A Field Experiment on Dust Emission by Wind Erosion in the Taklimakan Desert

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ABSTRACT

Dust emission by wind erosion in surface is a serious problem in many arid regions around the world, and it is harmful to the ecological environment, human health, and social economy. To monitor the characteristics of saltation activity and to calculate the threshold wind velocity and sediment discharge under field conditions have significance on the research of dust emission by wind erosion. Therefore, a field experiment was conducted over the flat sand in the hinterland of the Taklimakan Desert. One sampling system was installed on the flat sand surface at Tazhong, consisting of a meteorological tower with a height of 2 m, a piezoelectric saltation sensor (Sensit), and a Big Spring Number Eight (BSNE) sampler station. Occurrence of saltation activity was recorded every second using the Sensit. Each BSNE station consisted of five BSNE samplers with the lowest sampler at 0.05 m and the highest sampler at 1.0 m above the soil surface. Sediment was collected from the samplers every 24 h. It is found that saltation activity was detected for only 21.5% of the hours measured, and the longest period of saltation activity occurring continuously was not longer than 5 min under the field conditions. The threshold wind velocity was variable, its minimum value was 4.9 m s^{-1}, the maximum value was 9.2 m s^{-1}, and the average value was 7.0 m s^{-1}. The threshold wind velocity presented a positive linear increase during the measurement period. The observation site had a sediment discharge of 82.1 kg m^{-1} over a period of 24 h. Based on hourly saltation counts, hourly sediment discharge was estimated. Overall, there was no obvious linear or other functional relationship between the hourly sediment discharge and wind velocity. The results show that the changes of sediment discharge do not quite depend on wind velocity.

Key words: wind erosion, saltation activity, threshold wind velocity, sediment discharge, Taklimakan Desert

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1. Introduction

Deserts make up about one fifth of the total land surface in the world. The dust emission by wind erosion occurring in deserts not only affects regional environment and climate change but also results in wind-sand disasters, such as buried roads, farmland and other facilities; causing serious loss of production. Thus, it is important to research sandstorms associated with wind erosion. Important matters for research on wind erosion include characteristics of sand activity on the earth's surface, threshold wind velocity and the change of sediment discharge. The threshold wind velocity is one of the important parameters in sandstorm prediction and it has an important effect on the accuracy of the forecast.

Some researchers conducted relevant research between the 1930s and 1940s (Chepil and Milne, 1939; Bagnold, 1941). Aerodynamic principles and major factors of influence for soil wind erosion, and the

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relation of the movement for a single particle and sediment transport rate to wind velocity and particle size were studied deeply through field experiments. The frequent breakouts of sandstorms have drawn the attention of the global scientific community to the soil wind erosion, and more and more research work has been carried out. In the following years, a great number of field observation experiments were conducted and mathematical models were established, covering the sediment transport rate, the physical mechanisms and influencing factors for surface soil wind erosion, and the relation of dust emission rate to wind velocity (or friction velocity) and earth's surface conditions (including soil moisture and vegetation) (Kawamura, 1951; Zingg, 1953; Jakubov, 1955; Owen, 1964; Woodruff and Siddoway, 1965; Gillette et al., 1974). Later, in the 1990s, the tendency of the studies on wind erosion was apt to meticulous field observation experiments. Gillette et al. (1997) studied the relation between vertical sand flux and wind velocity in desert areas through field observation experiments. Shao et al. (2002) carried out long-term field experiments in the Australian desert, and established comparatively consummate dust emission model. Stout (2003, 2004, 2007, 2010) and Stout and Zobeck (1996) conducted long-term field observation experiments on dust emission by wind erosion, making use of piezoelectric saltation sensors in Texas and New Mexico, and analyzed the activity characteristics and parameters of dust emission in these regions. In recent years, Chinese scholars have carried out a great number of field observation experiments on dust emission by wind erosion. Zhou et al. (2002) studied the characteristics of sandstorm kinetics and motion of fine dust particles using field observation. Niu and Zhang (2004), Shen et al. (2004a), Cheng et al. (2006), Zhu and Zhang (2010), and He et al. (2011) observed the critical wind velocity and the threshold friction velocity in different desert regions in China, and obtained quite exact values. Shen et al. (2003, 2004b), Wang et al. (2004), Zhang et al. (2007), and Yang et al. (2011) calculated the dust emission rate for different underlying surfaces and weather processes using different methods. The above studies have laid a foundation for further research on dust emission by wind erosion. Since soil erosion is affected greatly by the characteristics of the underlying surface, the obtained parameters of dust emission and the computation models of threshold wind velocity and sediment discharge had regional restriction questions (Yang et al., 2011). Thus, more field experiments will have to be conducted so as to understand the characteristics of soil wind erosion in different research areas.

