Controlling blown sand along the highway crossing the Taklimakan Desert

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Abstract

The Taklimakan Desert is the largest dunefield in China and the second largest shifting dunefield in the world. Control of the blown sand is important for the highway and oil bases there. Comprehensive studies suggest that the effective and feasible measures to control the blown sand include reed checkboard barriers, upright clustered reed fences, upright reed fences, upright nylon net fences, chemical and clay fixers and artificial vegetation. In practice, based on the type and extent of blown sand damages, various control measures are combined to form effective shelter systems. Reed checkboards and fences are the most widely used along the highway because reed is the most easily available material. Nylon net fences are also widely used in places where sand drift is weak to speed up engineering construction. Chemical and clay fixers are useful to consolidate the side slopes of the road but not to be extended on a large scale due to their prohibitive cost. Artificial vegetation, which has provided a pleasing environment, is practiced in Tazhong to control blown sand. Because of their strong dependence on water, vegetative measures can be only recommended in areas where the ground-water is easily available and of reasonably good quality. Fully taking advantage of the road cross-section can avoid the damages by blown sand.

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1. Introduction

Drifting sand and migrating dunes present a major threat to agriculture, forestry, roads, railways, and other communication and distribution systems in many parts of the world. The problems are particularly acute in desert regions where the ground surface is covered by dry loose sands, precipitation is rare, and vegetation is almost absent. Attempts to limit the damage caused by blowing sand have a long history. Such measures that include avoiding, removing, transporting, trenching, planting, paving, paneling, fencing, and oiling have been suggested (Kerr and Nigra, 1952; Cooke et al., 1982). The need for more effective measures of sand control has become more apparent in the past 50 years owing to economic growth and urban development related to exploitation of oil and gas resources in arid areas such as the Middle East (Cooke et al., 1982; Pye and Tsar, 1990) and central Asia. The techniques to control blown sand have been operated in four distinct natural and social circumstances: wind-erosion control on agricultural fields; the control of dust; the management of coastal dunes and dunes in semi-arid areas; and the control of sand dunes and drifting sand in deserts (Livingstone and Warren, 1996). The blown sand problems in Taklimakan Desert of China did not receive any attention until the latest decade when exploration and development of the petroleum reserves in the central desert created an urgent need to establish a blown sand control system.

Though it has been the resort of explorers for centuries (Hedin, 1896), the Taklimakan Desert has the reputation of the so-called Death Sea due to its prohibitive environments. Located in the Tarim Basin, the hinterland of Northwest China, with an area about 338,000 km², the Taklimakan Desert is the largest dunefield in China. With more than 80% of shifting dunes, it is also the second largest mobile dunefield in the world (Zhu, et al., 1980). After years of prospecting, the Taklimakan Desert is found to bear rich petroleum reserves and large-scale exploitation of the resources was initiated in the early 1990s. To facilitate successful development a highway crossing the desert was to be constructed. Among the primary concerns with respect to the highway construction is how to prevent the wind-blown sand from encroaching upon the highway. A state key research project ‘A Comprehensive Study on the Blown Sand Control along the Desert Highway’ was proposed in the eighth 5 year (1991–1995) plan of China.

The petroleum-transportation highway crossing the Taklimakan Desert that was started in 1991 and completed in 1995 has been successfully protected against wind-blown sand. The highway connecting the State Highway 314 at the northern end and joining the State Highway 315 at the southern end has a total length of 560 km, of which 447 km crosses shifting dunefield (Fig. 1). A comprehensive shelter system consisting of mechanical, vegetative and chemical measures has been established throughout the highway construction. In total, about 57 km² reed checkboard barrier, 234 km clustered reed fences and 434 km nylon net fences were established. The successful blown sand control practices that have ensured the highway’s normal function deserve to be extended in other areas.
2. Physiographic environment

Basically, the approaches to control wind-blown sand fall into five categories: (1) reducing or eliminating sand supply upwind; (2) preventing surface sand from entrainment and dunes from mobilization by interfering the interface between airflow and sandy surface; (3) diverting drifting sand from protected target; (4) enhancing sand transport capacity so that no settlement takes place nearby the protected object; and (5) reducing the wind erodibility of sand by cementing materials. However, the specific control measures to be taken are dependent on the local physiographic environment, material availability, required life expectancy of the shelter system and economic feasibility. Control of shifting dunes is an important aspect of applied aeolian geomorphology (Cooke et al., 1982; Livingstone and Warren, 1996). The theoretical considerations for blown sand control mainly include movement of aeolian sand, dynamics of wind erosion, and geomorphology of dunes (Kerr and Nigra, 1952). Climate and the rare vegetation along the highway are significant factors for blown sand control.

