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Sand harm in Taklimakan Desert highway and sand control

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Reputed as a wonderful achievement of the world´s highway construction history, the Taklimakan Desert highway is now facing serious sand drift encroachment problems due to its 447- km-long passage of sand sea consisting of crescent dunes, barchan chains, compound transverse dune ridges and complex megadunes. To solve some technical problems in the protection of the highway from sand drift encroachment, desert experts have been conducting the theoretical and applied studies on sand movement laws; causes, severities and time-space differentiation of sand drift damages; and control ways including mechanical, chemical and biological measures. In this paper the authors give an overall summary on the research contents and recent progress in the control of sand drift damages in China and hold that the theoretical research results and practices in the prevention of sand drift encroachment on the cross-desert highway represent a breakthrough and has an epoch-making significance. Since the construction of protective forest along the cross-desert highway requires large amount of ground water, what will be its environmental consequence and whether it can effectively halt sand drift encroachment on the highway forever are the questions to be studied urgently.

Sand harm in Taklimakan Desert highway and sand control HAN Zhiwen, WANG Tao, SUN Qingwei, DONG Zhibao, WANG Xunming (Laboratory of Blown Sand Physics and Desert Environment, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China) Abstract: Key words: CLC number: 1 Introduction Located in the hinterland of central Asia, the Taklimakan Desert is famous for its extremely dry climate and the name of the world´s second largest active sand desert. Since the end of the 19th century desert scientists have done much work on the development of the desert´s aeolian sand landforms (Zhu et al., 1981; Zhu et al., 1988; Wu, 1987; Li et al., 1990; Zhou et al., 1996), its origin (Zhu et al., 1980; Wu, 1981), environmental changes (Li et al., 1993; Li et al., 1995), grain-size features, mineral composition (Zhu et al., 1981; Li et al., 1995), resources (Xia et al., 1993), flow field and sand activity features (Ling, 1988). They made a series of macroscopically qualitative elucidations and microscopically quantitative analyses on some multidisciplinary problems and achieved numerous important results. In order to speed up the prospecting and development of gas and oil resources in the Tarim Basin, a cross-desert highway was successfully built at the beginning of the 1990s. The highway starts from Lunan 35 km north of the Tarim River and extends southward to connect the No. 315 national road 15 km east of Minfeng, with a total length of 519 km (Figure 1a). The relief along the cross-desert highway is high in the south and low in the north, with relative height difference of 360 m. Surfacial materials along the highway mainly consist of fine sand with a mean grain size of 0.087 mm. The region has complex and diversified aeolian sand landforms, frequent duststorms and serious sand disasters; the climate is extremely dry, annual mean precipitation is less than 40 mm, with great variability; annual evaporation exceeds 3000 mm, or more than 70 times the annual precipitation; and annual mean temperature is 12-13oC. Natural vegetation in the hinterland of the desert is sparse, including 12 species under 12 genera in 9 families, and dominated by perennial herbs (account for 50%) (He, 1997). In order to avoid destructive damages of sand drift to the highway, an integrated protective system of stabilization-blockage type consisting of 1×1 m semiburied reed checkerboard barriers and porous upright fences were set up along the highway (Figure 1b). For scientific and rational construction of the protective system along the cross-desert highway, desert scientists in China have made a series of in-depth studies on sand movement processes; causes, distributions and severities of sand damages; as well as some technically difficult problems. This paper gives a review and summary on the progress made in recent ten years in the study of sand damage control along the cross-desert highway. 2 Main research contents and results 2.1 Dynamic processes of sand drift damage 2.1.1 Phy sical indicators of sand drift damage The degree of sand drift damage is related to the intensity of blowing sand activity, the stronger the blowing sand activity, the higher the damaging degree. Therefore, the intensity of blowing sand activity can reflect the degree of sand drift damages. With regard to the intensity of wind action some researchers use frictional wind as its measurement, but others have quite different views. This is because frictional wind velocity is obtained from the velocity determination rather than the force determination, and it is not a precise mechanical concept. In fact, frictional wind velocity itself is a concept obtained from fixed bed experiment. Although Bagnold (1941) put forward the mobile bed concept of frictional wind velocity and related it to the drag force of sand movement, the connotation of the drag force of sand movement is quite complex, containing sand surface drag, seepage pressure, resistance of grain shape and frictional resistance of grains etc. Therefore, the frictional wind velocity obtained from the wind velocity gradient determination is very difficult to characterize the physical quantity of wind action (Dong et al., 1997). Generally, mechanical determination is difficult in the field study of sand drift activity. One major concern for researchers is how large a wind velocity causes and to what degree does sand damage. Of various physical quantities used to express sand drift activity, researchers generally select the threshold wind velocity for sand movement and sand transport rate (g.cm-1 min-1) to describe the degree of sand drift damages, and define the severity of sand drift damage through establishing the function relation between sand transport rate (Q) and wind velocity (V). 