We took Tazhong — the hinterland of the Taklimakan Desert as a research site for the field wind erosion observation experiment. The distance between Tazhong and the desert edge is 220 km, where the climate is very dry with annual precipitation of 25.0 mm, sandstorm weather is over 100 days annually, the vegetation is sparse, and sandy desert accounts for about 90%. In this paper, based on the field data collected during a sandstorm occurring in Tazhong on 21 July 2008, the characteristics of sand saltation activity and its relation with meteorological elements are analyzed. The threshold wind velocity at a height of 2 m and sediment discharge at 0–200 cm above the soil surface were measured, and the sediment discharge per hour was estimated according to relations of saltation particle numbers with sediment discharge. The ultimate purpose is to obtain a new understanding of dust emission by wind erosion for this area.

2. Field experiment

The site of the experiment is in a flat sandy land between two high longitudinal dunes in Tazhong, and its surrounding underlying surfaces are made up of drift sand. Wind velocity, air temperature, air humidity, and saltation activity are measured by a sampling system which consists of a 2-m tall meteorological tower, a BSNE (Big Spring Number Eight) sand sampler tower, two piezoelectric saltation sensors, and a data collector (CR1000; Campbell) (figure omitted, see Fig. 2 of He et al. (2011)). Wind velocity is measured at a height of 2 m (WAA151; Vaisala), and air temperature and humidity are measured at a height of 1.5 m (HMP45D; Vaisala). All variables are sampled at a frequency of 1 Hz.

The sediment flux is measured by the BSNE sand sampler tower which consists of five BSNE samplers with openings centered at 5, 10, 20, 50, and 100 cm above the soil surface. With field and wind tunnel tests, the trap efficiency of the BSNE sand sampler was more than 90% at different wind speeds (Shao et al., 1993). Measurements were made from 0000 LT (local time; 2 h 25 min behind Beijing time) 21 to 0000 LT 22 July 2008, then the BSNE samplers were emptied in plastic bags, and the samples were weighed in the laboratory and weights were converted to sediment flux per square meter.

Occurrence of saltation activity is measured by piezoelectric saltation sensor (Sensit-H11LIN), which has a 360° active surface and, thus, has no need to rotate like a BSNE sampler. The center of the active surface of the Sensit is located 5 and 10 cm above the surface (figure omitted, see Fig. 2 of He et al. (2011)). As saltating aggregates strike the active surface, an electrical pulse is generated, and these pulses are counted and recorded using a data collector (CR1000; Campbell). The laboratory test results show that the Sensit-H11LIN could respond to particles with diameter more than 50 μm (Sensit Company, 2007). Other types of Sensit carried out a good measurement of sand saltation motion, which was proved by long-term field experiments (Gillette and Stockton, 1986; Stout and Zobeck, 1996). In this paper, the saltation data at the height of 5 cm are used to analyze the sand saltation characteristics, and the data are sampled at a frequency of 1 Hz as well.

