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Classification and regionalization of the forming environment of windblown sand disasters along the Tarim Desert Highway

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Through the systematic field survey and observations, the factor quantification as well as setting the criteria, the sand disaster-forming environment along the Tarim Desert Highway can be divided into four grades by the classification and regionalization based on fuzzy mathematics. The length of the regions with significant sand disaster accounted for 37.1% of the total highway length. Particularly, the area along the Tarim Desert Highway, based on the sand disaster-forming environment classification as well as the difference in the five basic landform units along the highway, combined with the difference of wind regime, can be divided into five regions, in which the length of the regions suffering severe sand damage occupied 64.3% of the total highway length. In addition, the index of disaster formation grade along the highway decreased from north to south, showing a repeated spatial pattern in small length scales.

Tarim Desert Highway, classification of forming environment of windblown sand disasters, regionalization

The Tarim Desert Highway runs north-south across the Taklimakan Desert, connecting the No. 314 National Road at its north end and the No. 315 National Road at its south end. It significantly shortens the travel distance across the desert, plays critical roles in facilitating the economic development in the southern part of the Xinjiang Uygur Autonomous Region and the large-scale exploitation of oil-gas resources in the Traim Basin, and in particular, it is one of the large source projects supporting West-East natural gas transmission project. Also it is important for strengthening the national defense as well as the stability of the Xinjiang Uygur Autonomous Region. The area along the desert highway is extremely arid and dry, with little precipitation and strong winds, leading to the intensive blown-sand activities and a great variety of sand dune types, very simple soil type, low vegetation coverage, and the mobile sand-dominated land surface in the area. Consequently, the windblown sand disaster is one of the most severe challenges to the Tarim Desert Highway. However, the formation of windblown sand disaster as well as its temporal evolution is very complicated, which is relative to various natural environmental and engineering factors. So the windblown sand disaster can be formed either suddenly or gradually. Therefore, the accurate prediction of the disaster occurrence is almost impossible. However, the

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natural environmental conditions as well as the highway's characteristics along the desert highway vary significantly[1−4], so it is possible to evaluate, classify, and regionalize the variation of aeolian environments along the highway. It is expected to provide significant insights to the prevention and control of the damages induced by windblown sand, and the understanding of the spatial variation of aeolian environments as well as the formation of windblown sand disaster.

1 Environmental characteristics along the Tarim Desert Highway

The Tarim Desert Highway, the longest highway across a drifting desert in the world, is located in the Tarim Basin, running north-south across the Taklimakan Desert from Luntai to Minfeng, whose desert section is 446 km long (Figure 1).

1.1 Wind regime

Most areas along the desert highway are dominated by strong northeast winds, except for the area around the south end of the highway, where the weak westerly winds are dominated. Based on the data analysis of the local weather stations along the highway, the annual average wind speed in its middle and north parts is 2.5 $m \cdot s^{-1}$, with wind activity intensity above 44000 and east-north-east (ENE), east (E), north-east (NE), and north-north-east (NNE) wind directions dominated, taking up about 60% of annual total wind activities. By contrast, in the south part of the highway, the annual average wind speed is 1.3 $m \cdot s^{-1}$ and the wind activity intensity is less than 2% of that in its middle and north part, and the dominated wind directions are west-south-west (WSW), west (W), and south-west (SW), accounting for 90% of the annual total wind activities[1,5].

1.2 Landform

The Tarim Desert Highway runs north-south in sequence through the areas with the landform of the complex transverse sand ridges, the dome-like dunes, the large complex longitudinal sand ridges, the complex longitudinal sand ridges, and the complex transverse sand ridges. Particularly, the area along the highway is dominated by the large complex ridges as well as the wide interdunes between sand ridges, where the dunes exhibited a great variety of shapes and very different sizes. The dune type includes the complex longitudinal ridges, the complex transverse ridges, the dome-like dunes, the dunes and the dune chains, the ridges, and the barchans. The height of the complex ridges as well as the secondary dunes on the top of complex ridges is 20—70 m and 3 m, respectively, while the height of the dunes located in interdunes is less than 3 m, and more than 60 % of the sand surface in the area is covered with mobile dunes[4,6].

