Design, fabrication and evaluation of a mechanical transducer for real time measurement of tilth aggregate sizes

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Abstract: Development of real time and continuous sensing systems for soil physical and mechanical properties provides a valuable tool to obtain inexpensive and rapid information of soil current status and future management in the context of precision agriculture. This study aimed to design, fabricate and evaluate a mechanical transducer to measure aggregate sizes in real time by determining dynamic strain behavior of commercially available spring tines in field experiments. Dynamic strain was measured with strain gauges mounted on the spring tines and respective circuits. Signals acquired from strain gauges were received and saved by a data-acquisition system and then analyzed. The results of field experiment data was correlated to standard sieve data. The results show that the transducer's output voltage increases with increasing aggregates mean diameters and estimated liner equation was D=13. 827V−33.536 with a correlation coefficient of R^2=0. 93. Mean weight diameter (MWD) was obtained with putting the average of the output signals in the equation. Calculated diameter of the mechanical transducer was approximately 25% higher than standard sieve analyses.

Keywords: aggregation, mechanical sieve, mechanical transducer, real time measurement, strain gauge

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1 Introduction

Soil management requires knowledge of soil texture, structure and its physical and mechanical properties. The term soil tilth refers to the soil's general suitability to support plant growth, or more specifically to support root growth. Tilth is technically defined as "the physical condition of soil as related to its ease of tillage, fitness of seedbed, and impedance to seedling emergence and root penetration" (Alimardani, 2008). A soil with good tilth has large pore spaces for adequate air infiltration and water movement. Roots only grow where the soil tilth allows for adequate levels of soil oxygen. It also holds a reasonable supply of water and nutrients. Soil aggregation is one of the main controlling factors of physical erosion and storage of water and nutrients and water flow. Knowing the soil aggregation size is a crucial parameter to determine the degree of tillage required by land. In order to improve the uniformity of seedbed by varying the degree of secondary tillage and also preparation of suitable seedbed for germination and crop growth, a real time measurement system is required. Aggregate size distribution is affected by management and thermal factors. Management factors include tillage intensity and time. Temperature factors include precipitation, intensity and number of cycles of soil wetting and drying, freezing and melting at the soil surface. Aggregate size distribution affects the emergence of sprouts and flow of air, water and solution nutrients in the soil. Possibility of wind erosion decreases with increasing aggregate size so that large aggregates cause a reduction in wind speed (Alimardani, 2008). The development of real time and continuous sensing systems to measure soil properties provides a

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valuable tool to obtain inexpensive and rapid information of soil current status and future management in the context of precision agriculture.

Mechanical sensing systems using the effects of clod size on the vibrational characteristics of the spring tines pose an alternative to the visual sensing of soil tilth size as well as the mechanical sieve for evaluation of soil aggregate size distribution. The success of a mechanical sensing system to measure the accurate and precise aggregate size distribution is dependent upon both sensing tool properties and the physical properties of the soil tilth.

1.1 Soil aggregation

Soil aggregation is determination of the range of particle size in soil and their weight distribution and is expressed as a percentage of total dry weight of soil (Yousefzadeh- fard, 2006).

Sieve analysis or aggregation test is an attempt to obtain aggregate size distribution in soil sample. Column of specific sieves with their floor grid made of steel wires were used in the experiment. The holes at the bottom of the sieves have accurate and specified size in which holes' sizes are reduced from top to bottom of the sieves column (Barja M. Das, 2008). In this procedure, certain weight of dry soil is placed on largest (upper) sieve, and then sieves column is placed in the sieve shaker and vibrated. Then, sieves are separated from the sieve column. Soil residue on each sieve is weighted and the soil residue percentage is calculated. If w_i be the weight of soil residue on the sieve i on the top of sieve column and w be the total weight of soil, weight percentage remains on the sieve (R_i) is given as::

$$R_i\% = \frac{W_i}{W} \times 100 \qquad (1)$$

And the weight of soil passing through the sieve (P_i) is given as:

$$P_i\% = 100 - \sum_{i=1}^{n} R_i \qquad (2)$$

where, n is the total number of sieves.

The results of this test are provided in graphical form to identify the type of gradation of the aggregate. The complete procedure for this test is outlined in the American Society for Testing and Materials (ASTM) C 136 (ASTM International standard worldwide, 2006) and the American Association and State Highway and Transportation Officials (AASHTO) T 27 (AASHTO The voice of transportation. To 27, 2006).