Reliable climatic information is essential to assessing the local blown sand activities whereby control measures are taken. The most important climatic factors influencing blown sand activities along the highway are the wind and precipitation determining the moisture content in the sand. However, little meteorological data were available in the central desert until the early 1990s when it was possible to set up meteorological stations in the inner desert. The general wind direction in the central desert used to be roughly constructed by alignment of the dunes (Zhu et al., 1980). Three meteorological towers were set up in Xiaotang, Mancan and Tazhong along...
the predetermined highway route in 1991 (Fig. 1). Climate in the Taklimakan Desert is hyper-arid, characterized by low precipitation and high evaporation. Observations from 1992 to 1998 show that the annual mean wind speed in Xiaotang, Mancan and Tazhong is 2.57, 2.41 and 2.16 m s\(^{-1}\), respectively, strong wind mainly occurs between April and August (Fig. 2). Precipitation decreases from edge to the center of desert, with the mean annual precipitation of 52.7, 36.6 and 34.6 mm in Xiaotang, Mancan and Tazhong, respectively (Fig. 3).

Drift potential (DP), which is a measure of the energy of surface wind in terms of sand movement, is assessed using the method proposed by Fryberger (1979). The shifting dunefield along the highway has low-energy wind environment. The annual drift potential ranges from 7.33 (53.90 VU) to 15.24 (112.06 VU), with an increasing trend from edge to the center (Figs. 4 and 5). The greatest drift potential is in spring and summer, accounting for 96%, 87% and 93% of the annual total in Xiaotang, Mancan and Tazhong, respectively (Fig. 4). The resultant drift direction (RDD), the net trend of sand drift, generally is towards the southwest, turning more and more to the west into the desert (Fig. 5). The resultant drift potential (RDP) expressing net sand transport potential and RDP/DP, an index of the directional variability of wind, were also calculated. Wind regimes along the highway are of acute bimode, as indicated by RDP/DP (Fig. 5).

Vegetation is another important factor in assessing the activity of blown sand and counter-measures to be taken. Although vegetation is rare and shifting sand covers over 90% of the surface along the highway, arbores, shrubs and perennial grasses constitute significant cover influencing blown sand activities in the abandoned river channels on the flooding plains of the Tarim River and the low interdunes where the ground-water-table is high. Field investigation (He, 1997) reveals that the arbores and shrubs along the highway mainly include *Populus euphratica*, *Tamarix ramosissima*, *T. hispid*, *T. laxa*, *T. leptostachys*, *T. taklamakanensis* and *Calligonum taklamakanensis* etc. The perennial grasses include *Glycyrrhiza inflata*, *Phragmites communis*, *Inula salsoloides*, *Cynanchum kashgeriscum*, *Poacynum hendersonni*,
Fig. 3. Monthly precipitation along the highway.

Fig. 4. Monthly sand drift potential along the highway (wind speed is in m s\(^{-1}\), the calculated drift potential equals 0.136VU used by Fryberger, 1979).

Fig. 5. Sand drift potential roses along the highway (wind speed is in m s\(^{-1}\), the calculated drift potential equals 0.136VU used by Fryberger, 1979).
Heliotropium micranthum, Cistanche tubuloasa, Hexinia polydichotoma, Helogeton arachnoideus (M.B.) C.A.Mey and H. glomeratus Mq. etc. These plant species that are adapted to the dry and salinized environment in the desert are valuable resources for controlling the blown sand control by vegetative measures.

3. Types of blown sand damage

Blown sand presents problems to the highway in different ways, depending on sand dune geomorphology, local wind regime, route direction and the disturbance created in highway construction. In general, blown sand can bring damage to the highway by deposition of its drift, encroachment of moving dunes, erosion of the roadside slope and avalanche of the slipfaces of large dunes in road-cutting areas.

