

Stability mechanisms of barchan dunes: A case study of Hexi Desert area in Gansu Province

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Abstract. Barchan dunes, an important type of dunes, are distributed on the edge of oases. Research of stability mechanisms of barchan dunes is of great importance to the determination of regulation of aeolian sand movement on the edge of oases. However, the stability of barchan dunes remains an unresolved scientific issue. In this paper, the stability mechanisms of the top of barchan dunes in Hexi desert area of Gansu Province were analyzed. The results showed that: (1) in Hexi desert area of Gansu Province, patches of barchan dunes were distributed downwind on the edge of desert. The distribution areas were flat sandy-clay or sandy-gravel beaches. The lowlands among the dunes were wide and had the prominent prevailing wind. (2) The prevailing northwestern wind caused the highest point and sand ridge line of the dunes to coincide, and the dunes to move forward and become lower. The southeastern wind (opposite to the prevailing wind) caused the highest point and sand ridge line of the dunes to separate, the leeward slope to be eroded by wind and the dunes to rise. (3) The higher the barchan dunes were, the longer the two flanks were, and the smaller the angle was. (4) The wide flat beaches were vital to the formation of barchan dunes and a chain of barchan dunes. The largely prevailing wind was the key factor for the stability of barchan dunes and a chain of barchan dunes. The opposite wind and the corridor effect of the two flanks were key factors for the increase of barchan dunes in size and height. The speed and distribution frequency of the prevailing and opposite winds were factors restraining the height of barchan dunes and a chain of barchan dunes here.

1. Introduction

In most desert areas of Hexi region in Gansu Province, there are obvious prevailing wind directions, and there are no more than three groups of winds with similar power. That is, there is no repeated shaping process of contrary winds or gales in other directions. However, these high barchan dunes and a chain of barchan dunes can exist stably, and their top can not be scraped by wind. There are lots of reports on barchan dunes at home and abroad, but most reports focus on their morphological characteristics [1-4], flow field [5-7] and surface grain size [8-10] instead of stability of their top.

Xu Zhenwen *et al* [11] have analyzed the quantity, scale and sand granularity of barchan dunes in the Kumtag Desert and the Ulan Buh Desert as well as along Changli gold coast and Emerald Isles of Beidaihe. Bishop [12] and Durán *et al* [13] have suggested that the distribution of barchan dunes undergoes a process of self-regulation, and their size and spacing tend to be consistent with their movement and merging [14]. Hersen *et al* [3] have pointed out that the size and spacing of barchan dunes on each sand are consistent, and the bigger the barchan dunes are, the quicker the barchan dunes breed. Elbelrhiti *et al* [15] have suggested that big barchan dunes change into small barchan dunes after



the loss of sand materials on both sides, thereby maintaining the development pattern and size distribution of barchan dunes. During the interaction process of barchan dunes, their height distribution will not change [16, 17].

Airflow is the dynamic factor of formation of barchan dunes, so it is the focal point of research on barchan dunes [18]. Bourke [4] and Yang Yanyan *et al* [18] Zhang Cunlai *et al* [19] have pointed out that deposition is more intense than erosion in locations where the windward slope of barchan dunes becomes gentle, while erosion is more intense than deposition in other locations, and the sand transport rate and erosion intensity are the highest at their top. Based on the observation and research of moving dunes in the Mu Us Sandy Land, Yao Honglin *et al* [20] have suggested that when wind velocity increases to the threshold leading to sand movement, the top of the dunes is being eroded by wind; as wind velocity increases gradually, sand is accumulating at their top. Belrhiti *et al* [21] have pointed out that only when a stable polygon is formed on both flanks and at the top of a barchan dune can the barchan dune be invariant in shape during the process of movement.

To sum up, the top stability of barchan dunes remains an unresolved scientific issue in the field of desert ecology. Research on the top stability of barchan dunes not only has important academic value to the revelation of sand movement rules, invasion of sand flow, and expansion of desert on the edge of oases, but also has considerable practical significance to the construction of sand defense and stabilization, resource development and protection of ecological environment in desert areas.