2.1.2 The establishment of the threshold value of wind force responsible for sand drift damage-threshold wind velocity Air flow at the atmospheric boundary layer can exert a force on the surface materials, as wind velocity reaches a threshold value and sand particles gain enough momentum, some stationary particles begin to move, the wind velocity at which sand particles are set in motion is called the threshold velocity. The threshold velocity is a necessary critical condition for the occurrence of sand drift damages. Researchers have derived several theoretical formula to calculate the threshold wind velocity. However, due to the difference in boundary conditions used and different desert environmental conditions in different regions, the establishment of the threshold wind velocity at present is still based on the actual observations. In order to define the threshold wind velocity for sand movement in the Taklimakan Desert, the start-up wind velocity of naturally mixed sand (mean particle size d = 0.087 mm) along the cross-desert highway line was repeatedly measured (60 sets of fluid threshold velocity data, 45 sets of impact threshold velocity data) and its mean value was calculated. The results showed that the fluid threshold velocity at 2 m height for the naturally mixed sand was 6.0 ms-1 and the instantaneous impact threshold velocity was 4.8-5.3 ms-1, averaging 5.0 ms-1. Because the standard wind velocity at meteorological station was observed at 11.4 m height in 10 min interval and the threshold wind velocity for sand movement was measured at 2.0 m height, there exist a time interval and height difference between them. For this reason the wind velocity conversion relation at different time intervals and heights was established based on the statistical analysis of a large number of observation data (Table 1) (Dong et al., 1997; Chen et al., 1995). Calculated from this, the instantaneous fluid threshold velocity at 2 m height along the cross-desert highway was 6.0 ms-1, impact threshold velocity 5.0 ms-1, fluid threshold velocity in 1 min interval 5.2 ms-1, impact threshold velocity in 1 min interval 4.3 ms-1; while the instantaneous fluid threshold velocity at 11.4 m height was 7.8 ms-1, impact threshold velocity 6.63 ms-1, fluid threshold velocity and impact threshold velocity in 10 min interval were 7.4 ms-1 and 6.0 ms-1 respectively. 2.1.3 Relation between sand transport rate and wind velocity Sand transport rate, as a physical quantity to characterize the degree of sand drift damage, is a necessary basis for the rational formulation of sand drift control schemes. Owing to the complexity of field conditions, thus far there is still no theoretical formula to precisely calculate the sand transport rate in a specified region. Therefore, statistical analysis of field observation data is the only way used to define the relation between sand transport rate and wind velocity and further used to calculate the sand transport rates along the cross-desert highway line. From statistical analysis of observation data at a height of 0-20 cm, Dong et al. (1997) found that there is a power function relation between sand transport rate and 1 min mean wind velocity at 2 m height: Q = 0.07V2 - 1.29 (r = 0.83, 18 groups of samples). For direct use of automatically recorded 10 min mean wind velocity data at meteorological station in the calculation of sand transport rate, Wang Xunming et al. (1997) established the relation between 10 min mean wind velocity at the standard height of the meteorological station and sand transport rate using observed sand transport rates in 10 min interval and automatically recorded 10 min mean wind velocity (Table 2). From this the sand transport rate and its time-space distribution along the cross-desert highway were calculated. The intensity of blowing sand activity increased from the desert´s margin to its interior, with easterly wind as the sand-moving wind. Sand transport rate near the starting point of cross-desert highway in Xiaotang area varied between 3456.5-3615.4 t.km-1a-1, the corresponding value reached 5814.3 t.km-1a-1 in Mancan area and even reached 7000 t.km-1a-1 in Tazhong area of the desert´s hinterland. 