Dynamic mechanism of blown sand hazard formation at the Jieqiong section of the Lhasa–Shigatse railway

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ABSTRACT
Blown sand hazards at the Jieqiong section of the Lhasa–Shigatse railway are severe, and their formation mechanism is unclear. Moreover, sand prevention and control work cannot be carried out. Therefore, the dynamic mechanism of blown sand at the Jieqiong section of the Lhasa–Shigatse Railway was investigated by field observation, laboratory analysis, and calculation. Results show that the yearly sand–moving wind at the Jieqiong section commonly originates from the SW direction. The yearly resultant drift direction and the yearly resultant angle of the maximum possible sand transport quantity are NE direction. The angle between railway trend and sand transport direction is 5°–30°. During dry season, sand materials are blown up by the wind, forming wind–sand flow and movement to the NE direction, at which they are blocked by the railway roadbed. Consequently, accumulation occurs and causes serious damage. Strong wind and dryness are synchronous within a season. The directions of sand source and prevailing wind are consistent, thereby aggravating the blown sand dynamic further. The present results provide a reference for controlling sand hazards in the locale.

1. Introduction
Blown sand is a key parameter of the meteorology and atmospheric environments (Zheng and Singh 2018), moreover, blown sand is also an important factor that confounds railway construction and safe operations in sandy regions (Xie et al. 2013; Zhang et al. 2014). Land desertification along the Lhasa–Shigatse railway is severe because of a number of factors, such as dry and windy climate, rich source of sandy materials, sparse and low vegetation, short growing season, and intensive human activities (Dong et al. 1995). Large areas with moving dunes and semifixed dunes are
distributed on the valley bottom and valley slope, especially in the river broad valley (Liu and Zhao 2001); in addition, the ecological environment is fragile, the blown wind activities are strong, and gales with high wind velocity and long duration are frequent (Li et al. 1999). Given the distinct high elevation and cold temperature of the Qinghai–Tibet Plateau (Yang et al. 2007; Guo et al. 2017), the matter and energy balance of the system are altered by any small disturbance (Jiang et al. 2014; Huang and Wang 2016; Zhang et al. 2016; Cheng et al. 2017; Xie et al. 2017). The construction of railways inevitably destroys native sparse vegetation and fragile ecological environment to a certain extent and further exacerbates the surface blown sand activities along railways (Yan et al. 2001; Zou et al. 2002; Zhang et al. 2007a, b). The original, relatively stable dynamic balance of blown sand movement in plateaus is disturbed in the space domain with the appearance of railway roadbeds. Moreover, the moving path and intensity of wind–sand flow near the surface are altered. Consequently, blown sand hazards become prominent. Today, more than three sand hazard sections with a total length of 47 km are present along the Lhasa–Shigatse

Figure 1. Sketch map of the Lhasa–Shigatse railway and its study area—Jieqiong section.
railway, and they include the Xierong section, Quxu section, and Jieqiong section (including the Gobi section and farmland section); these sections are mainly distributed in the Jieqiong section, and they have become a direct threat to the safety of railways. However, the disaster-causing mechanism of blown sand hazards has not been intensively investigated and is limited because the construction and operation of the Lhasa–Shigatse railway only occurred recently. The dynamic mechanism of how blown sand hazards at the Jieqiong section of the Lhasa–Shigatse railway is formed remains unknown. Thus, sand prevention and control work cannot be carried out. Therefore, the dynamic mechanism of blown sand at the Jieqiong section of the Lhasa–Shigatse railway was investigated by field observation, laboratory analysis, and calculation to understand the sand hazard rules systematically and to provide bases for controlling sand hazards.

2. Study area and methods

The Lhasa–Shigatse railway is located in the southwest region of the Qinghai–Tibet Plateau, the middle reaches of the Yalu Tsangpo River and the two tributary valleys of the Lhasa River and Nianchu River, and the railway east from Lhasa City, which is the terminus of the Qinghai–Tibet railway; this railway also passes along the Lhasa River down to Quxu County, and it traces the Yalu Tsangpo River to the upstream after the county. The Lhasa–Shigatse railway is also line strides the Yalu Tsangpo River three times; it passes the Nyemo County, Rinbung County, and across the ridge of the Yalu Tsangpo River basin and Nianchu River basin at the Jieqiong section. It reaches the valley of the Nianchu River along the Nianchu River down and finally arrives in Shigatse City, which is an important city in the southwest of Tibet. The total length of the Lhasa–Shigatse railway is 253 km (Figure 1). The construction of this railway started in January 2011; it was opened to traffic in August 2014.