2. General situation of the study area and research methods

2.1. The study area

Hexi region (92°45'-104°15' E, 36°35'-42°45' N) in Gansu Province includes Wuwei, Jinchang, Zhangye, Jiuquan and Jiayuguan cities on the west of the Yellow River. The region is located on the north of the Qilian Mountains and is surrounded by the Tengger Desert in the east, the Badain Jaran Desert in the north, and the Kumtag Desert in the west. In the region, the area of desert and scattered sand is 754 km², and there are large numbers of tall barchan dunes and a chain of barchan dunes on the edge of oases. Minqin County is situated on the western edge of the Tengger Desert and on the northwest of Hexi Corridor, and barchan dunes and a chain of barchan dunes concentrate most densely here; most barchan dunes and a chain of barchan dunes are distributed on the NW edge of oases, namely the upwind edge of desert (figure 1).

2.2. Research methods

Based on the complete investigation of barchan dunes and a chain of barchan dunes on the edge of oases in Hexi region of Gansu Province, the flow field, wind erosion and accumulated sand of typical barchan dunes were observed. That is, two tall barchan dunes were chosen from Minxin County, and observation recorders of wind speed and direction were put in their key positions (figure 2). Wind speed at No. 1 dune was observed from April to September in 2014, and the highest point and sand ridge line of the dune separated at the initial stage of observation; wind speed at No. 2 dune was observed from April to September in 2015, and the highest point and sand ridge line of the dune coincided at the initial stage of observation. Meanwhile, wind erosion poles were put in the key positions of the dunes to measure the depth of wind erosion and thickness of accumulated sand. Moreover, sand sources around the dunes and vegetation before and after the dunes were observed. Wind speed and direction were observed at a height of 50 cm, and sampling was conducted one time every 20 min. Every 2 m/s was as a grade of wind speed, and the maximum wind speed was 14.9 m/s. To observe the depth of wind erosion and thickness of accumulated sand, one end of a No. 8 steel wire was buried underground, and the height of the steel wire above the ground was 30 cm. The height of the steel wire above the ground was observed. In this paper, the prevailing wind was NW wind, and wind opposite to the prevailing wind was SE wind. NW slope was defined as windward slope. The apex of the dunes referred to the highest point of the dunes, and the chord length was the distance between the endpoints of their two flanks; their length-width ratio was the ratio of their total length to total width; the thickness of back of a bow was the distance from the bottom

of windward slope to the bottom of leeward slope (figure 3). Climatic data were from local meteorological stations and China meteorological science data sharing service network.

2.3. Data analysis

Every 2 m/s was as a grade of wind speed of the prevailing wind, and the wind speed S was divided into five grades, including $S < 2$ m/s, $4 \text{ m/s} > S \geq 2 \text{ m/s}$, $6 \text{ m/s} > S \geq 4 \text{ m/s}$, $8 \text{ m/s} > S \geq 6 \text{ m/s}$, and $S \geq 8 \text{ m/s}$. The speed of wind opposite to the prevailing wind was small, so every 1 m/s was as a grade of wind speed. Data of wind speed were analyzed by using SPSS 13.0.