2.2 Sand dune migration rate Getting a clear understanding of migration rate and directio n of sand dunes is of vital importance to the construction of sand drift control system along the cross-desert highway, including the selection of sand control measures, rational protection width and structure etc. For this reason, the sand dune migration rate was monitored in a 100×100 m plot to the south of Xiaotang (40o49′N, 84o17.7′E) in three phases during the period 1991-1993, and a 1:2,000 topographic map was drawn. From the monitoring we have drawn the following conclusions (Han et al., 1993; Dong et al., 1998). (1) Sand dune migration rate (annual migration amount D). In the first phase sand dune migration rate was 4.81-10.87 ma-1, averaging 7.29 ma-1; in the second phase it was 3.33-8.89 ma-1, averaging 5.56 ma-1. According to Zhu Zhenda et al. (1988) such a dune migration rate belongs to the moderate to rapid migration categories in the Taklimakan Desert. (2) Relation between sand dune feature and migration rate. It has been demonstrated that there is a linear relation between sand dune migration rate (D), dune height (H), dune base area (S) and dune volume (V): D = a - bH, D = a - bS, D = a + bV-c and D = a - bS - cv, this is also in agreement with the findings of Bagnold (1941) and the observational results of Zhu Zhenda et al. Zhu Zhenda pointed out that under different underlying surfacial conditions and in different densities of sand dune regions in the Taklimakan Desert, there is a negative linear correlation between dune migration rate and dune height. Monitoring results along the cross-desert highway also showed that there is a better correlation between sand dune migration rate, dune height, dune base area and dune volume. (3) Sand dune migration direction. In the first phase sand dunes were migrating in S23o-40oW direction, averaging S31oW; in the second phase sand dunes were migration in S26o-57oW direction, averaging S41oW, or further shifted westward than the first phase. (4) Sand dune morphological changes during migration processes. Scattered dwarf dunes or sand sheets tended to be concentrated; eastern horns of some barchans dunes became straight to a certain degree; small dunes tended to develop into typical barchan dunes with two symmetrical horns; eastern horns of some asymmetrical barchan dunes turned westward; some symmetrical barchan dunes turned into embryonic crescent dunes or even cake-like dunes. This provides an evidence for the inverted development of barchan dunes. 2.3 Sand drift damages to the cross-desert highway and their differentiation laws Starting with the factors leading to the sand drift damages, Wang Xueqin et al. (1999) studied the horizontal and vertical differentiation laws of sand drift damages along the cross-desert highway and found that the horizontal differentiation of sand drift damages resulted from the combined action of many factors such as wind force etc. under different aeolian sand landform settings; while the vertical differentiation of sand drift damages can be embodied by different topographic positions, it is realized through the differentiation of a number of factors such as landform, effective sand supply, highway section form and sand control system etc. The intensity of sand drift damage can be defined as follows: S = (bL)L (1) where i = 1, 2, ... n is the sand damaging section within a landform unit; bi is sand damaging degree at the corresponding section; and Li is the length of sand damaging section (km). Through calculation and comprehensive analysis, the cross-desert highway was divided into five major horizontal sections: in the compound transverse dune ridge zone on the Tarim River alluvial plain (K76-K131) the intensity of sand damage S=0.65, or serious sand damage section; in the complex dome dune zone on the ancient lake plain at the northern part of the Tarim Basin (K131-K147) S=0.50, or slight sand damage section; in the central complex longitudinal dune ridge zone (K147-K378) S=0.61, or serious sand damage section; in the complex longitudinal dune ridge zone in the delta of the lower Yatonggus River (K387-K431) S=0.55, or moderate sand damage section; in the complex longitudinal dune zone at Minfeng uplift in the delta of the lower Niya River (K431-K522) S=0.49, or slight sand damage section. The vertical differentiations of overlying sand dune types, topographic space scale and wind force lead to the vertical differentiation of sand damages. Studies on sand drift damages at different topographic positions showed that (Wang and Huang et al., 1998) sand damage in the huge complex longitudinal dune ridge zone varied with topographic positions, ridge tops and passes were characterized by serious wind erosion and deposition which posed a potential sand burial threat or even directly buried the road surface by dune slip slope, these are the most serious sand damaging positions along the cross-desert highway line. Sand damage in the inter-ridge lowland was dominated by sand burial and rapid migration of dwarf dunes on the road surface, this is another sand damage form to the highway and next only to the sand burial at ridge top in the severity. In addition, outside sand supply in the transitional zone between ridge top and inter-ridge lowland also posed a potential sand burial threat to the protective system of the cross-desert highway. 2.4 Construction techniques and mechanism of the protective system to combat sand drift damages 2.4.1 Wind tunnel simulation experiments on several mechanical sand control techniques and their mechanisms In order to seek some new techniques to prevent sand drift encroachment on the cross-desert highway, Han Zhiwen et al. (2000) conducted wind tunnel simulation experiments to test the sand control effects of three kinds of film-covered sand bag barriers, including dense type (β=10%) , porous type (β=20%) and ventilative type (β=40%) and three kinds of upright reed fences of 2.5×2.5 m, 5×5 m and 10×10 m (aerial height is 50-80 cm). From the observations of flow field and erosion-deposition regimes under the experimental wind velocities u∞ = 7.0, 1