The Jieqiong section of the Lhasa–Shigatse railway, which belongs to the watershed of the Yalu Tsangpo River and Nianchu River was selected as the field observation site. As the most sand-damaged section of the Lhasa–Shigatse railway (Figure 2), the
Jieqiong section shows sand hazards covering an extent of approximately 10 km (Figure 1). The experimental observation site is located at 29°15′06″N and 89°12′14″E, with an altitude of 3980 m. Meteorological sensors presented a surface height of 2 m (Figure 2). The wind speed, wind direction, temperature, and humidity of the study site were observed, and data were recorded every 5 min. The observation time continued for more than two years (from May 2016 to June 2018).

According to the observational data, the statistics of wind speed, wind direction, and sand-moving wind frequency were first obtained. Then, the sand drift potential (DP) and the maximum possible sand transport quantity (Q) were calculated using the following methods.

Sand DP was calculated by the following formula (Bagnold 2005):

$$DP = V^2(V-V_t)t,$$

where DP is the sand DP expressed in vector units (VU), $V$ is the wind speed higher than the sand-moving wind (m·s$^{-1}$), $V_t$ is the sand-moving wind speed (m·s$^{-1}$), $t$ is the time affected by sand-moving wind and is expressed in frequency. As previously described in detail and according to the relevant research results in the locale (Han et al. 2014), the sand-moving wind speed in the Jieqiong section was 5.0 m·s$^{-1}$ (Han et al. 2015). The resultant drift potential (RDP) (VU) and resultant drift direction (RDD) (°) were obtained by synthesizing the sand DP on the basis of the vector synthesis rule, an index of directional wind variability is the ratio of RDP to DP (RDP/DP).

Many methods were used to calculate the $Q$ (Owen 1964; Leatherman 1978; Anderson and Hallet 1986; Sarre 1988; Rasmussen and Mikkelsen 1991; Sorensen 1991; Al-Bakri et al. 2016). According to the local conditions and relevant research results, in this investigation, the calculation formula of $Q$ proposed by Ling (Ling 1994, 1997), which is a formula specially obtained based on the characteristics of sandy areas in China:

$$Q = 8.95 \times 10^{-1} (V-V_t) \times T,$$

where $Q$ is the maximum possible sand transport quantity (kg·m$^{-1}$·a$^{-1}$), $V$ is the wind speed greater than the sand-moving wind (m·s$^{-1}$), $V_t$ is the sand-moving wind speed (m·s$^{-1}$), and $T$ is the cumulative duration of wind speed with different ranges. In the calculation, the statistics of the frequency or time of different wind speed ranges at each direction was first obtained on the basis of 16 directions. Then, the $Q$ values in the 16 directions were calculated under the condition of different wind speed ranges at each direction was first obtained on the basis of 16 directions. Then, the $Q$ values in the 16 directions were calculated under the condition of different wind speed ranges to obtain $Q$ of each direction. The sum of $Q$ in 16 directions is the total $Q$ (kg·m$^{-3}$·a$^{-1}$). Finally, the resultant quantity (RQ) (kg·m$^{-1}$·a$^{-1}$) and resultant angle (RA) (°) of the maximum possible sand transport were obtained by synthesizing $Q$ in 16 directions on the basis of the vector synthesis rule.
3. Results

3.1. Wind speed and wind direction

The average wind speed at the Jieqiong section of the Lhasa–Shigatse railway was 2.34 m s⁻¹ (May 2016 to Apr 2017), 2.52 m s⁻¹ (May 2017 to Apr 2018), the instantaneous maximum wind speed was 20.63 m s⁻¹ (May 2016 to Apr 2017), 22.14 m s⁻¹ (May 2017 to Apr 2018) and the maximum wind speed for a 5 min average was 13.59 m s⁻¹ (May 2016 to Apr 2017), 15.10 m s⁻¹ (May 2017 to Apr 2018). The average wind speed was high in spring, the average wind speed was low in winter (Figure 3). According to the yearly wind direction at the Jieqiong section (Table 1), the SW wind direction was prioritized, accounting for 14.28% (May 2016 to Apr 2017), 16.00% (May 2017 to Apr 2018) of the yearly total. The frequency of static wind was 13.51% (May 2016 to Apr 2017), 13.11% (May 2017 to Apr 2018).