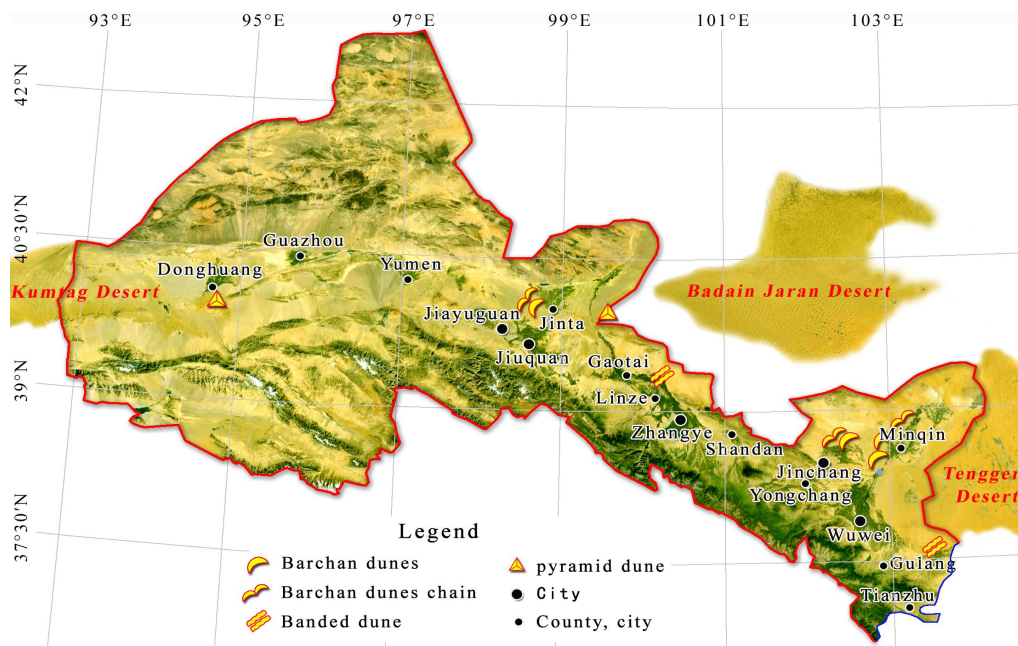


Figure 1. Distribution of barchan dunes in Hexi desert area of Gansu area.

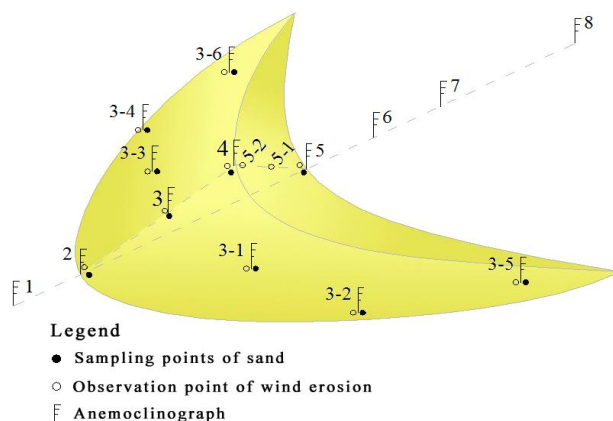


Figure 2. Observation sampling points of barchan dunes.

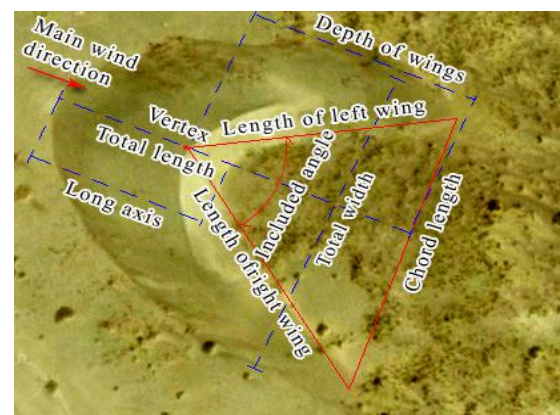


Figure 3. Feature representation of barchan dunes.

3. Results and analysis

3.1. Distribution environment of barchan dunes

Barchan dunes are often formed open sandy-clay or sandy-gravel beaches. Barchan dunes develop from patches of sand and sand piles, that is, after encountering obstacles such as bushes and gravel, sand flow

piles up to form patches of sand firstly and then peltate sand piles and prototype of barchan dunes [18], thereby developing into barchan dunes.

In the desert areas of Hexi region in Gansu Province, barchan dunes were the most on the edge of oases in Minqin in the east, followed by the edge of oases in Jinta in the west, while there were few barchan dunes in the middle of Hexi Corridor. The basic characteristics of barchan dunes are shown as follows: their average height was 8.1 m, and the maximum was up to 11.6 m, while the minimum was 3.6 m; the thickness of back of a bow averaged 101.1 m, and the maximum reached 155.7 m, while the minimum was 64.1 m; their total length averaged 162.3 m, and the maximum was 294.4 m, while the minimum was only 86.5 m; their total width averaged 188.9 m, and the maximum reached 227.4 m, while the minimum was 57.3 m; the slope of leeward slopes averaged 31.8°, and the slope of the steepest slope was 32.9°, while the slope of the gentlest slope was 30.1° (table 1)