1.3 Sand

Most areas along the Tarim Desert Highway are covered with mobile sands, mainly consisting of fine and very fine sand particles. There are plenty of sand sources, whereas in the area of coarse sand flat, silt soil, sparse

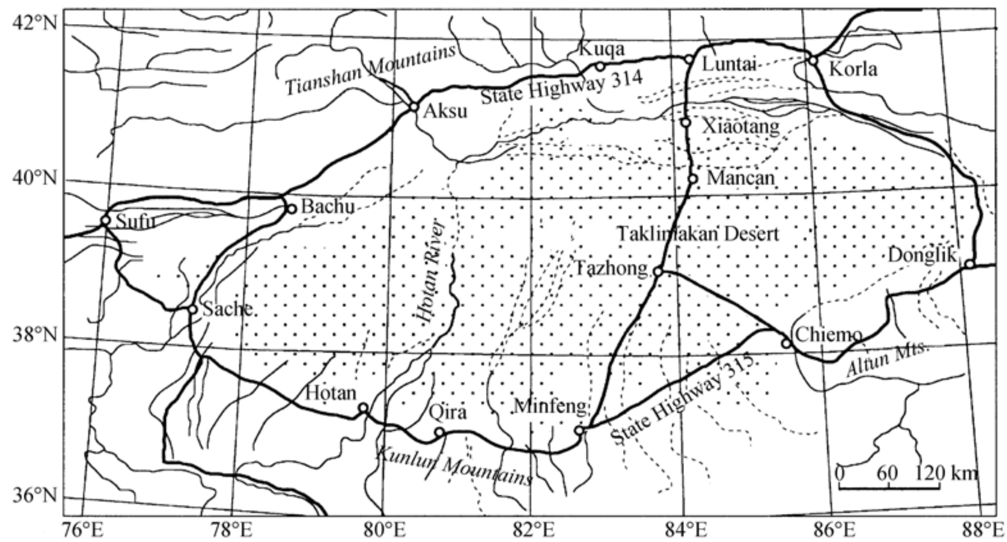

Figure 1 The geographic location of the Tarim Desert Highway.

dunes and sparse plant-growing sandy ground in inter-dunes, the sand source is relatively scarce[1,4,7].

2 Data acquisition

The survey was conducted along the Tarim Desert Highway, and the landform, dune distribution, relative height of terrains, vegetation type, vegetation coverage, and soil types were all recorded. A database has been set up based on these data.

3 Classification and evaluation of formation environment of windblown sand disaster

3.1 Quantification of environmental factors

The windblown sand disasters along the Tarim Desert Highway depend on wind speed and the sand availability, which are affected by landform, soil properties, and vegetation, as well as their interplays between the sands and winds[8,9].

(i) Wind-force intensity. Wind is the force and the first step of the formation of sand disasters[8,10,11]. The wind-force intensity can be calculated from the intensity index of effective wind in all directions and the included angle between the wind direction and the highway (eq. (1)). It is obvious that the larger the wind-force intensity and the angle, the stronger effects of the wind on the highway.

$$S = \sum \left(D_i \times |\sin(\alpha_i)| \right), \tag{1}$$

where S is the characteristic value of the wind-force intensity, D_i $(D_i = \sum (V_{ij} - 6.0)^3)$ is the intensity index of effective wind in the direction i, a_i is the included angle between the wind direction and the highway, V_{ij} is the wind velocity in which j is the direction of effective wind, while i is the times of sand-moving wind in one wind direction (the numbers from 1 to 16 represent the wind direction of N, NNE, NE,⋯, WNW, NW, NNW, respectively).