3. Analysis of the results

3.1 Field test of Sensit

In order to verify its applicability in the Taklimakan Desert, the Sensit is used in the field test together with the BSNE sand samplers. The particle sizes of surface soil and sediment transport samples at the height of 5 and 10 cm in Tazhong are shown in Tables 1 and 2. The surface soil samples include dune sand, flat sand and sand from longitudinal dunes. For over 97% of 14 surface soil samples, the particle sizes are greater than 50 μm (Table 1). This is similar to the sediment transport samples at heights of 5 and 10 cm (Table 2). The number of saltation particle numbers and the weight of the sand collection quantity trapped by the BSNE sand sampler within specified times at the height of 5 cm are shown in Fig. 1. A good linear relation is kept between the number of saltation particles and sand collection quantity, with a correlation coefficient of 0.97, which is consistent with the results of Gillette et al. (1997). The fact that they are not completely consistent may have been caused by several factors. One is that the Sensit presents poor striking reaction for sand at a grain size of less than 50 μm

Table 1. The grain size distribution (%) of surface soil samples

Soil samples	Surface	
	$\leqslant$ 50 μm	$\geqslant$ 50 μm
1	3.8	96.2
2	4.5	95.5
3	0.0	100.0
4	0.0	100.0
5	8.6	91.4
6	0.0	100.0
7	0.0	100.0
8	0.1	99.9
9	0.0	100.0
10	0.0	100.0
11	1.5	98.5
12	3.2	96.8
13	3.6	96.4
14	6.4	93.6
Average	2.3	97.7

Table 2. The grain size distribution (%) of sediment transport samples at the height of 5 and 10 cm

Soil samples	5-cm height		10-cm height	
	$\leqslant$ 50 μm	$\geqslant$ 50 μm	$\leqslant$ 50 μm	$\geqslant$ 50 μm
1	0.5	99.5	1.6	98.4
2	0.9	99.1	4.3	95.7
3	0.6	99.4	2.3	97.7
4	1.1	98.9	1.3	98.7
Average	0.8	99.2	2.4	97.6

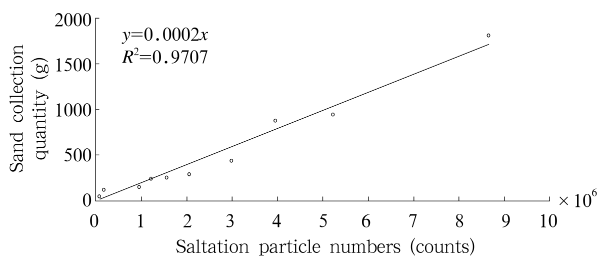

Fig. 1. Saltation particle numbers and sand collection quantity trapped by the BSNE.

while the BSNE sand sampler can still collect that sand, the other is that the Sensit can not distinguish between a striking pulse evoked by a gout of sand or a particle of sand when both wind velocity and density of particles in sand flow are high. Throughout the field test, the Sensit generally presented a better applicability in the Taklimakan Desert, and its test results show the real characteristics of sand saltation activity.

3.2 Intensity of saltation activity

Intensity of saltation activity is expressed as a dimensionless ratio of the total number of saltation seconds divided by the total number of seconds within the period of measurement. Thus, the minute intensity of saltation activity is simply the minute total of saltation seconds divided by 60 s, which is represented by letter γ. The sandstorm started at about 0900 LT 21 July 2008 and stopped at 2200 LT 21 July, lasting about 13 h. The change of intensity of saltation activity during the sandstorm is shown in Fig. 2. Before the sandstorm came up (0900 LT 21 July), transitory saltation activity was measured at around 0650 LT, and no saltation activity was monitored by Sensit at other time. Moreover, there was no saltation activity between the end of the sandstorm (2200 LT 21 July) and 0000 LT 22 July either. During the observation period, saltation activity was only 18538 s, which made up 21.5% of the entire observation time and 39.6% of the whole process of the sandstorm.

According to the statistical data, the continuous 1-min saltation activity was not more than 28 min during the observation (Table 3), which appeared between 1019 and 1810 LT 21 July, and between 1300 and 1500 LT for 19 min. The wind velocity rose from 7.4 to 10.2 m s^{-1} when continuous saltation activity occurred, indicating that saltation activity was not continuous even if wind velocity was higher. The maximum value of 5-min intensity of saltation activity was 0.98 and those of 0.5- and 1-h intensity of saltation activity were 0.89 and 0.75. As the time step length increased, intensity of saltation activity dropped. During the observation, the length of the period of continuous saltation activity did not exceed 5 min. It was shown that there was little continuous occurrence of saltation activity in natural environment, which is consistent with the result by Stout and Zobeck (1997) and Stout (2003).

