by human gait

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Abstract

A force platform, which can provide three dimensional forces and moments on its top surface, was used to study force transmitted by human gait below the soil surface in order to understand detonation of antipersonnel landmines. Soils of varying depth were packed on the top surface of the platform to measure the forces transferred from the soil surface. Experimental variables included subjects (people), soil depth, soil type, moisture content, and compaction level. Soils used in this study were sand and sandy loam. There were medium and high two compaction levels for each soil. Sandy loam soil included two moisture contents; sand tested involved two moisture contents and dry sand. Soil depth varies from 0 (bare platform) to 200 mm. Five subjects with different weights were selected and used in this study.

The subsoil force and its duration were measured for different subjects at a depth up to 200 mm. The impulse in subsoil was then calculated and used in evaluating the effect of different subjects on the force transfer in soil. The results indicated that loose soil can transfer larger force to subsoil than dense soil; test results showed that heavier subjects also created larger subsoil forces than lighter ones. Whether the effect of soil depth on subsoil impulse was significant was depended on the soil conditions. For the sand with 5.5% moisture content and bulk density of 1800 kg/m^3, soil depth significantly affected subsoil impulses. For the sandy loam soil, the mass of subject increased from 50 to 100 kg resulted in 100% increase in subsoil impulses at all four depths; for the sand, the mass of subject increased from 55 to 100 kg approximately. This resulted in 80% increase in subsoil impulses under all four depths regardless of moisture content and bulk density. The results of this study will helpful for designing new equipment and evaluating existing machines for neutralizing landmines.

Keywords: Force profile; Subsoil Layers; Human gait; Landmine Neutralization

1. Introduction

It is estimated that there are more than 100 million landmines in the ground over 70 countries, 350 million in stock, and even more being laid at a rate of 2.5 million a year [1]. More than 50 countries have manufactured about 200 million antipersonnel landmines in the last 25 years [2]. Landmines are and will still be a significant problem for the safety of people and economic development of affected countries [1]. Landmines are generally buried within 10–150 mm of the surface. There are two common classifications for landmines: antipersonnel (AP) landmines and anti-tank (AT) landmines. The major differences between these two types of mines include their size, amount of explosive, and force required to activate. AP mines require 19.6–245 N to detonate; and AT mines require 1470–3430 N to detonate. The operation of landmines differs from model to model, but the basic operation includes the use of a force sensing pad or trip wire, a firing mechanism and an amount of explosive. Landmines restrict the use of land and delivery of aid and relief. The United Nation (UN) standards for humanitarian mine clearing requires 99.6% clearing to a depths of 200 mm below the ground surface.

Development of mechanical demining devices has increased rapidly over past 15 years. Commercial and mil-

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itary machines, such as mine hammers, flails, rollers, ploughs, and combination equipment have been employed in the activities of landmine neutralization. The use of mechanical systems for demining operations was first employed by military organizations during the World War One [2]. The primary use of such systems was to provide a breaching system in which a tank or other vehicle cleared a path in a minefield, providing a passageway for troops, but not to demine the area. Devices such as rollers and chain flails were primarily employed. In 1980's, the demining activities shifted to humanitarian purposes. Mechanical demining devices were adapted for the military machines such as rollers and chain flails. All these devices transfer force and displacement from soil surface to the subsoil. However, the suitability of demining devices for different environment and terrain conditions has not been thoroughly studied; knowledge of the proper usage of demining machines is not available [3–5]; the effectiveness of most demining machines is unknown. Moreover, the subsoil force under human locomotion, which is to detonate landmines, has not been studied. Therefore, it is of essence to understand the force transfer in designing and evaluating mechanical demining devices, particularly, to understand the force transfer due to human locomotion.

Stress distribution in soil under the action of vehicles has been studied since 1960's. These achievements were well documented [6–10]; but, no adequate means exist to clearly predict the stress distribution in soil. Considering soil an elastic material, Boussinesq equation was used to determine stress distribution in soil by a point load with sufficient accuracy [11]. Researchers studied vertical displacement of sub-layers [12,13]; Abou-Zeid [14] studied displacement and pressure in subsoil using a soil box with acrylic glass walls. Unfortunately, not much knowledge related has been used by the designers of demining devices. Besides, basic information on force transfer from soil surface to subsoil is not available. Therefore, the study of force transfer due to human locomotion in soil was conducted to acquire a basic database for designing new equipment and evaluating existing machines.