1.2 Mean weight diameter (MWD)

Van Bavel (1949) proposed that aggregates be assigned an importance or weighting factor that is proportional to their size. The mean weight diameter (MWD) is equal to the sum of the mean diameter ($\overline{X}_i$) of each size fraction multiplied by the proportion of the total sample weight (R_i) occurring in the corresponding size fraction, the summation is carried out over all n size fractions, including the one that passes through the finest sieve. Van Bavel (1949) concept of the MWD has been used widely. However, its calculation in the integral form involves plotting points on a graph determining the area enclosed. This is a time consuming process. Youker and McGuiness (1956) suggested that the summation type calculation as in Equation (3) be used in place of the graphical approach (Carter and Gregorich, 2006):

$$MWD = \sum_{i=1}^{n} \overline{X}_i R_i \qquad (3)$$

where, n: Number of sieves; $\overline{X}_i$: Mean diameter of sieve number i, mm; R_i: Proportion of soil weight residue on the sieve number i to the total soil weight sample.

Sieve process might cause the destruction of soil aggregates but since the samples are transported slightly and sieve does not continue a lot, results can be illustrated as in the field conditions (Carter and Gregorich, 2006).

Diaz-Zorita et al., (2002) discussed the duration of sieving. They illustrated the change in Geometric Mean Diameter (GMD) as a function of sieving duration and offered time interval from 15 to 120 seconds. For many soils, sieving for 30 seconds is often adequate (Braunack and McPhee, 1991).

1.3 Soil aggregation measuring methods

There are different methods to evaluate soil surface roughness and aggregate size distribution. In general these methods can be classified into contact and non-contact measurement techniques (Jester and Klik, 2005). Laser (Harral and Cove, 1982), ultrasonic (Scarlett et al., 1997), gamma rays (Oliveira et al., 1998), fiber-optic sensor (Zuo et al., 2000), rigid blades (Bogrekci and Godwin, 2007), computer vision and image analysis (Bogrekci and Godwin, 2007), roller chain (Merrill, 1998; Saleh, 1993), penetrometer (Olsen, 1992) and pin meter (Kuiperes, 1957; Podmore and Huggins, 1981). Pin meter or profile meter is one of the contact methods to evaluate soil surface roughness that was resported by Kuiperes (1957) and Podmore and Huggins (1981). Podmore and Huggins (1981) concluded that pin meter reached measurement of 2 mm and required the highest measurement time compared to other measurement methods. Roller chain is the other contact methods for measuring soil surface roughness. This procedure was reported by Saleh (1993) and Merrill (1998). The authors reported the method is low cost, doesn't require trained manpower and the measurement accuracy was 5 mm. Another method of measuring soil roughness is image processing. Nellist (1961), Spruijt (1974), Spoor et al., (1976), Stafford and Ambler (1990), Sandri et al., (1997) used images for determining soil tilth quality. Stafford and Ambler (1990) worked on application of image analysis in field using a real-time sensing system for seedbed structure. The aim of this application was to characterize seedbed structure across a field automatically and to use the sensed information to control a seedbed cultivator. A video camera mounted on the rear of the cultivator produced an image of the seedbed surface at the rate of three frames per second. Image analysis algorithms were developed to identify and size aggregates in the surface layer. The computed aggregate size distribution compared well with objective assessments of seedbed condition by sieve analysis. Ranking of seedbeds also compared well with the farmer assessment (Bogrekci and Godwin, 2007).

In order to evaluate soil aggregation, mechanical transducers were introduced by Godwin and Bogrekci (2007). In this case, spring tines with strain gauges were used and evaluated in field conditions. In the research, the effects of sensing speed, depth, direction, tine type and tine rake angle, soil type were examined independently. Godwin and Bogrekci (2007) used three soil tilth produced using a moldboard plow, a moldboard plow followed by a chisel tine, and a moldboard plow followed by a power harrow and two soil types, clay loam and sandy loam. They used mechanical sieve analysis and calculated mean weight diameter (MWD) in order to evaluate spring tines. The main aim of the study was to calibrate and evaluate the performance of the sensing tool to detect the soil tilth in field conditions; and compare measurement results with the results of a mechanical sieve analysis. The most important conclusion obtained by Godwin and Bogrekci (2007) was spring tines transducers can be used as a sensor in order to estimate the mean weight diameter of soil aggregation and clods. This work is a reproduction of the research carried out by Bogrekci and Godwin (2007) in order to observe differences.