(ii) Effects of landform. Both the spatial size and shape of geomorphic units can affect the movement of the air flow near the ground surface, thereafter exert influences on windblown sand disasters[1,2,4,9,12]. The simultaneous measurements of the wind speed at 2 m above the ground surface, which were conducted at the different morphologic regions in the large complex longitudinal ridges, showed that the wind speed decreased in the order of the top of sand ridges, the transition morphologic regions between sand ridge and interdunes, and the corridors or interdunes between sand ridges. Moreover, both the spatial size and shape of dunes were found to affect the spatial distribution of wind speed near ground surface. Therefore, the landform factors were introduced to indicate the comprehensive effects of dune morphology on the windblown sand disasters, in which the dune height is the most important index, reflecting the relief as well as the development scale and migration speed of dunes[13]. Generally speaking, the lower the height of dunes, the faster their migration speed, and consequently, the more quickly the disaster is formed by them, but with a small hazard degree. By contrast, although the large-scale dunes migrate slowly, their hazard degree can be very high[14]. In this work, both the relative height of terrains and the height of secondary dunes on sand ridges were adopted as the indices to evaluate the landform effects. The landform factors can be classified into four levels (Table 1).

Table 1 The influencing intensity classification of the landform factors

Grades	Criteria for evaluation		Eigenvalue
	Relative height of terrain (m)	Height of secondary dunes (m)	
First	>30	>5	1.0
Second	20—30	3—5	0.8
Third	10—20	1—3	0.4
Fourth	<10	<1	0.4

(iii) Amount of available sand. The amount of available sand is one of important factors affecting the windblown sand movements as well as the aeolian landform, which is associated with the soil composition at the ground surface and the vegetation coverage and moisture distribution in soil[8]. The sands along the Tarim Desert Highway consist mainly of fine and very fine sand particles, and the ground surface is primarily covered with the drifting sands[15]. As a result, there are plenty of sands available. However, the vegetation and the soil moisture along the highway vary significantly, leading to the variation in sand mobility. Thus this paper applied the vegetation coverage, soil properties, height of dunes as well as their spatial distribution pattern to evaluating the amount of available sand (Table 2).

Table 2 The classification and index value of the level of the available sand amount

Grades	Criteria for evaluation	Eigenvalue
First	Large dunes and dune-chains with a density about 80%—100%, aeolian sandy soil, no vegetation	1.0
Second	Dense dunes and dune chains with medium density growing the *Calligonum* and *Tamarix* (dune density 60%—80%), sparse dunes and dune-chains without vegetation (dune density 40%—80%), mostly aeolian sandy soil	0.7
Third	Dunes and dune chains (silt soil, dune density less than 60%), sparse dunes and dune-chains with the *Calligonum* and *Tamarix* (dune density 20%—40%), flat sand surface without vegetation, some relict solonchak, semi-fixed aeolian sandy soil, and flat ground covered by coarse sand	0.4
Fourth	Silt soil with *Populus euphratica* Oliv, nabkha dunes of *Tamarix*, reed, flat sandy surface, and sparse dunes (dune density 20%—40%), some solonchak soil, meadow soil and takyr soil	0.1

3.2 Classification and evaluation model

(i) Basic idea. The formation environment of windblown sand disasters is a complex system consisting of multiple factors, and in particular, no clear and quantitative correlation has been identified among the factors yet. Therefore, based on the quantification of all factors as well as the essential idea of fuzzy mathematics, the quantitative evaluation and classification of the formation environment of windblown sand disasters can be achieved by means of the linear transformations[16]. Specifically, after dividing the highway into several sections based on their aeolian environmental characteristics, a fuzzy matrix can be constructed by incorporating the wind intensity, the landform factors, and the amount of available sands of each highway section as its elements and assigning a weight to each element. The formation environment of sand disasters can be evaluated and classified by calculating the hazard grade value of each highway section and comparing them with the given threshold value after standardization.

(ii) Model. Based on the idea of fuzzy mathematics[16,17], a state vector that characterized the environmental factors of disaster formation can be written as $v=v\{v_1, v_2, v_3\}$, in which v_1, v_2, and v_3 represent the wind intensity, the influence of landform, and the amount of available sands, respectively. Then, a 3×250 fuzzy matrix μ can be constructed by $\{\mu_{1j}, \mu_{2j}, \mu_{3j}\}$ ($j=1, 2, \cdots, 250$) in which j is the serial number of the highway sections and μ_{1j}, μ_{2j}, and μ_{3j} is the wind intensity, influence of landform, and the amount of available sands in the jth section of the highway, respectively.