The highway runs between 82.5°–84.5°E, and 37°–42°N, a little to the east of the mid-line of the Taklimakan Desert (Fig. 1). The northern 116 km is free from blown sand damage because it is on the contemporary flooding plains of the Tarim River, the surface is covered by well-cemented silt and clay deposits that are unsusceptible to wind erosion. Vegetation also provides effective shelter to the ground surface thanks to available ground-water. From K116 south the highway passes shifting dune area where blown sand problems are closely related to the dune geomorphology. The shifting dunefield can be divided into three aeolian geomorphological units: (1) old flooding plain of the Tarim River, characterized by transverse dunes and palaeo-river channels; (2) compound dome-shaped megadune area characterized by dome-shaped megadunes and salinized inter-megadune flats; and (3) complex longitudinal megadune area characterized by huge longitudinal megadunes and inter-megadune coarse-sand flats.

K116–K168 used to be the southern flooding plain of the Tarim River (Fig. 6). Old river channels 3–7 m deep are well preserved in most places. The most typical aeolian landforms are compound barchanoid chains aligned in NWW–SEE direction, 500–1000 m wide, 1000–3000 m long, 10–15 m above the interdune flats. Upwind (to the north) the barchanoid chains are wind-eroded blowouts. Downwind (to the south) the barchanoid chains are small dunes such as crescent dunes, dome dunes, embryonic crescent dunes and sand sheets. The small dunes less than 2 m high, advancing about 5–7.5 m annually (Dong et al., 2000) present the major problems.

K168–K183 is highly salinized fine sand flats dotted by compound dome-shaped megadunes (Fig. 7), which are elevated 30–50 m above the inter-megadune flats, 500–1000 m in diameter, superimposed by trellis dunes. Road-cutting through the megadunes disturbed their stability and caused sand avalanche. The inter-megadune flats are 1000–4000 m wide, where linear dunes less than 1 m high, less than 1000 m long and spaced 15–30 m are distributed. Salt dominated by NaCl forms 2–4 cm thick crusting, in some places the thickness can reach 15–20 cm. The ground-water-table ranges from 4 to 10 m. So the majority of the inter-megadune flats is protected by salt-resistant vegetation and wind-erosion-resistant crusting. The primary blown sand problem is the elongation of the linear dunes.
From K183 south the highway enters complex longitudinal megadune area. The complex dome-shaped megadunes are gradually connected to form NNE–SSW aligned complex longitudinal megadunes (Fig. 8). The megadunes are 50–80 m above
the inter-megadune flats, spaced 1000–3000 m, elongated many kilometers, and
mainly superimposed by compound barchanoid dunes and trellis dunes 15–20 m
high. Road-cuttings are inevitable when the highway passes the megadunes, making
the sand avalanche a striking problem. The inter-megadune flats are usually covered
by coarse sands 2–3 mm thick, approximately the diameter of the coarse sand. The
coarse surface sand layer is the wind lag deposit, which is stable and in equilibrium
with the local wind except disturbed. Fast moving small dunes such as crescent
dunes, dome dunes, linear dunes and sand sheets are developed on the inter-
 megadune flats, presenting problems to the highway.

4. Shelter system

4.1. Principles of blown sand control

Based on the type and extent of the blown sand damage principles for designing
the blown sand control system of the highway are:

(1) In the very active sand sections attempts are made to increase the surface
roughness to prevent blown sand drift from generating in the shelter system and
upright fences are set in the frontal edges to prevent sand drift from entering the
shelter system. (2) In the wind erosion sections, efforts are made to consolidate the
side slope of highway from being eroded. (3) In the fast moving small dune sections
dune-fixing measures are taken to prevent the mobile dunes from encroaching. (4) In
the coarse sand-covered or salt-crusted flat sections the stable surface nearby the

Fig. 8. Typical landscape of the complex longitudinal megadune area. (Aerial photo of 1992, central point
location: 83°45'E, 38°55’N. Linear dunes are formed between and compound barchanoid dunes
superimposed on the longitudinal megadunes.)
highway is protected from disturbance and side slopes of the highway are smoothed to transport the passing sand drift over. (5) In high road embankment sections over which wind is accelerated the side slopes are rounded, smoothed and consolidated to form cross-sections resistant to wind erosion but favorable for sand drift to pass. (6) Disturbance to the natural vegetation is avoided; (7) In the sections, nearby oil field where oil workers live vegetative measures are taken to control blown sand on one hand and provide pleasing environment on the other.