2 Materials and methods

In this study, a mechanical transducer with three spring tines and related electronic circuits was constructed to measure aggregate sizes in real time. Tine transducer was made of both mechanical and electronic parts. Mechanical part consisted of spring tines and chassis; and electronic part consisted of strain gauges and related circuits (Isavi, 2012).

2.1 Spring tines and their specifications

Figure 1 shows the tine used for sensing clods sizes. To minimize errors due to rugged farmland and changes in working depth caused by it, the mechanical transducer composed of three tines was fabricated. Tines were made of commercially available and inexpensive spring steel.

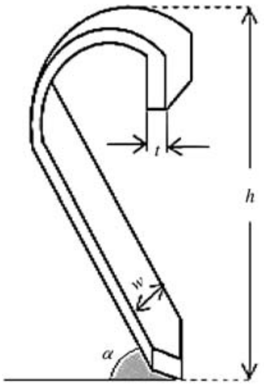

Figure 1 Spring tines used for sensing clods

The key geometry and mechanical characteristics of spring tines are given in Table 1.

Table 1 Tine geometry and mechanical characteristics

Geometry characteristics	Value	Mechanical characteristics	Value
Height, *h*	660 mm	Elasticity modulus, E	190 GPA
Width, *w*	60 mm	Poisson ratio	0.29
Thickness, *t*	5 mm	Thermal expansion coefficient, $\frac{1}{°C}$	17.3×10^{-6}
Rake angle, *α*	75°		

2.2 Electronic equipment of mechanical transducer and data acquisition system

Brighton (1997) considered three transducer types. These were linear variable displacement transducers (LVDTs), potentiometers, and strain gauges. As LVDTs are expensive and delicate for the field conditions and potentiometers are unsuitable for high-frequency applications, a strain gauge system was selected as the most cost effective and reliable solution (Bogrekci and Godwin, 2007). Two strain gauges with 12 V power supply were used in the form of Wheatstone half-bridge circuit to increase the accuracy of measurement with strain gauge and reduce the influence of temperature on the output results. The strain gauge placed under the tine was in tension (R_G+ΔR) and the strain gauge on the tine was in compression (R_G–ΔR) (Strain Gauge Measurement – A Tutorial, 1998). Figure 2 shows Wheatstone half-bridge circuit (Kuphaldt, 2006).

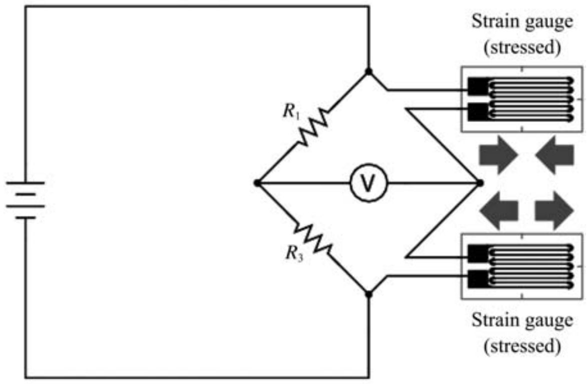

Figure 2 Wheatstone half-bridge circuit

In order to use the strain gauges effectively, the locations of strain gauges were carefully chosen by computing the location of the highest potential strain as shown in Figure 3, on the tine body using finite element analysis and ANSYS software. The tine was simulated by the software at first and then a horizontal force was applied and the maximum shear strain was obtained.

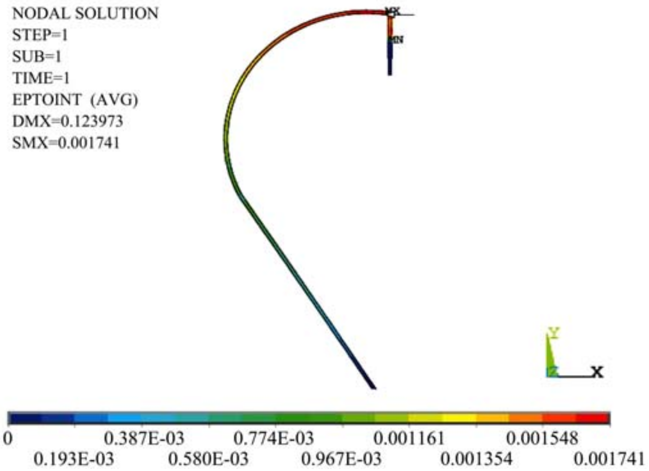

Figure 3 Simulated tine and the maximum strain point found by ANSYS

The bridge output corresponding to each tine was connected to a voltage amplifier to increases output voltage by 1000 times. Then the amplified voltage was stored on a memory card by a data acquisition system. Data acquisition system was designed to store voltage data in every 0.1 second. The entire test required 15 seconds to complete as such total of 150 data of voltage were stored in each test. Figure 4 shows circuits associated with the data acquisition system and amplifiers.