Distribution environmental characteristics of barchan dunes are shown as follows: barchan dunes were located on the downwind edge of desert or scattered sand, namely on the upwind edge of oases. For instance, barchan dunes in Minqin desert area were distributed on the upwind edge of oases in western Minqin; barchan dunes in Jinchang desert area were distributed on the edge of desert and oases in northern Jinchang; barchan dunes in Jinta desert area were located on the edge of scattered desert on the west of oases in Jinta (figure 1). A chain of barchan dunes could be found in regions where barchan dunes appeared. Open and flat gravel beaches were distributed in front and at the back of barchan dunes; the average width of upwind beaches was 224.1 m, while the maximum was up to 662.9 m; the average width of downwind beaches was 359.9 m, while the maximum reached 697.3 m. There was a single main wind direction. For example, the main wind direction was NW in Minqin and Jinchang desert area and NW and WNW in Jinta desert area. The forward direction of barchan dunes changed from N45°W—N48°W in Minqin desert area to N63°W in Jinta desert area. All barchan dunes were moving dunes, that is, there was nearly no vegetation on their windward slopes and leeward slopes; vegetation was sparse in beaches in front and at the back of barchan dunes, and vegetation coverage ranged from 0.5% to 4.0 %.

Table 1. Morphological characteristics of barchan dunes in Hexi desert area of Gansu.

No. of dunes	Plots	Height (m)	Thickness of back of a bow (m)	Length (m)	Width (m)	Slope of a leeward slope (°)	Forward direction (°)	Length of upwind beaches (m)	Length of downwind beaches (m)
1	Minqin 1	9.8	123.3	214.6	202.5	32.6	N48°W	662.9	378.0
2	Minqin 2	11.2	155.7	294.4	227.4	32.2	N48°W	163.3	491.6
3	Minqin 3	9.5	120.5	197.5	209.8	32.1	N48°W	134.2	176.6
4	Minqin 4	3.7	78.7	86.5	81.8	31.8	N48°W	251.8	367.8
5	Minqin 9	7.9	90.8	112.5	81.5	32.9	N45°W	214.3	253.3
6	Minqin 10	7.6	86.7	136.8	64.7	31.5	N46°W	137.9	430.1
7	Minqin 11	11.6	104.4	183.6	57.3	31.6	N46°W	179.7	243.1
8	Minqin 12	8.6	64.1	131.4	77.9	30.1	N46°W	135.2	697.3
9	Jinchang 1	8.4	130.3	197.6	123.2	31.7	N55°W	227.4	372.1
10	Jinta 1	6	83.7	125.3	104.8	31.5	N63°W	250.4	129.5
11	Jinta 2	5.3	73.5	104.8	76.6	31.7	N63°W	108.2	419.8

3.2. Main and anti-main wind direction process

3.2.1. Forward movement and drop of the apex of barchan dunes and its coinciding with a sand ridge line in the main wind direction. In Minqin desert area, the main wind direction was NW and the forward direction of barchan dunes was NW-SE, while the wind speed causing sand movement ranged 4.5—5.0 m/s [22]. The highest point and sand ridge line of No. 1 barchan dune separated before observation. The

observation results of wind speed show that when wind speed was ≥ 8 m/s at the upwind reference point, wind speed between the highest point and sand ridge line of barchan dunes was smaller than the wind speed at the upwind reference point, that is, there was a weak wind zone between the highest point and sand ridge line of barchan dunes (Figure 4(a)). As the highest point and sand ridge line of No. 2 barchan dune coincided, wind speed was the largest at the top of the barchan dune (Figure 4(b)).

According to the observation results of wind erosion from March 31 to May 8 in 2014, under the effect of prevailing wind (NW wind), various parts of barchan dunes on windward slopes were being eroded by wind to a degree, and wind erosion depth was 6.7 cm at the bottom of windward slopes, 13.0 cm in the middle of windward slopes, 16.8 cm between the highest point and sand ridge line of barchan dunes, 6.0 cm in the middle of the western flank of barchan dunes, 0.0 cm on the edge of the western flank, 11.0 cm in the middle of the eastern flank of barchan dunes, and 0.5 cm on the edge of the eastern flank respectively. That is, wind erosion was the strongest at the top of barchan dunes, and the height of barchan dunes dropped.

The highest point and sand ridge line of barchan dunes were often separate in spring. When gale and sandstorm happened, sand flow rose along the windward slopes of barchan dunes to the highest point, and then load flow continued to move along the windward slopes under the effect of inertia force (figures 5(a) and 5(b)). The height between the highest point and sand ridge line of barchan dunes was lower than the highest point of barchan dunes, so there was a weak wind zone between the highest point and sand ridge line of barchan dunes.