3.2. Sand-moving wind

The frequency of yearly sand-moving wind at the Jieqiong section of the Lhasa–Shigatse railway was 10.31% (May 2016 to Apr 2017), 13.59% (May 2017 to Apr 2018). It was high in spring, on the contrary, the frequency of sand-moving wind was low in winter (Figure 3). The monthly variations of sand-moving wind frequency and average wind speed at the Jieqiong section showed good consistency (Figure 3). According to the monthly variations of dominant sand-moving wind direction at the Jieqiong section (Table 2), the SW and WSW directions of sand-moving wind at the Jieqiong section were dominant in winter and spring, respectively. The S direction of sand-moving wind was dominant in summer.

According to the yearly sand-moving wind at the Jieqiong section (Table 1), the SW wind direction of sand-moving wind was given priority, accounting for 23.49%
(May 2016 to Apr 2017), 22.90% (May 2017 to Apr 2018) of the yearly total. The WSW, SSW, S, and SSE wind directions were also occurred relatively high, the other wind directions of sand-moving wind rarely occurred.

The frequency and direction of sand-moving wind in each month at the Jieqiong section were synthesized as vectors. The monthly variations are shown in Figure 4.
The yearly synthetic frequency of sand-moving wind was 64.62% (May 2016 to Apr 2017), 69.64% (May 2017 to Apr 2018), and the yearly synthetic direction of sand-moving wind was 207.58° (May 2016 to Apr 2017), 203.07° (May 2017 to Apr 2018), which indicated a SSW direction.

3.3. Sand drift potential

According to the monthly sand DP, RDP, RDD, and RDP/RD at the Jieqiong section of Lhasa–Shigatse railway (Figure 5, Table 1), the sand DP and RDP were high in spring and were low in winter. The RDD was at NE direction in winter and spring and at N and NNE directions in summer and autumn. The RDP/RD in summer and autumn was lower than that of the RDP/RD in winter and spring. These results suggested that the wind direction was dispersed in summer and autumn and was single in winter and spring.

The yearly sand DP at the Jieqiong section was 58.99 VU (May 2016 to Apr 2017), 96.73 VU (May 2017 to Apr 2018) (Table 3), which indicated a low wind energy environment (≤200 VU). The yearly RDP was 46.15 VU (May 2016 to Apr 2017), 78.69 VU (May 2017 to Apr 2018), and the yearly RDP/DP was 0.78 (May 2016 to Apr 2017), 0.81 (May 2017 to Apr 2018), which suggested an intermediate (0.3 to 0.8) and high (≥0.8) ratio. The yearly RDD was 38.31° (May 2016 to Apr 2017), 34.56° (May 2017 to Apr 2018), which indicated a NE direction.

3.4. Maximum possible sand transport quantity

According to the monthly variations of Q at the Jieqiong section of the Lhasa–Shigatse railway (Figure 6, Table 2), the Q and RQ were high in spring and
were low in winter. The RA was at the NE direction in winter and spring, and the RA was at the N and NNE directions in summer and autumn.

The yearly Q at the Jieqiong section was 146.69 kg·m⁻¹·a⁻¹ (May 2016 to Apr 2017), 244.49 kg·m⁻¹·a⁻¹ (May 2017 to Apr 2018) (Table 3), and the wind speed range with the maximum contribution was distributed at 7–8 m·s⁻¹ (May 2016 to Apr 2017), 8–9 m·s⁻¹ (May 2017 to Apr 2018), which accounted for 22.85% (May 2016 to Apr 2017), 22.84% (May 2017 to Apr 2018) of the yearly total (Table 4). The yearly RQ was 116.69 kg·m⁻¹·a⁻¹ (May 2016 to Apr 2017), 200.84 kg·m⁻¹·a⁻¹ (May 2017 to Apr 2018), and the yearly RA was 39.14° (May 2016 to Apr 2017), 35.27° (May 2017 to Apr 2018), which suggested a NE direction.