0.0 and 15.0 ms-1, it has been found that there were several function zones present around the three kinds of film-covered sand bag barriers, including retarded circumfluence zone at the corner near the barrier; lift-accelerating zone downwind of the barrier; back flow zone behind the barrier; and near-surface low-velocity back flow zone. The wind velocity at the front edges of three kinds of upright fences, 2.5×2.5 m, 5×5 m and 10×10 m in size, gradually increased, the maximum value occurred over the first grid on the windward side, then gradually reduced due to retardation, and became stable at the distance of 15-20 m from the barrier. Furthermore sand deposited uniformly in the protected area. Different kinds of film-covered sand bag barriers, including dense type, porous type and ventilative type could be used to control different forms of sand damages and to protect different installations. The 5×5 m and 5×10 m upright fences were suitable to control large area of sand drift damages, under various experimental wind velocities sand deposition in the protected area was uniform. The 5×5 m upright fences were suitable to protect the road section in the area with multidirection wind and complex terrain. The 5×10 m upright fences were suitable to protect the road section in the area with flat terrain and single direction wind. The 10×10 m upright fences were suitable to protect the installations in the flat area suffering from slight sand damage. Qu Jianjun et al. (2001) conducted the wind tunnel experiments on the sand control effects of nylon net fences and found that nylon net fences have air permeability and ventilative function, with an optimal porosity of β= 40-45%, and can effectively control wind erosion to a distance of 30H or more. Their sand-blocking efficiency exceeds 70% under moderate wind velocity and exceeds 50% under very strong wind. In addition, nylon net fence has a certain sand-deflecting function, its critical angle is 45o, if the angle exceeds 45o, its sand-deflecting efficiency will be reduced. In view of the fact that sand dune migration manifests in the oscillation of dune crest line, several researchers conducted small-scale experiments on sand control techniques of dune crest using film-covered sand bag barriers (Lu, 1997). They thought that sand control of dune crest is an integrated technique of stabilization, blockage, transport and diversion, and can be used to protect the installations in reticulate dune fields and barchan chain areas, where dune crest oscillation is evident. 2.4.2 Chemical sand stabilization experiments To seek suitable chemical materials for the sand damage control along the cross-desert highway, Han Zhiwen et al. (2000) through a series of indoor and outdoor experiments selected four kinds of better erosion-resistant chemical stabilizers of LVA, LVP, WBS and STB. Experiments showed that LVA, LVP, WBS and STB have a particle size of 0.2-0.5 ?滋m; viscosity 12-15 pa.s and compressive strength 1.0-12.1 Mpa; no precipitation occurs under 10-70oC; incombustible; weight loss under low temperature of 10--20oC is 0-1.8%. Strength loss under ultraviolet lamp for 300h is 0-42%; under the experimental wind velocities u∞ = 5, 7, 10, 15, 20 and 25.3 ms-1, deflation rate varies between 0 and 4.0 gh-1.100cm-2. Spraying experiments in 1,200 m2 plot along the cross-desert highway showed that they can form a 0.2-0.5 cm binding crust, with better permeability. Their binding crusts have a higher strength and elasticity and can withstand man´s trampling. LVA, LVP, WBS and STB have proved to be suitable for sand damage control along the Taklimakan Desert highway. 2.4.3 Vegetal sand control experiments Biological sand stabilization is a permanent solution to sand damage problems. During the national 8th-Five Year Plan period some "pioneer experiments" on the construction of green lands were initiated in the hinterland of the Taklimakan Desert, some 51 plant species were successfully introduced using underground saline water, a number of solar energy vegetable sheds and psammophyte garden were set up. During the national 9th-Five Year Plan period, various biological sand control techniques were studied at some road sections suffering from serious sand damage and oilfield bases. As a result, about 20.3 ha of nursery seedlings were established and 700,000 shrubs were planted in the hinterland of the desert, in addition to greening system in oilfield bases and 3,100 m sandbreak forests along the cross-desert highway. In the meantime, the dynamical changes of soil, water and salts in the experimental plot were studied (Zhou et al., 2000) and the changes of blown soil physiochemical properties were monitored (Gu et al., 2000). The results showed that prolonged irrigation with 4.08 g.l-1 saline groundwater did not result in salt accumulation in large area of soils in the hinterland of the desert. Salt accumulation in local soil layer was attributed to poor drainability of clay soil layer. Water-salt movement mainly occurred as three forms, i.e., evaporation-salt deposition, leaching-desalinization and keep relatively stable. In the cultivated green fields soil clay content increased, but soil density and bulk density reduced; salt content in 50 cm surfacial soil layer decreased but nutrient content increased. Analytical results of trace elements showed that (Shan et al., 2001) available trace element content was higher in cultivated green field than in moving sand, except a few soil layers available Mo, Cu and Zn contents were less than 0.05 mg.kg-1; available Fe, Mn and B contents were lower than the critical values. Available trace element content