$$\mu=\begin{bmatrix} \mu_{1\ 1} & \mu_{1\ 2} & \cdots & \mu_{1\ j} & \cdots & \mu_{1\ 250} \\ \mu_{2\ 1} & \mu_{2\ 2} & \cdots & \mu_{2\ j} & \cdots & \mu_{2\ 250} \\ \mu_{3\ 1} & \mu_{3\ 2} & \cdots & \mu_{3\ j} & \cdots & \mu_{3\ 250} \end{bmatrix},$$
$$j=1,\ 2,\ \cdots,\ 250. \quad (2)$$

In addition, because each factor contributes differently to the formation of windblown sand disasters, a weight has been assigned to each factor according to the field studies as well as the expert judgments (Table 3). Specifically, a weight vector $\omega=\{\omega_1,\ \omega_2,\ \omega_3\}$ was introduced in which ω_1, ω_2, and ω_3 represent the weight of factor 1, 2, and 3, respectively, and $\sum\omega_i=1$ ($i=1,\ 2,\ 3$).

Table 3 The weight value of each factor

Wind intensity	Influence of landform	Sand abundance
ω_1=0.3	ω_2=0.4	ω_3=0.3

Finally, the value of β was calculated by $\beta=\omega\mu$, i.e., $\beta_j=\sum_i \omega_i\mu_{ij}$ ($i=1, 2, 3; j=1, 2, \cdots 250$).

(iii) Results of evaluation and classification. The hazard characteristic value of all 250 highway sections were calculated and compared with the assigned threshold value after standardization to classify the disaster-forming environment of each section (Table 4).

Table 4 Classification standard of the sand disaster-forming environment along the highway

Grades	First	Second	Third	Fourth
Scores	>0.75	0.75—0.65	0.65—0.55	<0.55
Description	serious	very serious	moderate	mild

As shown in Table 4, among all 250 highway sections, 41 s belonged to the first grade disaster-forming environment, with a length of 45.6 km, accounting for 10.3% of the total desert highway length; 73 to the second grade, with a length of 118.2 km, occupying about 26.8% of the total desert highway length; 53 to the third grade; with a length of 76.8 km, making up about 17.4% of the total desert highway length; 83 to the fourth grade, with a length of 201.1 km, accounting for 45.5 % of the total desert highway length (Table 5).

Table 5 Classification results of sand disaster-forming environment along the highway

Grades	First	Second	Third	Fourth	Total
Number of road sections	41	73	53	83	250
Length of road sections (km)	45.6	118.2	76.8	201.1	441.7
Length proportion of each grade (%)	10.3	26.8	17.4	45.5	100

4 Regionalization of sand disaster-forming environment

4.1 Regionalization criteria and principles

The landform is believed to play the major role in the formation of windblown sand disasters, although both the vegetation and soil properties also have some effects on it, thus a comprehensive analysis is needed. Because of the engineering difficulties in constructing the sand-preventing systems, the regionalization of the disaster-forming environment should be as simple as possible, that is, the adjacent sections with a small difference in the disaster-forming environment should be merged into a larger section, whereas those with a large environment difference had to be assigned into the different sections. Therefore, based on the specific environmental characteristics along the Traim Desert Highway and the linear characteristics of the highway, as well as the requirements in sand-preventing practice, the following regionalization principles are adopted: (1) the comprehensive consideration of the primary and secondary factors; (2) similarity and difference; and (3) the ease in integrated control of windblown sand disaster.

Because of the regional combination difference in wind intensity as well as wind direction, the area along the desert highway exhibits five basic landform units. As a result, by considering differences in both the landform units and the wind conditions, the area along the highway can be divided into five regions in terms of the formation environment of windblown sand disasters: Region I was dominated by the compound transverse ridges in the alluvial plain of the Tarim River, with serious windblown sand disaster; Region II was located in the transition plain in the southern part of the Tarim River, dominated by dome-shaped complex dunes, with only slight sand disaster; Region III was the ridge-mound area in the middle of the Tarim Basin, dominated by the complex longitudinal ridges, with serious sand disaster; Region IV was the downstream delta area of the Yatongguz River, dominated by the complex longitudinal ridges, with an intermediate sand disaster; Region V consisted of both the downstream delta area of the Niya River and the area of North Minfeng Upheaval, dominated by the complex ridges, with only slight sand disaster. The detailed information of each region, including beginning and ending mileage along the highway and the characteristics of primary environmental factors are listed in Table 6.