Table 3. Intensity of saltation activity and wind speed measured on 21 July 2008

Serial number	Time (LT)	Intensity of saltation activity	Wind speed (m s^{-1})
1	1019	1	7.4
2	1039	1	7.5
3	1105	1	8.4
4	1129	1	8.4
5	1155	1	8.7
6	1311	1	8.0
7	1343	1	10.0
8	1345	1	10.0
9	1348	1	8.8
10	1351	1	9.1
11	1352	1	8.8
12	1353	1	10.2
13	1354	1	9.2
14	1356	1	8.8
15	1402	1	9.2
16	1403	1	9.2
17	1404	1	9.1
18	1408	1	9.0
19	1412	1	8.9
20	1415	1	9.5
21	1418	1	9.7
22	1427	1	9.0
23	1437	1	9.3
24	1457	1	8.8
25	1511	1	8.9
26	1722	1	9.8
27	1808	1	8.9
28	1810	1	8.6

Saltation activity is affected by meteorological elements such as wind velocity, air temperature, and humidity. It can be seen from Fig. 2 that wind velocity at night was lower and no saltation activity occurred, while saltation activity occurrence came along with greater wind velocity, starting at 0900 LT 21 July 2008. Wind velocity reached the highest level at around 1400 LT while saltation activity remained correspondingly intense. As the wind speed was going down, saltation activity decreased gradually, until the saltation activity finally ended. Saltation activity corresponded well to wind velocity. The changes of air temperature and humidity at the height of 1.5 m during the observation are shown in Fig. 3. At night, when temperature was lower and humidity was at higher level, the corresponding wind velocity was lower, and there was no occurrence of saltation activity. When air temperature rose and humidity went down quickly after 0900 LT in the morning, wind velocity increased gradually and saltation activity could be detected with enhancing intensity. When air temperature rose to the maximum during daytime, air humidity decreased to the minimum, at that point, the maximum wind velocity during daytime was monitored, as it was for the saltation activity. This "wind-temperature synchronization" phenomenon in desert regions is conducive to the occurrence of saltation activity.

3.3 Threshold wind velocity

The time fractional equivalence method (TFEM) proposed by Stout (2004, 2007) is used in this paper to compute the threshold wind velocity during the observation. The formula is as follows:

$$u_{\mathrm{t}} = \overline{u} - \sigma \cdot \Phi^{-1}(\gamma), \tag{1}$$

where u_{t} is the threshold wind velocity, $\overline{u}$ is the average wind velocity per minute, σ is the standard deviation of wind velocity per minute, and γ is the intensity of saltation activity ($0 \leqslant \gamma \leqslant 1$). When $\gamma = 1$, it indicates continuous occurrence of saltation during observation; when $\gamma = 0$, there is no saltation activity occurring; Φ is the normal distribution function of γ. The minute threshold wind velocity at 2-m height was computed according to Eq. (1) (Fig. 4). It can be seen that the threshold wind velocity was variable under the field conditions. During the observation, the minimum threshold wind velocity was 4.9 m s^{-1}, and the maximum was 9.2 m s^{-1}. The mean value was 7.0 m s^{-1}, and the standard deviation was 0.95, indicating that the field threshold wind velocity value was not stable.

In previous studies, threshold wind velocity was often found constant. However, it has to be considered that meteorological elements, such as air temperature and humidity, change continuously in the field. Air temperature is an important thermal factor that exerts influences upon sand movement, and then exerts a certain impact upon the change of threshold wind