When sand flow passed the highest point of barchan dunes, a large quantity of sand settled (figure 5(b)), so the highest point of barchan dunes moved forward until it coincided with the sand ridge line. Afterwards, a large quantity of sand fell on the upside of the leeward slope and then slipped down freely, so barchan dunes moved forward (Figure 5(c)). From March 31 to May 8, the bottom of the leeward slope moved forward by 1.34 m.

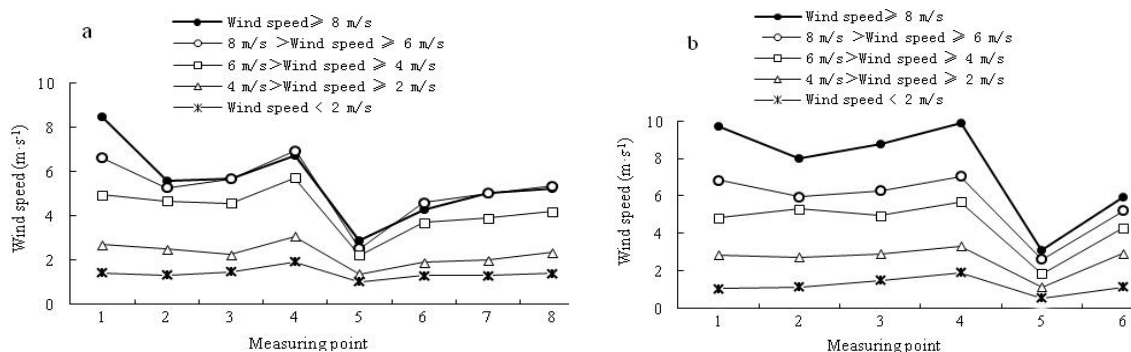


Figure 4. Change trends of wind speed in various parts of the dunes in the main direction.

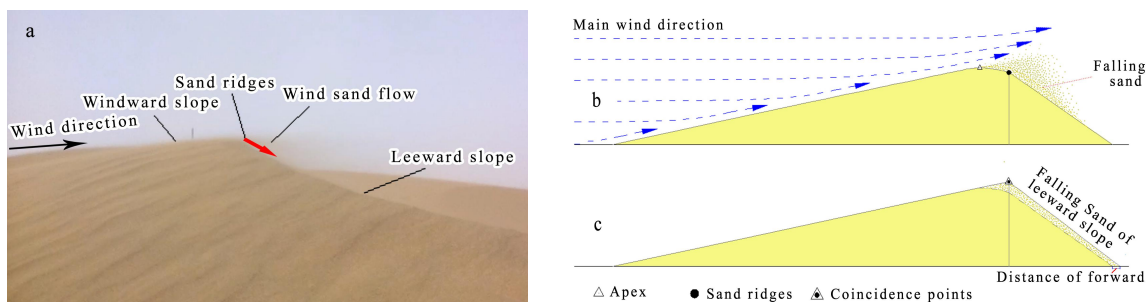


Figure 5. Schematic diagram of the main wind direction process.

3.2.2. Rise of the apex of barchan dunes and its separation from a sand ridge line in the anti-main wind direction. After spring, the highest point and sand ridge line of barchan dunes in Minqin desert area

coincided. In summer, SE wind would appear here. As its wind speed reached the speed causing sand movement, wind in a SE direction (or ESE and SSE direction) blew across a large quantity of sand on their leeward slopes, and the sand passed sand ridge lines and continued to move upward along their leeward slopes. The larger the wind speed was, the higher the sand moved. Their leeward slopes were steep, and sand was fine, so the sand moved by sand flow upward was high; coarse sand fell and deposited on the upside of their windward slopes, while fine sand fell at the bottom of their windward slopes or even far (Figures 6(a) and 6(b)).

If SE winds with wind speed high than wind speed causing sand movement were frequent in summer, wind erosion appeared on the upside of their leeward slopes, and the leeward slopes became gentle; the the highest point of barchan dunes separated from the sand ridge lines and moved toward the windward slopes; the height of barchan dunes increased at the same time (Figure 6(c)).