The objectives were: (a) to examine subsoil forces due to human locomotion and (b) establish profiles of subsoil forces at different depths using different soils with different moisture contents and bulk densities.

2. Materials and methods

2.1. Description of test facilities

A force platform shown in Fig. 1 (AMTI ORG-6 platform, AMTI Inc. Watertown, MA), which can measure three dimensional forces and moments acted on its top surface, was used in this study. The forces on the top surface can be represented with its six corresponding components Fx, Fy, Fz, Mx, My, and Mz. The dimension of this platform is approximately 0.46 m by 0.5 m. To measure subsoil forces, a walkway was built and the platform was set in a soil box located in the center of the walkway (Fig. 2). The soil box was 0.62 m long and 0.63 m wide. The heights of the soil box and the walkway were adjustable depending on the soil depth required by the tests, but they were always adjusted to the same height. The computer shown in Fig. 2 was to record and process measured forces using AMTI software. Instant measurements were displayed on the monitor to observe each individual test.

2.2. Experimental conditions

Experimental variables included weight of subject (people), soil depth, soil type, moisture content, and soil compaction level. Walking gaits were natural ways of walking for each subject. No special training or practices were done. Shoes worn by subjects were regular walking shoes; shoe soles were similar rubber-type materials without high heels. To identify differences caused by human gaits, three different subjects with similar weights were also tested on one soil conditions. Measurements were subsoil forces. Each test was repeated three times. Experimental conditions are listed as follows.

(1) Subjects: 5.
(2) Depths: 0, 50, 100, 150, and 200 mm.
(3) Soil: sand; sandy loam (sand 78%, clay 10%, and silt 12%).
(4) Tested soil conditions:
- sandy loam with 14% (d.b.) moisture content and a bulk density of 1520 kg/m^3;
- sandy loam with 14% (d.b.) moisture content and a bulk density of 1200 kg/m^3.
- sandy loam with 7% (d.b.) moisture content and a bulk density of 1520 kg/m^3;
- sand with 5.5% (d.b.) moisture content and a bulk density of 1800 kg/m^3;
- sand with 5.5% (d.b.) moisture content and a bulk density of 1500 kg/m^3; and
- sand, dry and 1500 kg/m^3 bulk density.

3. Experimental procedure

The quantity of the soil required to fill in the soil box on the top of the platform was calculated according to the volume of the box and the desired soil bulk density. The length (0.62 m) and width (0.63 m) of the box were fixed. Hence, the volume of the box was determined by the soil depth. Using this volume and desired soil moisture content and bulk density, the weight of soil needed to fill in the box was then calculated. To get desired soil moisture content, soil was weighed and then placed in a large container. Its initial moisture content was measured by taking three samples and oven-dried for 24 h at 105 °C. Appropriate amount of water was added according above measurements to achieve desired moisture content level. After every

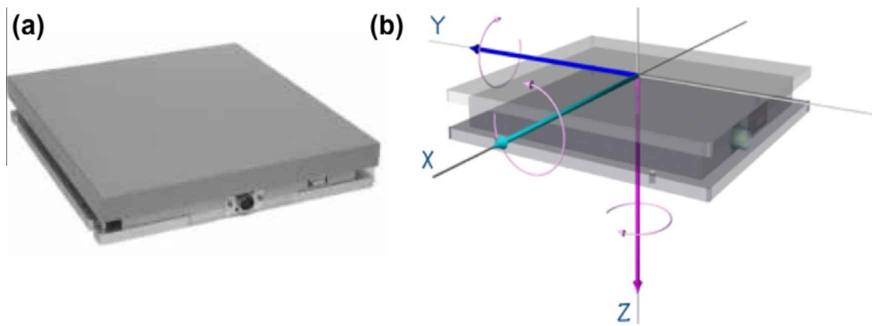

Fig. 1. The platform used in this study (AMTI ORG-6 platform, AMTI Inc. Watertown, MA). (a) the force platform and (b) the coordinate system of the platform.