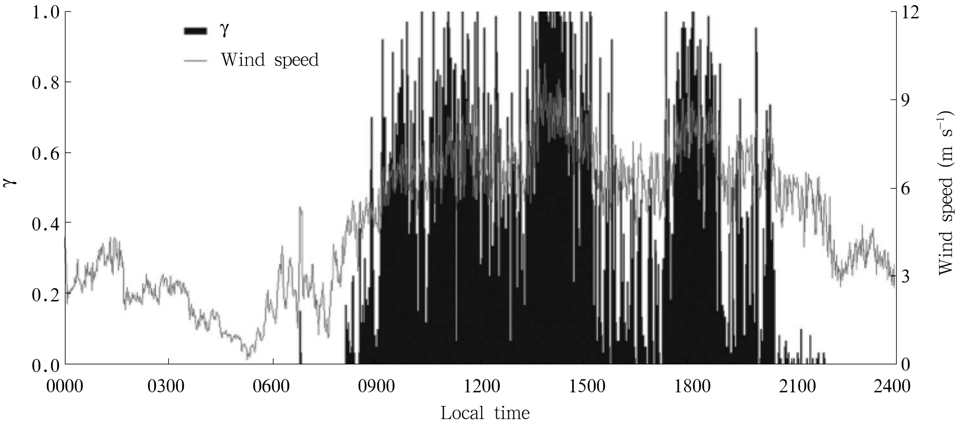

Fig. 2. Intensity of saltation activity γ and wind speed.

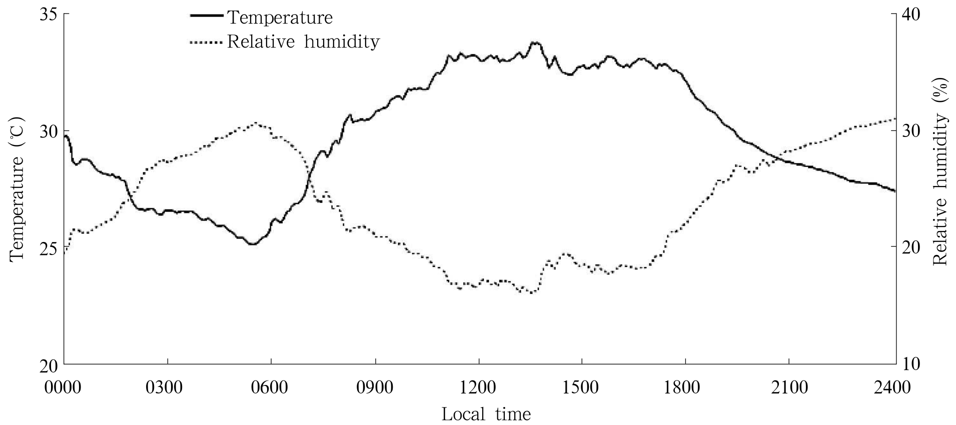

Fig. 3. Temperature and relative humidity measured at 1.5-m height.

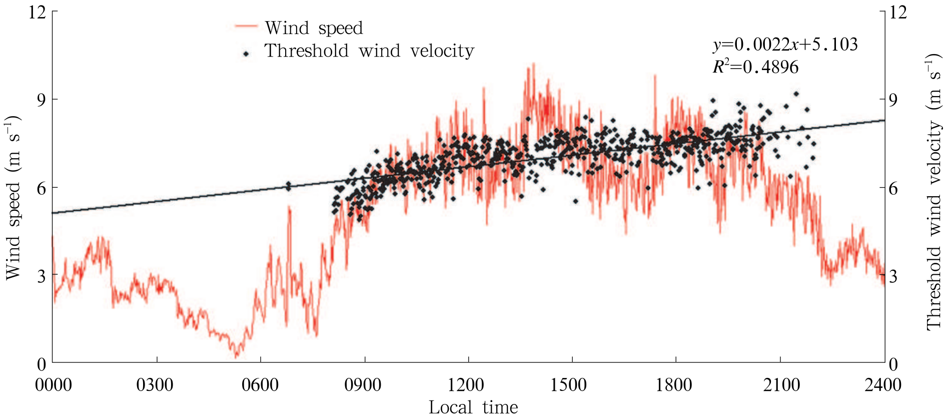

Fig. 4. Wind speed at 2-m height and threshold wind velocity.

velocity. Air humidity can affect soil humidity and the higher the soil moisture is, the higher the threshold wind velocity is. Moreover, the soil surface changes slightly, going with the movement of sand particles during sandstorms, such as the changes of particle size and compactness among particles. These changes of the soil surface condition can also affect threshold wind velocity. The above-mentioned factors are found to have affected the threshold wind velocity in the field experiment.