4.2 Basic features of each region

The regionalization results are shown in Table 7. Specifically, the average hazard value of Region I was 0.643, in which the length of the first, the second, the third and the fourth grade highway section occupied 23.29%, 31.31%, 23.76%, and 21.55% of its total length, respectively. The average hazard value of Region II was 0.490, without the first grade highway section there, and the length of the fourth grade section accounted for 71.51% of its total length. However, the average hazard index value of Region III was 0.603, in which the length of the first, the second, the third and the fourth grade highway section made up 14.31%, 31.80%, 18.62%, and 32.58% of its total length, respectively, while the average hazard value of Region IV was 0.532, without the first grade highway section there, and the length of the second and the fourth grade section occupied 23.53% and 66.49% of its total length, respectively. Similarly, the average hazard value of Region V was 0.436, without the first grade highway section there, and the length of the fourth grade section made up 69.70% of its total length. In short, the overall length of sections that had serious, moderate, and slight sand disaster accounted for 64.34%, 12.70%, and 22.96% of the total highway length, respectively.

5 Spatial distribution of sand disaster-forming environment

The sand disaster-forming environment along the desert highway exhibited a certain spatial pattern as the result of the effects of landform and wind regime.

From the grade of the sand disaster-forming environment, the first grade sections mostly lay in the pass areas, sand ridges and transverse regions between sand ridges and interdunes with intensive windblown sand activities, large relative height (> 30 m), the large secondary dunes

Table 6 The regionalization of sand disaster-forming environment along the desert highway and the characteristics of primary factors

Areas of windblown sand disaster-forming environment	Beginning and ending mileage	Characteristics of primary factors concerning the windblown sand disaster-forming environment
I. Serious disaster area in compound transverse ridges in the alluvial plain of the Tarim River	K119+300—K173+600	strong wind, the compound transverse ridges, ridge 20—30 m high, widespread alluvial deposits in interdune areas
II. Slight disaster area in compound dome-shaped dunes in the transition plain in the southern part of the Tarim River	K173+600—K191+500	strong wind, compound dome-shaped dunes，dunes 30—40 m high, flat interdunes with high vegetation coverage
III. Serious disaster area in large compound longitudinal ridges in the middle of the Tarim Basin	K191+500—K391+700	strong wind, high compound longitudinal ridges, ridge 50—70 m high, wide and flat interdune areas
IV. Moderate disaster area in compound longitudinal ridges in the downstream delta area of the Yawtongguz River	K391+700—K477+500	weaker wind, compound longitudinal ridges，ridge 30—50 m high, wide interdune areas
V. Slight disaster area in compound ridges in the downstream delta area of the Niya River and the area of North Minfeng Upheaval	K477+500—K561+000	weak wind, compound ridges, ridges 30—40 m high, shallow groundwater table, high vegetation coverage

Table 7 The results of the regionalization along the Tarim Desert Highway

Regions	I	II	III	IV	V
Length (km)	54.3	17.9	54.3	56.1	83.5
First-grade section (%)	23.39	0	14.31	0	0
Second-grade section (%)	31.31	16.76	31.80	23.53	14.25
Third-grade section (%)	23.76	11.73	18.62	9.98	16.05
Fourth-grade section (%)	21.55	71.51	35.28	66.49	69.70
Average score of each grade	0.643	0.490	0.603	0.532	0.436
Integrated evaluation results	serious disaster	slight disaster	serious disaster	moderate disaster	slight disaster