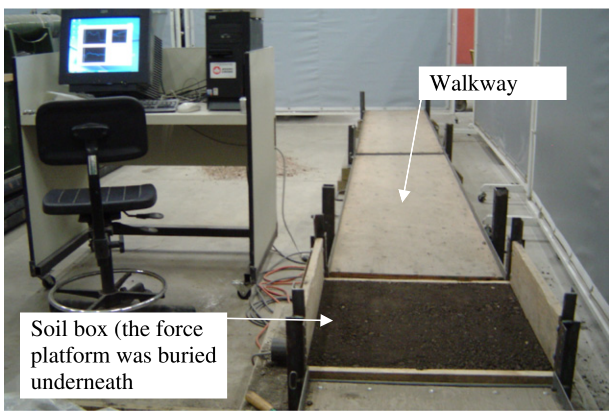

Fig. 2. Experimental facility.

walk test, three more soil samples were taken from the soil box to check the final moisture content. All soil samples were dumped back to the soil box to keep the same amount of soil.

To receive uniformly-packed soil condition, soil was weighed and filled into the soil box in three layers, and one layer at a time. Each layer was filled and packed uniformly, and then next layer was filled in. The soil surface of a previous layer was scratched to receive a better layer bond. Total weight of soil in the soil box was determined using desired bulk density and moisture content.

After soil preparation, a subject was asked to walk through the walkway and step on the soil with either right or left foot. To receive a close-to-normal walk pattern, subjects were trained under the experimental conditions before tests. The footprints were equally-spaced on the soil surface to reduce the impact of soil movement under a footprint on another. The space between any two adjacent footprints was kept wider than two times of a footprint width to minimize the interaction between footprints. The interaction between footprints was observed from instant force display on the computer. The interaction would be significant if the sand with lower bulk density was stepped on for three times. Therefore, sand was re-prepared after it was stepped for two times. For sandy loam soil, this interaction was not found if stepping on it for three times. Walking was repeated three times for each subject.

After examining all subjects, soil depth was changed and soil moisture content and bulk density were kept the same. The height of the walkway was also adjusted to the same height, and additional soil was added in the soil box accordingly. This procedure was repeated for every combination of moisture content and bulk density.

3.1. Data analysis

Analysis of variance (ANOVA procedure, SAS for Windows version 8.0) was used to detect significant differences in experimental data. Letters are used to indicate significant differences. Common letters indicate no significant difference. Significant differences were detected by means comparison test of Duncan's test at a significance level of 0.05.

4. Results and discussion

4.1. General description of subsoil force

Measured vertical force due to human locomotion varied on a footprint as shown in Fig. 3. The force distribution on the footprint varied with each individual walk. The duration of the impact on soil was <1 s. In most cases, the maximum subsoil force occurred under the heel. Table 1 gives the maximum force obtained with two subjects under either their heels or toes.

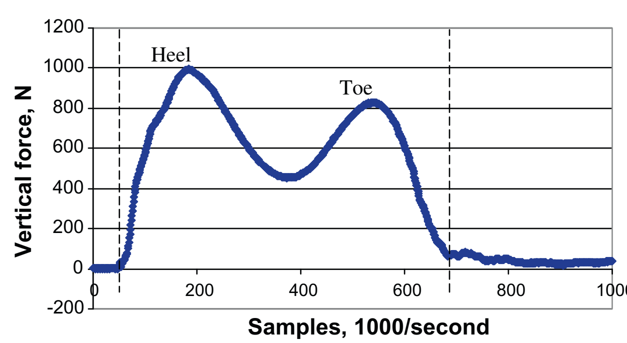

Fig. 3. Vertical force under a foot of a 79-kg subject (sandy loam soil with a bulk density of 1520 kg/m^3 and moisture content of 14% d.b., 10-cm depth).

Table 1
Maximum forces at different depths due to human locomotion.

Depth, cm	Maximum force under either heel or toe (N)							
	Subject 1 (59 kg)				Subject 2 (100 kg)			
	5	10	15	20	5	10	15	20
Sandy loam 14%[a], 1520[a] kg/m^3	663.5e (31.3[b])	627.5ef (49.9)	617.8f (15.5)	568.9d (21.5)	1108.6a (27.2)	984.3ab (72.2)	996.7ab (43.3)	933.2b (39.2)
Sandy loam 14%, 1200 kg/m^3	673.0ef (18.8)	696.8ef (28.8)	719.9e (20.5)	703.1f (19.1)	1129.0a (109.5)	964.2b (54.0)	1133.6b (81.5)	1058.9bc (45.7)
Sandy loam 7%, 1520 kg/m^3	651.6e (51.7)	704.0f (48.1)	631.5ef (40.8)	614.8f (10.1)	1094.0a (89.9)	1000.9a (124.7)	955.2b (100.4)	830.6b (100.9)
Sand 5.5%, 1800 kg/m^3	663.1a (56.5)	618.9f (37.1)	575.4d (13.2)	463.9fe (81.4)	1096.6b (12.7)	1017.b (35.4)	915.3c (99.9)	1017.5bc (44.2)
Sand 5.5%, 1500 kg/m^3	662.6 def (27.3)	651.1 d (6.9)	668.0 de (38.3)	576.0 ef (5.7)	1154.1 a (43.1)	1344.7 c (50.6)	1313.3 c (149.9)	1026.6 bc (14.6)
Sand dry, 1550 kg/m^3	656.3e (17.5)	736.9f (39.0)	637.6ef (18.0)	589.7d (13.3)	1138.2ab (60.2)	1061.0ab (42.0)	1075.5bc (60.3)	1017.6bc (53.7)