4.2. Blown sand control measures

4.2.1. Upright fences

The function of upright fences, which are set at the upwind frontal edges, is to block sand drift from entering shelter system, change the nearby airflow field, and prolong the shelter system’s time of efficacy. Fences have to be renewed every a few years because sand will accumulate immediately nearby once they are set. Three kinds of upright fences were employed: (1) Porous reed fences 1.1 m high and with porosity about 35% are used on small dunes where the sand drift is not very strong. (2) Close clustered reed fences 1.3 m high and with porosity less than 10% are used on large dunes where the sand drift is very strong. The reed clusters are 5–7 cm in diameter. (3) Porous nylon net fences 0.8 m high and with porosity about 60% are used in the interdune flats where sand drift is the weakest to speed up the construction work. All the three kinds of upright fences effectively checked the sand drift and changed the airflow field but the close clustered reed fences prove to be the most effective, as is evidenced by the field measured airflow fields around different upright fences (Fig. 9).

The upright reed fence and clustered reed fence usually have an affected fetch of 20–25 times the fence height. To save cost the 10–20 m wide belt behind fence was remained unprotected for sand to accumulate. The sand drift on the windward slope increases from the foot to crest. Upright fences are set on the windward slope, 1–2 m to the crest to check the stronger sand drift.

4.2.2. Reed checkboard barriers

The function of reed checkboard barrier is to increase the aerodynamic roughness of ground surface so that the wind speed exerted on sand particles is below the initiation threshold, whereby sand drift is checked and a shifting dune stabilized. Field measurements show that the aerodynamic roughness length can be increased 400–600 times by checkboards along the highway. Because of the easy availability of reeds, reed checkboards constitute the main body of the shelter system (Fig. 10). The advantage of reed checkboards over straw checkboards used in other areas of China lies in their longer time of efficacy. The 1 m × 1 m specification was chosen for the reed checkboard barrier considering the economic and construction feasibility and the fact that the aerodynamic roughness decreases almost linearly with an increase in the specification (Lin, 1980). The exposed height of checkboard is 10–15 m above the ground surface. Checkboard barrier is also used as the pioneer measure for vegetative methods because the fine sedimentation deposited within
checkboards is favorable for the germination of some ephemeral plant when precipitation occurs.

4.2.3. Chemical and clay fixers

The function of sand fixers is to cement sand surface to increase its resistance to wind erosion. The main chemical fixers include emulsified crude oil, emulsified asphalt, high-salinized water, L-P polymer. The easily available clay mixed by the local high-salinized water is another kind of sand fixer. Most of the chemical fixers prove to be effective but their cost is prohibitive, so they were primarily used to}

![](image)

Fig. 9. Field-measured airflow field around upright fences. (H is the height of the fences. The flow isolines are wind speeds in m s⁻¹, the sheltered distance of the nylon net fence is no more twice of the fence height, those of the upright porous net fence and close clustered reed fence exceed 12 times of the fence height. Reversed airflow area is formed behind both porous reed fence and close clustered reed fence, but that behind close clustered reed fence is much bigger.)

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consolidate side slopes of high road embankment to form round and smooth cross sections favorable for sand transport over.

4.2.4. Artificial vegetation

Permanent stabilization of mobile sand can often only be achieved effectively through the development of a vegetation cover. However, attempts at vegetative stabilization should consider the inter-relationships between the following habitat factors: character of substrate, thickness of sand deposit, degree and nature of salinization, water storage capacity, nutrients and structure of soil, quantity and quality of available water, etc. (Cooke et al., 1982). Along the highway the most outstanding limiting factor is water. The conditions favorable for vegetation along the highway include rich solar radiation and ground-water in some places. There are about 2800 sunshine hours a year and the annual vegetation-growing period can reach 2050 h, accounting for 74% of the total time. The depth of phreatic water is 120–150 m, and that of confined ground-water is 150–170 m in the interdune areas. In some low interdunes the ground-water-table is only 4–10 m. But the water quality is very poor for vegetation, with salinity of 4.3–4.8 g l\(^{-1}\). So the key to establishing artificial vegetation is to select proper plant species and develop techniques to irrigate using the high-salinized ground water.


Fig. 10. Typical reed checkboard barriers (K\(_1\)16–K\(_1\)20).
Wells are made to pump the ground-water for irrigation. Drip irrigation proves to be the most ideal management method because it saves water and results in less salt accumulation.

Large-scale extension of vegetative measures is difficult along the highway because irrigation by the high-salinized ground-water in the desert is a fund- and labor-consuming tasks. They are only practiced along the highway nearby oil bases in Tazhong where the oil workers live. Consequently, 6300 m of the highway is protected by artificial vegetation and the artificially vegetated area reaches 34 hm². Plant seedlings are fragile and easily damaged by blown sand at the beginning stage. The vegetative solution requires the use of a combination of mechanical, chemical and botanical methods at least until the vegetation has become firmly established. Usually, the blown sand is first stabilized by reed checkboards barriers within which vegetation is planted (Fig. 11).