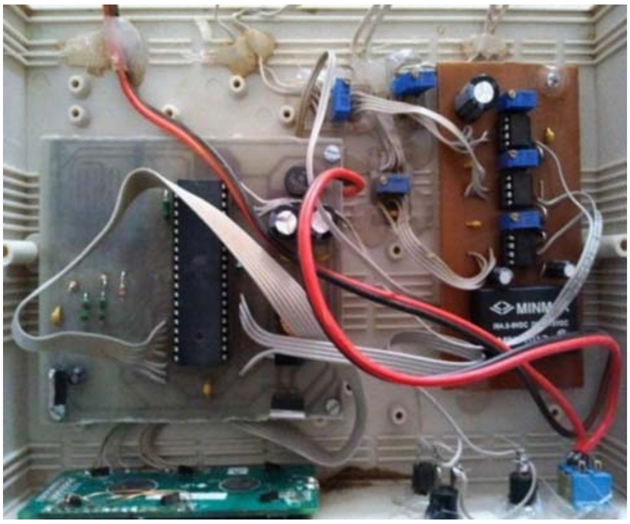

Figure 4 Circuits associated with the data acquisition system and amplifiers

2.3 Field experiments

Field experiments were conducted in three steps. At first to calibrate the transducer, soil were screened by standard sieves with 50, 37.5, 25, 12.5, 4.75, 2 and

0.6 mm average diameter and soil remaining on each sieve was placed in rows based on average diameter. The aim of this experiment was to determine output voltage of each tine in contact with aggregates with 50, 37.5, 25, 12.5, 4.75, 2 and 0.6 mm average diameter.

Second step was performed to compare results obtained from transducer and standard sieve values to calculate the accuracy of the transducer. Soil tilth in this step was produced using a moldboard plow followed by chisel tines.

Third step was performed to evaluate the transducer. Soil tilth was produced using a moldboard plow. Soil type was clay loam. The properties of soil are given in Table 2. After experimenting with transducer, obtained MWD was compared with results of sieve analysis.

Table 2 Soil properties

Soil use	Step one & two	Step three
	Clay loam	Clay loam
Sand %	20	24
Silt %	25	28
Clay %	55	48
Moisture %	18.65	20
Tillage	A moldboard plow followed by chisel tines	A moldboard plow

3 Results and discussion

Mechanical transducer was designed and constructed in order to evaluate soil aggregate size distribution in real time. Spring tines with strain gauges were used and examined in field conditions. At first, in order to calibrate the transducer, the aggregates were separated with standard sieve series and placed in rows based on the mean diameters and afterward, tines were passed through the rows. Next, mean weight diameter of soil tilth produced by use of a moldboard plow was measured by transducer and the result was compared with reference data obtained by sieve analysis

3.1 Tine transducer calibration

In order to calibrate the transducer, soil were screened by standard sieve series and soil residue on each sieve was placed in rows according to average diameter. Tines were passed through the rows and voltage data from tines strain were recorded and stored on the memory card. This strain was caused by the force of aggregates on tines. Figure 5 shows the average voltage as recorded of each row.

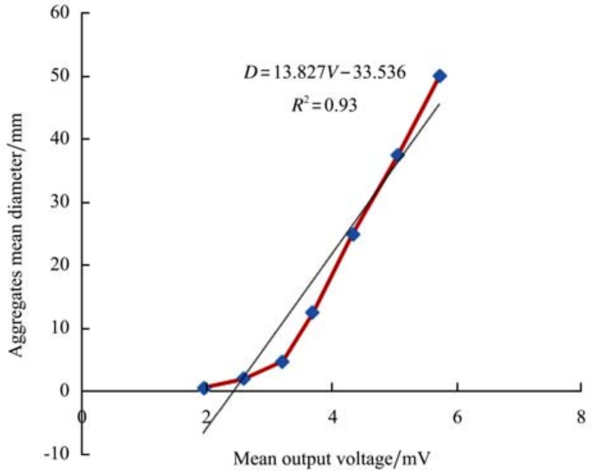

Figure 5 Signals obtained from tines in contact with soil rows

As it is clear from Figure 5, the relationship between diameter and output voltage can be estimated with a linear regression equation as Equation (4), so that the coefficient of determination between estimated equation and obtained data equals R^2=0. 93.

$$D=13.827V-33.536 \tag{4}$$

where, D: Aggregates diameter, mm; V: mean output voltage, mV.