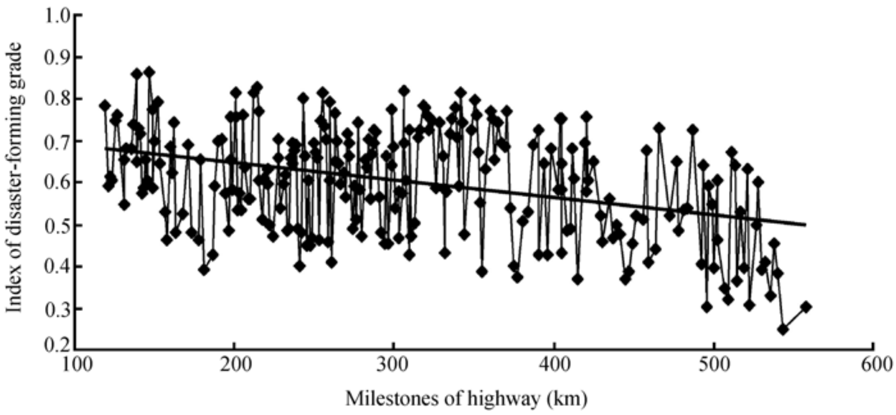

Figure 2 Sand disaster-forming grade along the Tarim Desert Highway.

densely overlaying on sand ridges (height > 5 m, density 100%), the deep road cuttings, the complicated road section, while the second grade sections were mostly located in the pass area and the transition regions with anrelative height about 20—30 m as well as the secondary dunes moderately densely overlaying on sand ridges (3—5 m high, relative density > 80%). The third grade sections were in the transition regions and ridges with a small relative height about 10—20 m and the moderate density secondary dunes (1—3 m high, density 60%—80%). However, the fourth grade sections were located in the lowlands between ridges, where the relative height of terrains was less than 10 m and the dunes were low (height <1 m) and distributed sparsely (density < 40%). In addition, the hazard value decreased from north to south, even though it showed a repeated spatial pattern in small length scales (Figure 2).

Moreover, as shown by the five regions of sand disaster-forming environment, the disaster possibility of the environment that was primarily affected by the wind intensity, the topographic relief and the underlying landform, decreased from north to south. Based on the calculation of the disaster possibility values in all five regions, except for Region II whose disaster possibility value was relatively small because a large portion of it lay in the wide flat land in interdune areas, the damage possibility value of Region I, III, IV, and V (distributed from north to south) decreased, i.e., the overall disaster-forming potential decreased from north to south (Figure 3).

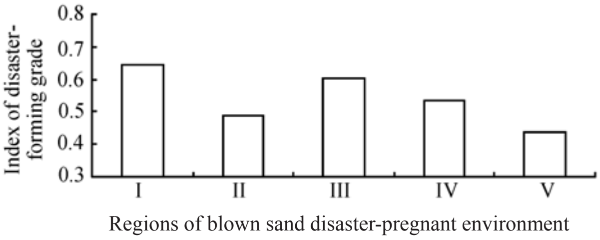

Figure 3 The spatial distribution of disaster possibility along the desert highway.

6 Conclusion

Through the quantification of the wind intensity, the landform effects, and the amount of available sands, as well as the model analysis and the proposed classification criteria, the sand disaster-forming environment along the Tarim Desert Highway has been classified into four grades. The length of the first and second grade sections, in which the windblown sand disaster was serious, occupied 10.3% and 26.8 % of the total highway length, respectively; that of the third and fourth grade sections accounted for 17.4% and 45.5% of the total highway length.

Based on the difference in the five basic landform units along the highway, together with the wind regime, the area along the Tarim Desert Highway can be divided into five regions in which the length of the regions showing the serious, moderate, and slight windblown sand disaster occupied 64.3%, 12.7%, and 23.0% of the total highway length, respectively.

In addition, the grade of disaster-forming environment along the desert highway, affected by the landform as well as the wind regime, decreased from north to south, showing a repeated spatial pattern in small length scales.

And there was significant difference in the disaster-forming environment that was characterized by the aeolian landform with a great variety of scales and shapes at different locations. The difference resulting from the wind activity on the underlying landform can thereafter be utilized to indicate the regional characteristics of disaster-forming environments. Particularly, the regional features of the disaster-forming environment can be represented by the landform difference, i.e., the difference in the dune size, shape, type as well as the spatial distribution of dunes. Therefore, the study on the classification and regionalization of disaster-forming environment is the prerequisite for revealing the formation process and spatial distribution of windblown sand disaster, also provides insights in the prevention of windblown sand disaster.

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