4.3. Shelter system for different highway sections

In practices, the above-mentioned measures are combined together so that they benefit each other to form complete shelter systems that produce the optimum effect. The selection of the structure, composition and width of the shelter system is determined by the type, extent of the blown sand damage and required expectancy.
More emphasis is paid on the upwind (eastern) side than the downwind (western) side.

In the continuous shifting dune sections the area within shelter system is completely fixed, but the measures constituting the shelter system are dependent on the cross-section of the highway that determines the airflow field and thus influences blown sand damage. These sections have the most severe blown sand problems, so upright clustered reed fences usually are set at the frontal edge of the shelter system. In road-cutting sections the highway is in the wind wake area where sand settle down (Fig. 12), priority should be put on the fixation of the shifting dunes on both sides of the road so that less sand is transported to the road. The structure of the shelter system is: highway → checkboard-fixed side slope → checkboard barriers → sand accumulation belt → clustered reed fences. For high-embanked road over which airflow is accelerated (Fig. 13), efforts are made to check the sand transport further away and let the reduced sand transport over the road. Chemical fixer is used to consolidate the side slope on one hand and reduce the roughness on the other. The structure of shelter system is chemical-fixed side slope → checkboard barriers → sand accumulation belt → upright clustered reed fences. For flat road cross-section over which airflow has no change (Fig. 14), no special attention is needed for the side slope. The structure of shelter system is: highway → checkboard barriers → sand accumulation belt → upright clustered reed fences. The width of the shelter system for the continuous shifting dune sections is 110–130 m on the eastern (upwind) side and 70–90 m on the western (downwind) side.

In the isolated shifting dune sections where the blown sand problem is less severe than the continuous shifting dune sections, the main purpose of shelter system is to stabilize shifting dunes. The dunes are usually smaller. It is not necessary to set upright clustered reed fences at the frontal edge. The width of the shelter system is

![Wind direction diagram](image_url)

Fig. 12. Airflow field over road-cutting. (\(K_{117.2}\), the flow isolines are wind speeds in m s\(^{-1}\). A wake area favorable for sand deposition is formed at the leeward side of the dune. At the windward side wind is accelerated so that erosion will occur.)
reduced compared with the continuous shifting dune sections. The structure of shelter system is: highway→isolated checkboard barriers→sand accumulation belt→upright reed fences. The width at the eastern (upwind) side is 50–70 m and that at the western (downwind) side is 30–50 m.

In the coarse sand-covered sections where the blown sand problems are the least severe, the main purpose of shelter system is to check sand drift far from highway and keep the stable surface near the road bed so that the remained sand drift will be transported over the highway. Checkboard barriers set far from the road to check the passing blown sand drift farther away. To speed up construction, nylon net fences are set at the frontal edge of the shelter system. The structure of shelter system is highway→bare coarse sand belt (30–40 m)→checkboard barriers (15–20 m)→sand accumulation belt (10–15 m)→upright nylon fences.
In the salinized crusting sections the main purpose of shelter system is to keep a fixed smooth flat surface for sand drift to pass. The side slope is fixed by salinized clay and within the 60m wide belts on both sides of the highway obstacles are eliminated to create open space and the active sand patches are fixed by high-salinized water.

The structure of the vegetative shelter system in Tazhong section is: highway → checkboard-fixed side slope → vegetation in checkboards barriers (20–30 m) → sand accumulation belt (10–15 m) → upright reed fences. The upright reed fences are set at the frontal edge is to prevent the blown sand drift from encroaching upon the vegetation. The function of the checkboard barriers is to prevent the blown sand damage to the plant seedlings before they are firmly established.

5. Concluding remarks

Blown sand control practices along the highway crossing the Taklimakan Desert show that the blown sand problems in shifting dune field can be controlled. The highway has been free of blown sand devil for at least 8 years. Reed or straw checkboards are cheap, convenient and effective measures. Upright fences are effective in blocking sand drift to prolong the effective time of shelter system. Chemical fixers can be used in limited area mainly to increase the resistance of sandy surface to wind erosion. Artificial vegetative measures are recommended where ground-water is of reasonably good quality and easily available. To save cost the width and structure of shelter system should be determined by the type and extent of the local blown sand damage. Properly taking the advantage of road cross-sections can also avoid blown sand damages.

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