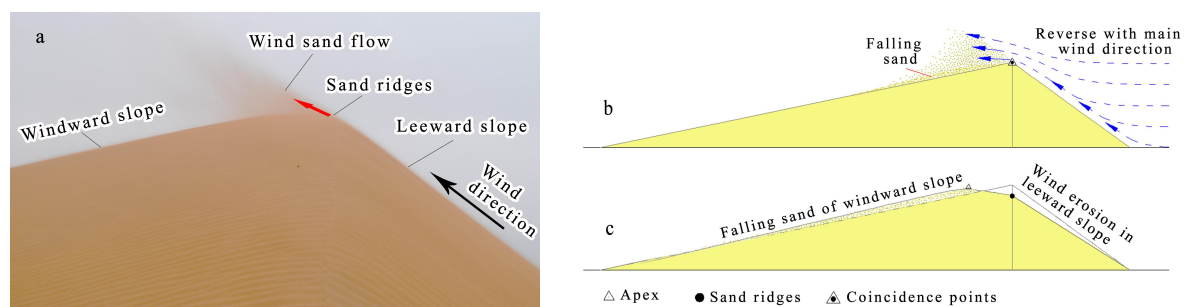


Figure 6. Schematic diagram of the anti-main wind direction process.

3.3. Functions of their two flanks as galleries

3.3.1. Features of wind speed in the anti-main wind direction. In Minqin desert area, wind speed was high in NW (including WNW and W) direction but slow in SE (including ESE and E) direction (figure 7). Therefore, the forward direction of most barchan dunes was NW—SE, that is, NW was the main wind direction of barchan dunes, while SE was their anti-main wind direction. According to table 1, the observation results of wind speed in NW direction at No. 1 barchan dune are shown as follows: wind speed reduced from the open upwind ground (No. 1 observation point) to the bottom of its windward slope (No. 2 observation point); wind speed increased from the bottom of its windward slope to its top (No. 4 observation point); wind speed was the smallest at the bottom of its leeward slope (No. 5 observation point), and then it rose gradually (Figure 4(a)).

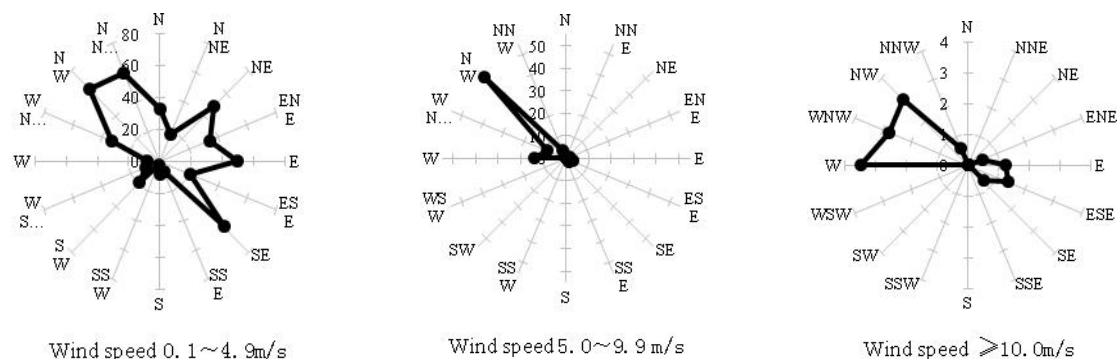


Figure 7. Distribution of wind speed and wind direction in Minqin desert area from 2000 to 2014.

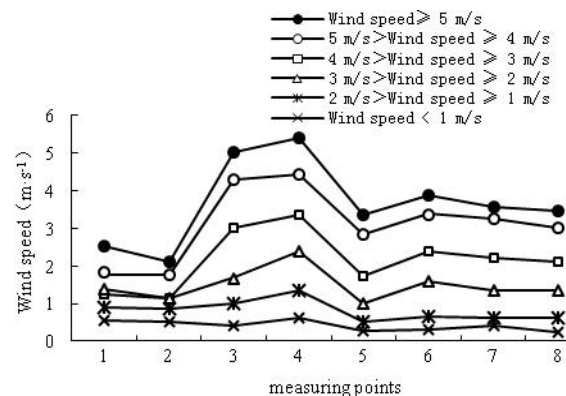


Figure 8. Change trends of wind speed in various parts of the dunes in the opposite direction.