[a] Moisture contents and bulk densities are dry basis.
[b] Standard deviation calculated with three replications; data with different letters differs significantly (Duncan test at a significance level of 0.05).

To consider the differences of walking habits and gaits between individuals, impulse was used to evaluate the impact transferred to the subsoil. The impulse was calculated with the area under the curve between those two dashed lines shown in Fig. 3.

4.2. Subsoil forces in sandy loam soil

Subsoil impulses varied significantly with subjects as shown in Fig. 4. Subsoil impulse increased with increasing mass of subject at the depths of 5, 10, and 15 cm; but there was one exception at the depth of 20 cm. The subsoil impulses tended to decrease when the depth increased though this was not statistically significant. The average subsoil impulse of all five subjects decreased with increasing depth; the average subsoil impulse for all subjects at 20-cm depth was significantly smaller than that at 5-cm depth.

Two-way statistical analyses were conducted to identify the effect of depth, mass of subject, and depth and mass interaction on subsoil impulses. The relationship obtained from regression analysis for the mass of a subject and the depth of soil is given in Eq. (1). Statistical analysis results indicated that only the mass of a subject significantly affected the subsoil impulses.

$$S_{andyloam} = 18.416 - 0.486D + 5.177W(N \cdot s) \tag{1}$$

where $S_{impulse}$ is subsoil impulse ($N \cdot s$); D is depth (cm); and W is the mass of a subject (kg).

At the lower compaction level, similar subsoil impulses were acquired as shown in Fig. 5. The mass of a subject was also the major factor affecting the impulses transferred to the subsoil. Results from statistical analysis also indicated that only the mass of subject significantly affected the subsoil impulses.

Compared to the results shown in Fig. 4, subsoil impulses at the lower compaction level reduced with increasing depth at a faster ratio though no significant differences detected. Only the heaviest subject produced significant smaller subsoil impulse at 20 cm depth than that at 5 cm depth for both higher and lower compaction levels. For both compaction levels, the mass of subject increased from 50 to 100 kg resulted in 100% increase in subsoil impulses at all four depths.

Subsoil forces were also measured using the same sandy loam soil with 7% (d.b.) moisture content and bulk density of 1200 kg/m^3. Comparisons in Fig. 6 shows that subsoil impulses at a 5 cm depth are lower at higher bulk density. For the lightest and heaviest subjects, increasing soil moisture content increased impulses in subsoil; but the subsoil impulses were reduced for other subjects. Similar trends were received for other soil depths.

4.3. Subsoil forces in sand

The impulses on the bare force plate without sand on its surface were also measured at the beginning of tests. These results were represented by zero depth in Fig. 7. Increasing soil depth reduced subsoil impulses for all subjects; but the ratios of decreasing were higher for those subjects with larger mass. The impulses transferred to the subsoil significantly reduced with decreasing the mass of subjects in any depth (Fig. 7).

Two-way regression analysis indicated that both depth and mass significantly affected subsoil impulse, but the effect of the interaction between depth and mass was not significant. The regression equation is as follow:

$$S_{sand} = 57.65 - 6.779D + 5.079W(N \cdot s) \tag{2}$$

Results from the loose sand with the same moisture content (5.5%) did not show a clear trend (Fig. 8). This might be caused by the unstable structure and non-uniformity of the loose sand. Subsoil impulses tended to decrease when the mass of subject decreases.