One can use more complex forecasting methods, including time series analysis (ARIMA) methods, weighted linear regression, or multivariate regression or stochastic modeling for forecasting.

The advantages to linear regression are that

a) It provides a single slope or trend,

b) The fit of the data remains unbiased,

c) The fit minimizes error and

d) It is consistent (Niroomand, 2008).

Figure 5 shows that larger the diameter of the aggregates higher is the output voltage of the transducer.

3.2 Calculation of mean weight diameter (MWD) by standard sieve analysis

Three soil samples were taken and analyzed in the laboratory by standard sieves to calculate MWD of aggregates of tilth produced using a moldboard plow followed by chisel tines. Results obtained from samples are given in Figure 6. MWD of first, second and third samples were calculated as 13.56, 12.29 and 13.81 mm, respectively.

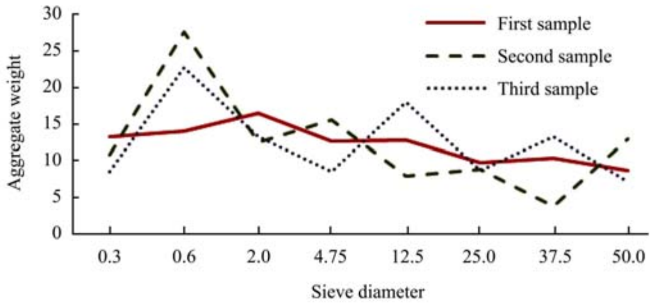

Figure 6 Results from standard sieve analysis of three soil samples

3.3 Calculation of mean weight diameter (MWD) using the tine transducer

In order to obtain MWD with tine transducer, tines were passed through the soil with speed of 5 km h^{-1} and depth of 70 mm.

Transducer data acquisition system, with each tines passing through the soil stored 150 data of voltage. Due to the possible error caused by fluctuating velocity in the first 5 seconds, the first 50 data was removed and the average of stored voltages was placed in Equation (4). MWD for first sample to third was calculated as 17.07, 15.41 and 17.34 mm, respectively. Figures 7, 8 and 9 shows obtained voltage from tine transducer for first, second and third sample, respectively.