At the same time, it is found that threshold wind velocity has nothing to do with wind velocity. In this observation, threshold wind velocity increased at the speed of 0.18 m s^{-1} per hour, while wind velocity started to increase around 0900 LT 21 July, and it came to the maximum at 1400 LT and then decreased. Thus, the change of threshold wind velocity only represents the change of the soil surface and atmospheric environment in the wind erosion process, rather than changes of wind velocity itself.

The gradual increase of threshold wind velocity in desert area was reverse to the result observed in farmland. The bread-crust of the soil surface was broken gradually by wind when wind erosion occurred in farmland, so the surface could easily be eroded by wind. As a result, threshold wind velocity gradually decreased in farmland (Chepil, 1945; Gillete et al., 1996; Stout and Zobeck, 1996). The reason why threshold wind velocity in desert area increases gradually with the occurrence of wind erosion is still unknown, but the following two points seem to have a certain influence:

(1) *Change of the underlying surface.* The underlying surface consists of flow sand at the observation site, without any bread-crust cover. Without considering the input of an external sand source, particles on the surface are finer while moisture content and compactness are smaller. In these conditions, saltation activity occurs at lower wind velocity. After fine sand particles are blown up, most of the remaining ones are rough particles. Moreover, moisture content of the lower-layer sand is relatively higher. Saltation activity can occur only when wind velocity rises.

(2) *Consumption of wind velocity energy by saltating particles.* When sand particles are blown up into the air, the air density increases since it contains moving particles, and resistance force rises accordingly. Thus, part of the wind energy can be consumed so that threshold wind velocity values have to be increased. The consumption is more striking as the particle density in the air increases.

The threshold wind velocity can be computed exactly by TFEM. However, this method can only be used to compute threshold wind velocity at the time when saltation activity is occurring, while it cannot be used to compute continuous threshold wind velocity.

3.4 Computation of field sediment discharge

During the observation, sediment flux at the heights of 5, 10, 20, 50, and 100 cm was measured by the BSNE sand samplers, and it below 100-cm height was fitted to the following equation:

$$q(z) = a(z+1)^b, \quad (2)$$

where $q(z)$ is sediment flux (kg m^{-2}) at the corresponding height, z is the height of the sampler opening above the soil surface (cm), and a and b are fitting parameters. The fitting curve is shown in Fig. 5.

Sediment discharge, passing the BSNE station, was determined by integrating Eq. (2) from 0 to 200 cm:

$$Q = \int_0^{200} q(z)\mathrm{d}z = \frac{a}{b+1}\left[(201)^{b+1} - 1\right], \quad (3)$$

where Q is the sediment discharge (kg m^{-1}). The sediment discharge was 82.1 kg m^{-1} for the BSNE station,

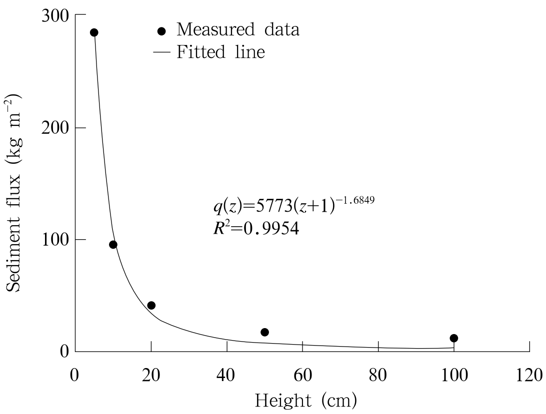

Fig. 5. Sediment flux at different heights above the soil surface.

which was calculated from sediment flux at the five different heights, using Eqs. (2) and (3).