The observation results of wind speed in SE direction at No. 1 barchan dune (figure 8) were contrary to that in NW direction. That is, on the one side of its leeward slope, wind speed increased gradually from the far observation point (No. 8 observation point) to the near observation point (No. 6 observation point) and reduced at the bottom of its leeward slope (No. 5 observation point). The acceleration of wind speed in SE direction on the one side of its leeward slope correlated positively with wind speed. For instance, from No. 8 observation point No. 6 observation point, ≥ 5 m/s, ≥ 4 m/s \rightarrow 5 m/s, ≥ 3 m/s \rightarrow 4 m/s, ≥ 2 m/s \rightarrow 3 m/s, ≥ 1 m/s \rightarrow 2 m/s wind speed increased by 0.417, 0.366, 0.272, 0.268, and only 0.031 m/s respectively. The variation of wind speed was the smallest at the bottom of its windward slope but the most obvious at the top of the dune. In the main wind direction, the variation of wind speed was the smallest at the bottom of its leeward slope (No. 5 observation point) but the most obvious on the smooth upwind ground of its windward slope (No. 1 observation point). The decrease of wind speed from the middle to the bottom of its windward slope was far larger than that from the top of the dune to the middle of its windward slope. In the main wind direction, the increase of wind speed from the bottom to the middle of its windward slope was close to that from the middle of its windward slope to the top of the dune.

3.3.2. Characteristics of sand accumulation in the anti-main wind direction. According to the observation results of wind erosion at No. 1 barchan dune in table 1, under the effect of the main wind (NW wind), the height of the dune dropped by 37.7 cm from March 31 to May 8 in 2014; the depth of wind erosion at the bottom and in the middle of the windward slope was 6.7 and 13.0 cm respectively; the depth of wind erosion in the middle and on the edge of its western flank was 6.0 and 0.0 cm respectively; the depth of wind erosion in the middle and on the edge of its eastern flank was 11.0 and 0.5 cm respectively. That is, wind erosion was the strongest at the top of the dune.

On September 21, 2015 after the anti-main wind process, the distance between the highest point and sand ridge line of No. 1 barchan dune was 8.3 m, and its height rose by 43 cm compared with that on May 22, 2015.

4. Conclusions

- The most obvious characteristics of distribution environment of barchan dunes and a chain of barchan dunes are shown as follows: firstly, they were distributed on sandy-clay or sandy-gravel beaches; secondly, they were distributed in flat regions (especially in ancient riverbeds), and the differentiation between barchan dunes and beaches as underlying surface was obvious; thirdly, upwind and downwind beaches around barchan dunes were open. On the flat and open underlying surface, sand flow ran smoothly. On the one hand, sand carried by sand flow rose along barchan dunes and accumulated on them; on the other hand, sand on both sides of barchan dunes was moved forward by gale to form two flanks of barchan dunes [6]. In Hexi

Corridor, patches of barchan dunes were distributed downwind on the edge of desert, and the average width of upwind beaches around barchan dunes was 246.4 m, while the average width of downwind beaches was 374.4 m,

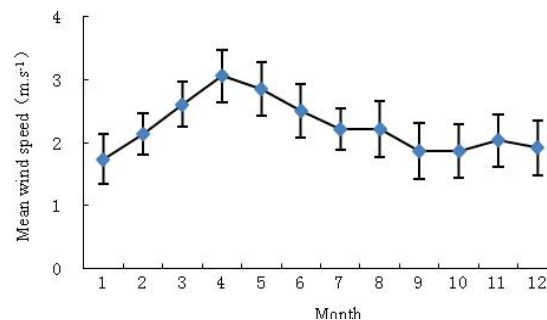


Figure 9. Average wind speed of each month in Minqin desert area, 1961-2016.