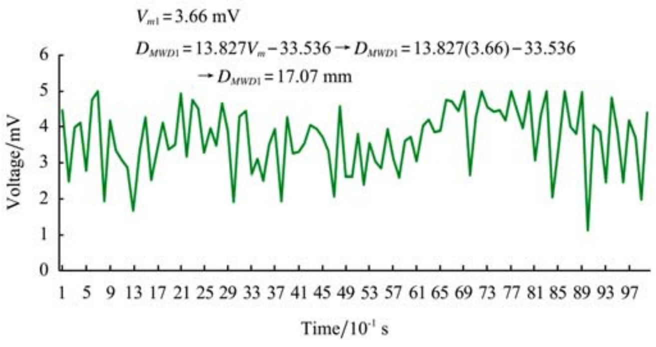

Figure 7 Voltage-time diagram obtained from first sample

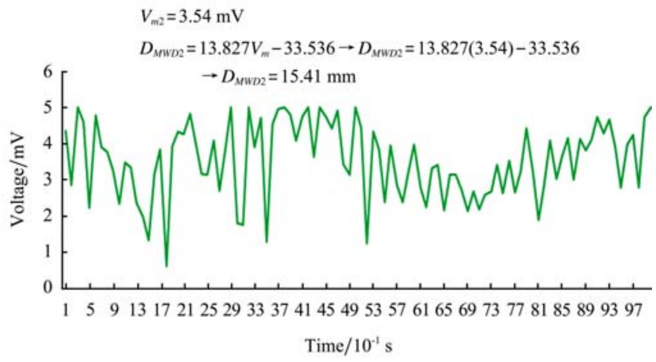

Figure 8 Voltage-time diagram obtained from second sample

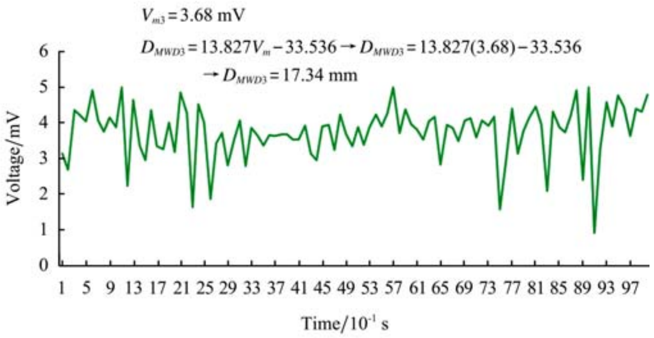

Figure 9 Voltage-time diagram obtained from third sample

3.4 Testing and evaluation of the tine transducer and cresult comparison with sieve analysis

In order to test and evaluate, tine transducer was tested in a tilth with clay loam soil and produced using a moldboard plow. MWD obtained by transducer was 33.94 mm. Figure 10 shows the obtained results from tine transducer.

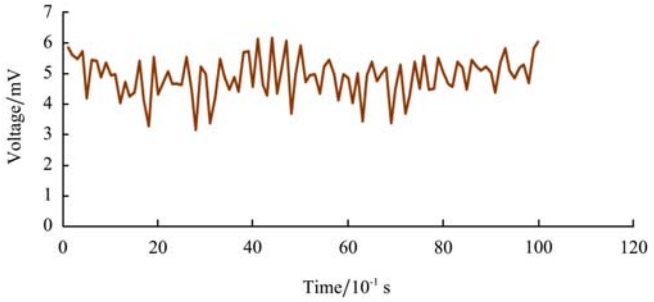

Figure 10 Voltage-time diagram obtained from tilth produced using a moldboard plough

In order to evaluate the accuracy and precision of the results of transducer, sieve analysis was performed in the same ground. Results from the sieve analysis are shown in Figure 11. MWD of the standard sieve analysis was 27.08 mm.

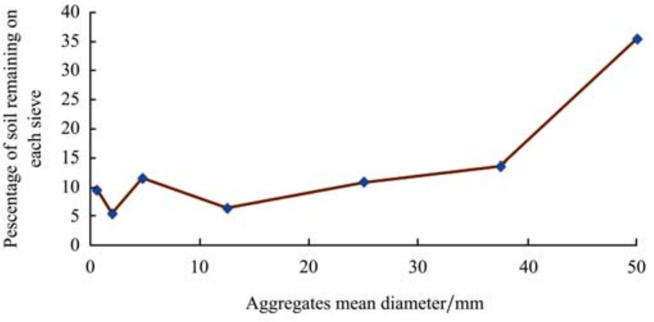

Figure 11 Results from the sieve analysis of tilth produced using a moldboard plough

3.5 Result analysis of the tine transducer

The results showed that in general calculated mean weight diameter by the mechanical transducer was bigger than results from standard sieve analysis. As it is clear from the results obtained, on average, MWD obtained from tine transducer was 25% greater than results from standard sieve analysis. Figure 12 shows comparison of the results from the transducer with the results from sieve analysis.

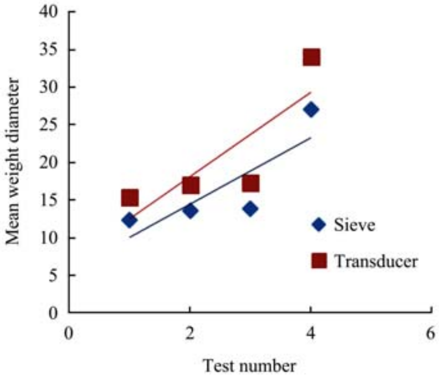

Figure 12 Comparison between the results of the mechanical transducer with the standard sieve analysis

The reason that mechanical transducer measured MWD greater than sieve analysis, returns to the testing method with sieves. There are probabilities of failure and change in aggregate size distribution during sampling and transport and this is the reason for larger aggregate size distribution by sieve analysis.

4 Conclusion

Design, construction and evaluation of a mechanical transducer to measure aggregate sizes in real time were conducted. The spring tines were tested by using the strain gauges in field conditions. The main conclusion is that the spring tine transducers can be used as sensors to estimate the mean weight diameter of a given clod size distribution. Specific conclusions are presented below.

1) The higher diameter of the aggregates, the higher output voltage of the transducer.

2) The relationship between diameter and output voltage can be estimated with a linear equation as D=13.827V−33.536 (Equation (4)) so that the coefficient of determination between estimated equation and obtained data equals R^2=0. 93.

3) MWD obtained from tine transducer is 25% greater than results from standard sieve analysis.

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