Table 3. Yearly sand DP and Q at the Jieqiong section of the Lhasa–Shigatse railway.

| Wind direction | May 2016 to Apr 2017 | May 2017 to Apr 2018 |
|----------------|----------------------|----------------------|
|                | DP (VU)              | Q (kg·m⁻¹·a⁻¹)       | DP (VU)              | Q (kg·m⁻¹·a⁻¹)       |
| N              | 0.24                 | 0.52                 | 0.15                 | 0.31                 |
| NNE            | 0.50                 | 1.10                 | 0.48                 | 0.97                 |
| NE             | 0.71                 | 1.45                 | 0.61                 | 1.26                 |
| ENE            | 0.68                 | 1.56                 | 0.46                 | 1.03                 |
| E              | 0.06                 | 0.12                 | 0.04                 | 0.09                 |
| ESE            | 0.08                 | 0.18                 | 0.02                 | 0.05                 |
| SE             | 1.29                 | 3.06                 | 1.74                 | 4.20                 |
| SSE            | 5.38                 | 12.78                | 10.94                | 27.15                |
| S              | 5.24                 | 12.42                | 11.86                | 28.75                |
| SSW            | 7.89                 | 19.52                | 11.85                | 29.56                |
| SW             | 12.44                | 46.93                | 33.27                | 85.73                |
| WSW            | 17.29                | 44.25                | 23.67                | 61.42                |
| W              | 0.60                 | 1.42                 | 0.65                 | 1.58                 |
| WNW            | 0.13                 | 0.32                 | 0.23                 | 0.56                 |
| NW             | 0.31                 | 0.72                 | 0.26                 | 0.61                 |
| NNW            | 0.16                 | 0.33                 | 0.50                 | 1.23                 |
| Total          | 58.99                | 146.69               | 96.73                | 244.49               |
4. Discussion

The annual precipitation at the Jieqiong section of the Lhasa–Shigatse Railway is 361 mm; this section is characterized by a semi-arid climate with high elevation and temperate zone. The period from June to September is the rainy season; the precipitation accounts for more than 90% of the yearly total, the air is humid (Figure 7), and the water content of the surface sand layer is high. Thus, the blown sand dynamic is weakened. The periods from October to May are the dry season; the precipitation is scarce, the air is dry (Figure 7), and the water content of the surface sand layer is low. Consequently, blown sand dynamic is aggravated because strong winds and dryness synchronously overlap. These results are consistent with the calculated results of sand DP and Q. The railway at the Jieqiong section moves toward the ENE–WSW direction approximately. Hence, the yearly synthetic direction of sand-moving wind was 207.58° (May 2016 to Apr 2017), 203.07° (May 2017 to Apr 2018), which indicated a SSW direction. The yearly RDD was 38.31° (May 2016 to Apr 2017), 34.56° (May 2017 to Apr 2018), which suggests a NE direction, and the yearly RA was 39.14° (May 2016 to Apr 2017), 35.27° (May 2017 to Apr 2018), which indicates a NE direction. Sand sources are located at the SW direction of the railway, and the angle between the railway trend and the sand transport direction is 5°–30°.

Table 4. Maximum possible sand transport quantity of wind speed from each range at the Jieqiong section of the Lhasa–Shigatse railway.

| Wind speed range (m·s⁻¹) | 5–6 | 6–7 | 7–8 | 8–9 | 9–10 | 10–11 | 11–12 | 12–13 | 13–14 | 14–15 | 15–16 |
|-------------------------|-----|-----|-----|-----|------|-------|-------|-------|-------|-------|-------|
| May 2016 to Apr 2017    | 3.15| 20.44| 33.52| 33.49| 26.86| 17.14| 7.95  | 3.19  | 0.97  | 0     | 0     |
| Q (kg·m⁻¹·a⁻¹)          |     |     |     |     |      |       |       |       |       |       |       |
| May 2017 to Apr 2018    | 3.63| 25.91| 48.16| 55.84| 44.39| 32.68| 20.81 | 9.66  | 2.44  | 0.62  | 0.36  |