was significantly higher in surface soil layer than in middle and lower soil layers, its content increased with the increasing vegetation age and was higher in grassland than in other sample plots. He Xingdong et al. studied soil salinization regimes under natural and irrigation conditions and soil salt dynamical changes caused by different irrigation methods (Duan et al., 2000). They pointed out that in the Taklimakan Desert region a better way to control salt damages is to irrigate fully and extend the irrigation cycle. From the experiments and studies described above, we have obtained various cultivation techniques of plants in the hinterland of the desert, such as planting shrubs in undulate dune field using saline water, raising seedlings with saline water, establishing protective forest in oilfield bases, and plant desert lawn etc. (Figure 2). Experiments also demonstrated that it is possible to cultivate sand-binding plants in the hinterland of the desert, we can in situ protect and introduce rare and endangered species or endemic species, and establish vegetation using local saline groundwater with a salinity of over 4 g.l-1. 2.5 Effect and rational width of protective forest system To understand the effect of the sand control system along the Taklimakan Desert highway from microscopic angle, a field survey and study were conducted on wind velocity profile and flow field structure within a certain range on both sides of the porous upright fence and the influences of the protective system on wind erosion and sand burial. The results showed that there were several characteristic zones with sudden velocity change present on both sides of the fence, further they varied greatly with the changes in the fence´s penetrating coefficient (?茁), it is the positions, scales and functions of these characteristic zones that decide the effects of the fences (Han et al., 1993). The upright fence installed on the top of complex longitudinal dune ridge caused several forms of sand damage: fence was buried by accumulated sand, advancing tongue-like dune buried the fence and base undermining rendered fence flattened. Burial width of semiburied fence differed greatly depending on landform type, dune position, direction of sand flow (dune) and sand damage severity. Sand burial rate generally varied between 3-10 m.a-1 (Wang et al., 1997). Sand accumulation rate gradually decreased from the front edge of 1×1 m fence to the interior of the fence. The sand burial rate of the fence mainly depends on the landform type in which the fence lies, dune position, effective starting wind speed, duration, intersection angle of the fence, and dune density etc (Wang and Chen et al., 1999). As a rule, the "stabilization-blockage type" protective system consisting of semiburied straw checkerboard barriers and porous upright fences has a better sand control effect. The design of the width of the sand control system is one of the engineering difficult points. Xu Junling (1982) and Feng Lianchang (1986) developed the theoretical model of the rational width of different protective systems. Considering various factors, Wang Xunming et al. (1997) developed the width model of sand control system along the Taklimakan Desert highway: W = Vsin?琢 + Qisin?琢?浊 + Lsin?琢(2) where W is protective width; V is mean migration rate of sand dike (dune); ?琢 is the intersection of (dune sand flow) migration direction and the highway line; Qi is annual sand transport rate (kg.m-1.a-1); ?琢i is the intersection angle of various-orientation sand transport rate and the highway line; Hi is in coming sand rate behind the upright fence; H is aerial height of semiburied barrier (newly erected barrier 0.18 m); hi is atmospheric dustfall, and annual height loss due to straw decaying is m; and L0 is wind-blown sand carried material deposition distance, normally 10-30 m are taken. It should be pointed out that these models are of trial exploration and have significant difference due to different footholds. At present, the rational width of sand control system is mainly defined from the qualitative judgement of protective requirement of installation and sand damage features. Accordingly, strengthening the study of rational width of sand control system along the highway and railway lines in desert regions as well as the development of models are an important subject facing desert researchers. 3 Conclusions (1) If we say the Taklimakan Desert highway is a wonderful achievement in the world´s highway construction history, the study on the aeolian sand movement laws, the causes, types, severities and time-space differentiations of sand drift damages in the hinterland of the desert, and the breakthrough made in the sand damage control using mechanical, chemical and biological measures will have an epoch-making significance. (2) The experimental and studied results on the biological sand control and the cultivation of vegetation with saline water are no doubt an encouraging advance. However, great care should be taken as we use these techniques in the construction of the "protective forest eco-engineering along the cross-desert highway". The Taklimakan Desert is located in the hyperarid region, annual precipitation is less than 30 mm, and groundwater resource is meager. According to calculation (Chen, 2001), even if drip irrigation technique is adopted, annual water requirement for irrigating one ha of trees amounts to 5,700 m3 or more. References

关键词： Taklimakan Desert; cross-desert highway; blown sand hazards; control technique