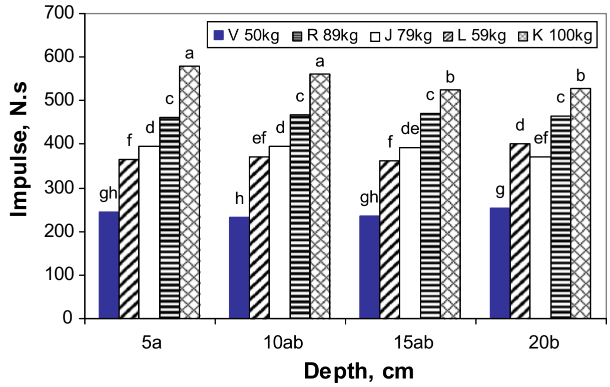

Fig. 4. Subsoil impulses for all subjects in the sandy loam soil with a bulk density of 1520 kg/m^3 and moisture content of 14% (d.b.). Bars with different letters on top differs significantly (Duncan test at a significance level of 0.05).

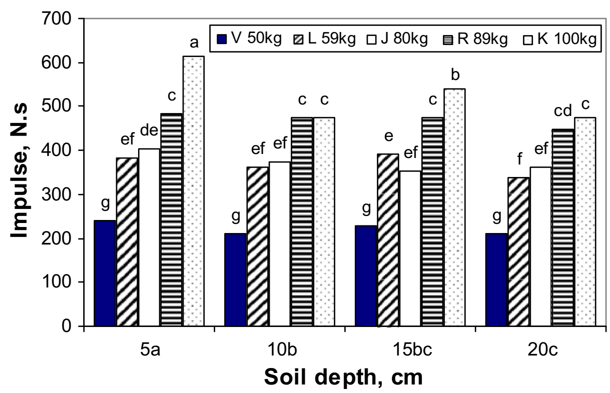

Fig. 5. Subsoil impulses for all subjects in the sandy loam soil with a bulk density of 1200 kg/m^3 and moisture content of 14% (d.b.). Bars with different letters on top differs significantly (Duncan test at a significance level of 0.05).

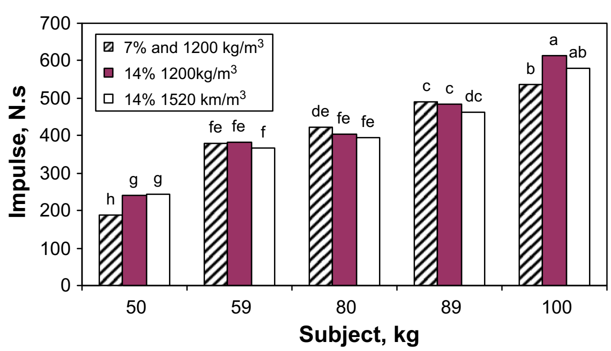

Fig. 6. Comparison of subsoil impulses at 5 cm depth for all subjects in the sandy loam soil with different moisture contents and bulk densities. Bars with different letters on top differs significantly (Duncan test at a significance level of 0.05).

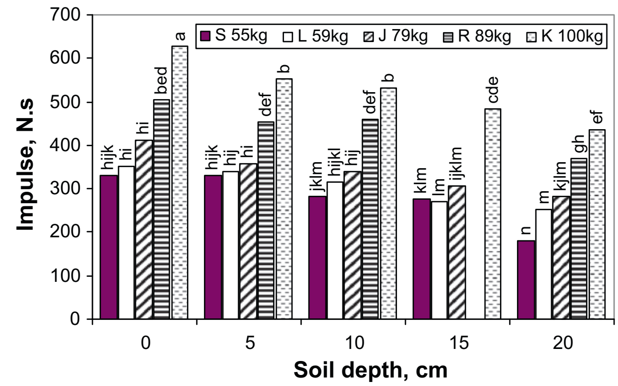

Fig. 7. Subsoil impulses for all subjects in the sand with a bulk density of 1800 kg/m^3 and moisture content of 5.5% (d.b.). Bars with different letters on top differs significantly (Duncan test at a significance level of 0.05).