Figure 6. Monthly variations in the maximum possible sand transport quantity at the Jieqiong section of the Lhasa–Shigatse railway.
The wind–sand flow transport is blocked by the emergence of the railway roadbed, thereby causing sand materials to accumulate near the railway and cause disasters. Referring to the wind tunnel experimental settings in the literature (Xie et al. 2020), the authors conducted a comparative experiment on the sand transport rate with and without the railway roadbed models. According to the measurement results of the wind tunnel experiment (Figure 8), the sand transport rates measured under the five experimental wind speeds (6, 9, 12, 15 and 18 m s\(^{-1}\)) without the railway roadbed are 5.76, 68.37, 215.80, 311.52, and 588.25 g cm\(^{-2}\) min\(^{-1}\), whereas those measured with the railway roadbed are 2.75, 58.59, 156.98, 358.92, and 488.53 g cm\(^{-2}\) min\(^{-1}\). Sand materials, which accounts for 10.42% of the total, were accumulated near the railway roadbed. Given that the sand sources were located at the SW direction and the supply of sand materials was adequate, which was consistent with the synthetic direction of the sand-moving wind, RDD, and RA. According to the relevant research results (Baddock et al. 2013; Li et al. 2018), the directions of sand source and prevailing wind were consistent, further aggravating the blown sand dynamic at the Jieqiong section.

Using “China strong dust storm sequence and its supporting data set” of China Meteorological Data Network (http://www.nmic.cn/site/index.html), the dust weather records of five observation stations along the Lhasa–Shigatse Railway were selected, the five stations are Lhasa (records started in January 1955), Konggar (records started in January 1991), Nyemo (records started in July 1973), Gyangzê (records started in November 1956), Shigatse (records started in December 1955) (Figure 1). Results show that the average annual frequency of dust weather at the five stations was 3.57, 0.29, 0.18, 6.52 and 5.96, respectively. The frequency of dust weather was high in winter and spring and was low in summer and autumn (Figure 9). Especially in spring, the dust weather overlaps with strong winds and dryness synchronously, which further aggravating the blown sand hazards of the Lhasa–Shigatse Railway.

Figure 7. Monthly variations in the relative humidity and average temperature at the Jieqiong section of Lhasa–Shigatse Railway.
5. Conclusions

The wind direction and the direction of yearly sand-moving wind at the Jieqiong section usually originate from the SW. The sand DP, RDP, Q, and RQ values are high in spring and low in winter. The RDD and RA are at the NE direction in winter and

![Figure 8. Sand transport rate measured in the wind tunnel experiment with and without the railway roadbed model.](image)

![Figure 9. Monthly variation of multi-year average of dust weather frequency at five stations along the Lhasa–Shigatse Railway.](image)

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spring and at the N and NNE directions in summer and autumn. The yearly sand DP is 58.99 VU (May 2016 to Apr 2017), 96.73 VU (May 2017 to Apr 2018), the yearly RDP is 46.15 VU (May 2016 to Apr 2017), 78.69 VU (May 2017 to Apr 2018), the yearly RDP/DP is 0.78 (May 2016 to Apr 2017), 0.81 (May 2017 to Apr 2018), and the yearly RDD is 38.31 °/C14 (May 2016 to Apr 2017), 34.56 °/C14 (May 2017 to Apr 2018), which indicates a NE direction. The yearly Q is 146.69 kg-m⁻¹·a⁻¹ (May 2016 to Apr 2017), 244.49 kg-m⁻¹·a⁻¹ (May 2017 to Apr 2018), the yearly RQ is 116.69 kg-m⁻¹·a⁻¹ (May 2016 to Apr 2017), 200.84 kg-m⁻¹·a⁻¹ (May 2017 to Apr 2018), and the yearly RA is 39.14° (May 2016 to Apr 2017), 35.27° (May 2017 to Apr 2018), which indicates a NE direction.

The trend at the Jieqiong section of the Lhasa–Shigatse railway and the sand transport direction present an angle of 5°–30°. During dry season, sand materials are blown up by wind, thereby forming wind-sand flow and movement to the NE direction; such flow and movement are blocked by the railway roadbed. Consequently, accumulation occurs and causes disasters. Moreover, strong wind and dryness are synchronous within a season. The directions of sand source and prevailing wind are consistent, further aggravating the blown sand dynamic of the section.

Disclosure statement

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