To understand wind erosion processes, sediment discharge data are needed at a much greater time resolution than 24 h. The Sensit data may be useful in this regard, if the relationship to sediment movement is known. Gillette et al. (1994) and van Donk et al. (2003) reported a linear relationship between Sensit count and sediment movement. The sediment discharge and Sensit count of 16 sandstorm processes in 2009 support the assumption of a linear relationship and the correlation coefficient R^2 is 0.93. The equation is:

$$y = 0.6 \times 10^{-4}x, \quad (4)$$

where y is sediment discharge (kg m^{-1}) and x is Sensit count (counts). Then, hourly sediment discharge was calculated from hourly Sensit count using Eq. (4) (Fig. 6). Wind erosion for the 24-h period occurred in a few hours (Fig. 6). This can be explained by the greater wind speed during this period of time. However, hourly sediment discharge was not inevitably going to increase with the change of wind velocity, and sediment discharge may not be so large as wind velocity. In this experiment, the maximum hourly sediment discharge was 18.2 kg m^{-1}, occurring at 1400 LT, while the maximum hourly wind velocity appeared at 1500 LT. Change of sediment discharge depends on the ratio of wind velocity and threshold wind velocity. It is known from the foregoing analysis that threshold wind

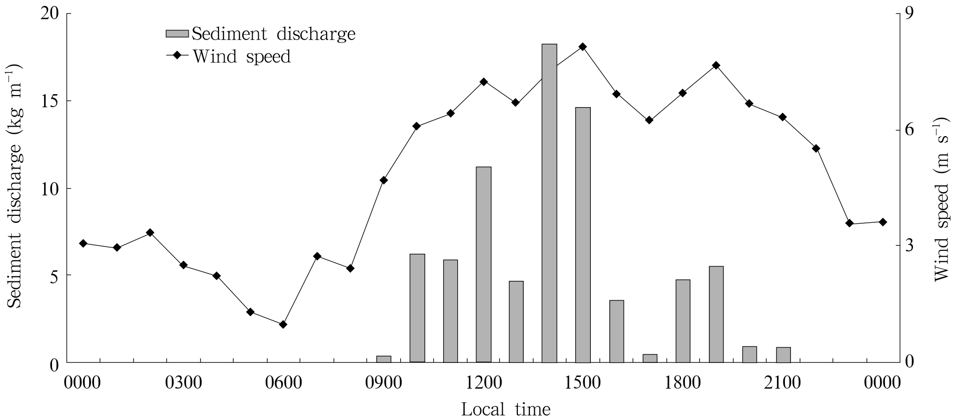

Fig. 6. Hourly sediment discharge and wind speed.

velocity was variable, and had nothing to do with change of wind velocity, which determines that the change of sediment discharge in field conditions was complicated. Thus, the exact sediment discharge can hardly be obtained by a simple empirical equation only with wind velocity.

4. Conclusions

It is proved by this experiment that the Sensit is a better choice to monitor the saltation activity in the Taklimakan Desert. However, the Sensit does have disadvantages, for example, its response towards the stroke of smaller particles is of low sensitivity, and the pulse formed by crowds of sand or a single particle cannot be distinguished by this sensor when wind velocity is higher. As a result, some errors are caused in the measured results, but as a whole, they are credible.

The saltation activity is significantly intermittent and it is not sequential even if wind velocity is continuously higher. When wind velocity is continuously higher, its energy or its effect upon particles is intermittent to some extent. In this experiment, the longest time for continuous saltation activity did not exceed 5 min. The saltation activity is closely related to meteorological elements, and the "wind-temperation synchronization" is conductive to the occurrence of particle saltation activity.

The threshold wind velocity is variable in the natural state because of changes of underlying surface and atmospheric environment. In this observation, the range of threshold wind velocity was 4.9 to 9.2 m s^{-1} at a mean value of 7.0 m s^{-1}, and it increased at 0.18 m s^{-1} per hour, which goes against the changing of threshold wind velocity of farmland (Chepil, 1945; Gillete et al., 1996; Stout and Zobeck, 1996).

The sediment discharge at the height between 0 and 200 cm was 82.1 kg m^{-1} during the observation, and hourly sediment discharge was not inevitably going to increase with the change of wind velocity, and sediment discharge may not be so large as wind velocity. The changes of threshold wind velocity are crucial to the complex changes of sediment discharge. It is far inadequate to obtain real field sediment discharge only by establishing empirical formulas simply with wind velocity. More data of sediment discharge and Sensit count are necessary so as to establish a more exact relation between the two factors, so that the sediment discharge of different time sequences can be calculated.

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