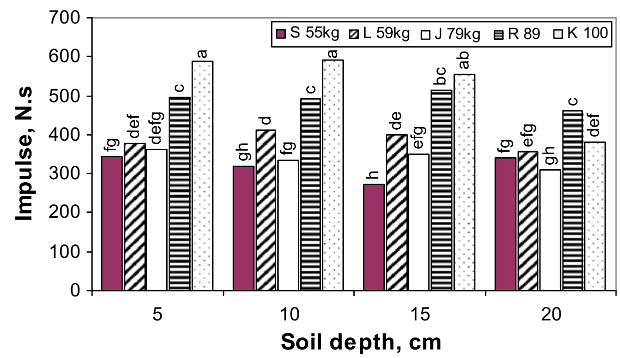

Fig. 8. Subsoil impulses for all subjects in the sand with a bulk density of 1500 kg/m^3 and moisture content of 5.5% (d.b.). Bars with different letters on top differs significantly (Duncan test at a significance level of 0.05).

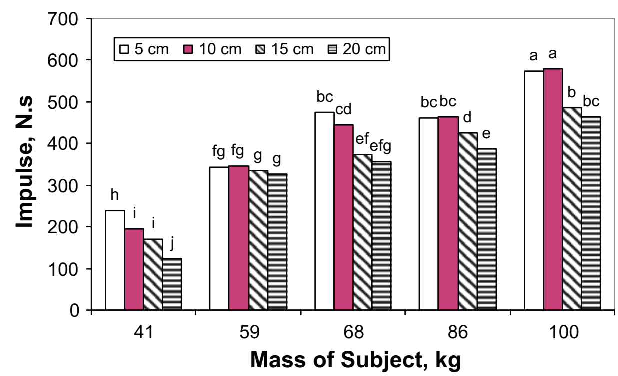

Fig. 9. Subsoil impulses for all subjects in dry sand with a bulk density of 1500 kg/m^3. Bars with different letters on top differs significantly (Duncan test at a significance level of 0.05).

Fig. 9 shows the results from the dry sand with a bulk density of 1500 kg/m^3. For any subject, subsoil impulses decreased when soil depth increased. The subsoil impulse decreased when the mass of a subject decreased. The mass of subject increased from 50 to 100 kg approximately resulted in 80% increase in subsoil impulses under all four depths regardless of moisture content and bulk density.

4.4. Effect of gait on subsoil impulses

Subsoil forces of three different subjects with similar weights ranged from 89 to 90 kg were measured on the

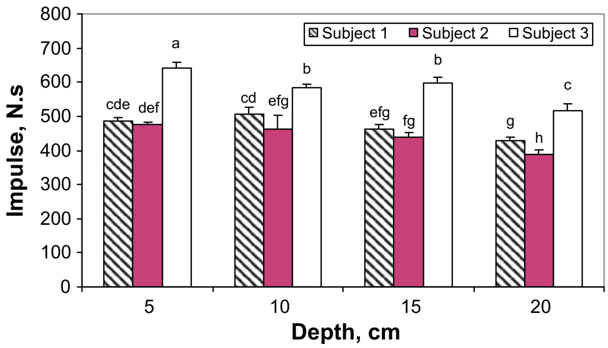

Fig. 10. Subsoil impulses for three similar weight subjects all subjects in the dry sand with a bulk density of 1500 kg/m^3. Bars with different letters on top differs significantly (Duncan test at a significance level of 0.05).

dry sand. Results were shown in Fig. 10. These three subjects created different subsoil impulses at any depth. For any subject, subsoil impulses decreased with increasing depth; and at the depth of 20 cm, the subsoil impulses were significantly lower than those at 5-cm depth. The subject three produced significantly higher impulses than the other two. This indicated that walking gait significantly affects subsoil forces. At any soil depth, the largest impulse among three subjects could be 25–5% higher than the smallest one.

5. Conclusions

Subsoil forces due to human locomotion were studied using a force platform. Conclusions are:

(1) Maximum subsoil forces occurred under either the heel or toe. For the normal walking speed and the subjects used in this study, maximum forces always located under the heel.
(2) Mass of a subject significantly affected the subsoil impulses for all the soil conditions used; higher mass caused greater forces transferred to subsoil.
(3) The effect of soil depth on subsoil impulse was not always significant depending on the soil conditions. For the sand with 5.5% moisture content and bulk density of 1800 kg/m^3, soil depth significantly affected subsoil impulses.
(4) For the sandy loam soil, the mass of subject increased from 50 to 100 kg resulted in 100% increase in subsoil impulses at all four depths; for the sand, the mass of subject increased from 55 to 100 kg approximately resulted in 80% increase in subsoil impulses under all four depths regardless of moisture content and bulk density.
(5) Walking gait significantly affected subsoil forces. The difference of subsoil impulses could be as high as 35%.

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