- Minqin desert area is mostly NW wind in spring and winter and the wind speed is larger. Mostly SE wind in summer and autumn and the wind speed is smaller (figure 9). Generally speaking, the separation of the highest point and sand ridge line of barchan dunes alternated with their overlap one time every year, and their overlap was frequent in summer, while their separation was common in autumn and winter. In special years, SE wind speed was small, or there was no separation in local regions sometimes; when NW wind speed was small in spring in a year, their separation appeared in the whole year. Existence and disappearance of the weak wind zone between the highest point and sand ridge line of barchan dunes took place by turn. Therefore, the height of barchan dunes fluctuated in a year. The apex of a barchan dune moved forward or back alternately within a year, and the movement distance mainly depended on the speed and frequency of NW and SE wind in the year. During the process, even if the speed and frequency of SE wind were high, the wind could erode the upside of a leeward slope to make its gentle. However, it could not make the base of a leeward slope move back, that is, the base of a leeward slope could move forward. Hence, the forward movement of a barchan dune should depend on the base of its leeward slope (No. 5 observation point).
- According to the observation results of wind erosion in various parts of barchan dunes, their top was the most unstable, namely being in the dynamic process of moving forward—moving back and rising—dropping. NW and SE wind were distributed alternatively in various seasons to maintain the basic shape of barchan dunes. The stability of barchan dunes was dynamic. If there was no SE wind causing sand movement, the highest point and sand ridge line of a barchan dune would not separate; the top of a barchan dune would be relatively stable; barchan dunes would move forward more quickly.
- Some scholars suggest that coarse sand changes into fine sand from the bottom of a windward slope to the top of a dune [23, 24], while other scholars have obtained the opposite conclusion [8, 25], which are related to the observation and sampling season. In fact, it is caused by seasonal alternation between NW and SE wind. In Minqin desert area, middle sand increased but fine sand decreased in quantity from the bottom of a windward slope to the top of a barchan dune, while fine sand tended to increase in the two flanks in early May. If observation was conducted in the late period of NW wind before the appearance of SE gale in late spring and early summer, similar results could be obtained. However, opposite results might be obtained if observation was conducted in autumn and winter.
- In Minqin desert area, the height of tall barchan dunes reached above 10 m (table 1), and barchan dunes lower than 4-5 m in height were small barchan dunes that were developing. The change of patches of sand and sand piles into peltate sand piles and prototype of barchan dunes started from the increase in the thickness of back of a bow [18]. When sand flow met patches of

sand and sand piles, airflow rose or its direction changed, so wind speed dropped, and sand accumulated. Small archan dunes were short and their windward slopes were short, and the wind aggregation role of the prevailing wind on windward slopes was smaller than that of tall barchan dunes, so the highest point and sand ridge line of small barchan dunes could not coincide mostly. As the back of a bow of small barchan dunes continued to thicken, the length of their windward slopes increased gradually, and their height also increased. Due to the increase of barchan dunes in height, sand flow changed into reflection eddy current on their leeward slopes, and sand falling slopes and sand ridge lines appeared on their leeward slopes gradually. With the formation and extension of their two flanks, the role of anti-main wind increased, and the increase of dunes in height accelerated. In specific environment, the accumulation and erosion of the main wind and anti-main wind were close, the height of dunes tended to be stable. In Minqin desert area, the height of barchan dunes increased in years when the power and frequency of the anti-main wind were high but decreased in years when they were low.

5. Conclusions

In Hexi desert area of Gansu Province, patches of barchan dunes and a chain of barchan dunes were distributed downwind on the edge of desert. The distribution areas were flat sandy-clay or sandy-gravel beaches. The beaches among the dunes were wide, and downwind beaches were more open than upwind beaches. There was the prominent prevailing wind direction in their distribution areas, and wind speed in other direction was small, or there was a gale blowing once in a while.

The prevailing northwestern wind caused the highest point and sand ridge line of the dunes to coincide, and the dunes to move forward and become lower. The southeastern wind (opposite to the prevailing wind) caused the highest point and sand ridge line of the dunes to separate, the leeward slope to be eroded by wind and the dunes to rise. NW wind was dominant here, so barchan dunes moved forward from NW to SE, while they were eroded by wind and the slope of their leeward slopes decreased under the effect of SE wind.

The length and angle between two flanks of barchan dunes were closely related to their height. That is, the higher the barchan dunes were, the longer the two flanks were, and the smaller the angle was. Two flanks of barchan dunes are one of important morphological characteristics to maintain the stability of barchan dunes.

The wide flat beaches were vital to the formation of barchan dunes and a chain of barchan dunes. The largely prevailing wind was the key factor for the stability of barchan dunes and a chain of barchan dunes. The opposite wind and the corridor effect of the two flanks were key factors for the increase of barchan dunes in size and height. The speed and distribution frequency of the prevailing and opposite winds were factors restraining the height of barchan dunes and a chain of barchan dunes here.

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