STATE-OF-THE-ART IN JAPAN ON CONTROLLING WIND-BLOWN SAND ON BEACHES

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In order to prepare general guidelines for controlling the wind-blown sand in the region from the shoreline to the landward end of the dry beach, a literature review was carried out focusing on Japanese experiences. The review showed that controlling wind-blown sand on a beach surface can be done by using a suitable combination and arrangement of sand fences and trenches

Keywords: wind-blown sand; controlling devices; beach surface; sand fence: trench

INTRODUCTION

Many economically important areas, often protected by limited fencing works, are located adjacent to sandy beaches and the intrusion of wind-blown sand causes significant problems in these areas (for example, Sato at al. 1999). Also, on nourished beaches wind frequently transports the sand away from the dry beach, advancing the need for re-nourishment (for example, Uda and Ishikawa 2005). In such areas, in order to prevent sand transport by wind from the beach leading to erosion and subsequent deposition in unwanted areas, it might be necessary to control the wind-blown sand in the region from the shoreline to the landward end of the dry beach. At present, no appropriate guidelines or criteria taking into account engineering aspects exist for controlling wind-blown sand on a beach surface. In order to fill this gap of knowledge and to prepare general guidelines, a comprehensive literature review was carried out focusing on Japanese experiences. Based on this review, the authors concluded that controlling wind-blown sand on a beach surface can be done by using a suitable combination and arrangement of sand fences, which are commonly used at present, and trenches, which have newly been proposed and come into practice in Japan. The objectives of this paper are to report on the main findings of the review and to provide recommendations on the optimum combination and arrangement of sand fences and trenches to manage wind-blown sand on beaches.

REVIEW RESULTS

Devices that have been effectively implemented to control wind-blown sand on beaches are sand fences, small artificial embankments, and trenches. The following cases from Japan constitute selected examples where these devices were successfully employed for managing wind-blown sand transport.

Sand Fences and Stockades

The most commonly employed structure to control wind-blown sand on beaches is the sand fence. Before 1950, many wide, non-vegetated, un-developed beaches with a width of more than 200 m existed in Japan. With the purpose of stabilizing beaches and utilizing them for land cultivation extensive afforestation works were carried out at over 100 beaches between 1850 and 1950 (Japan Forestry Association 1934, Hara 1960, Tanaka 1990). Trial-and-error approaches were employed to design fencing works, implying that these works progressively developed and adapted to local conditions. Documents describing the experiences from the design process provide information of great value to present-day applications. In the following are selected, typical examples presented.

For construction of foredunes at a designed location on a wide exposed beach the method of repeated placement of sand fences on a small dune formed by buried old sand fences was commonly used. In order to protect the foredune under construction, Togashi (1937) tried to create a low dune using a sand fence at a location in front of the foredune where the run-up waves would reach during ordinary storm conditions. The wind blew normal to the shoreline. The sand fence installed functioned as a trapping device for blown sand until the fence was buried and a small dune around 1.0 m high was formed. The low dune formed stored a certain volume of sand and it protected the foredune under construction from the high run-up waves during exceptional storms. The dune became a source for sand drift and played the role as a sacrificial dune. The authors tentatively denoted this dune as a run-up control dune due to its main functioning. The run-up control dunes have often been applied in creating foredunes around 10 m high along the coast of Aomori, Akita, and Yamagata Prefectures,

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which are located in the northern part of Honshu Island facing the Japan Sea. A conceptual illustration of the run-up control dune is shown in Fig. 1 together with other controlling devices such as the stockade, the low wide-crested dune, and the beach earthworks, which will be reviewed and discussed later. Formation of the same characteristic low dunes can be found in the USA. Photo 1 shows an example from Atlantic City, New Jersey.

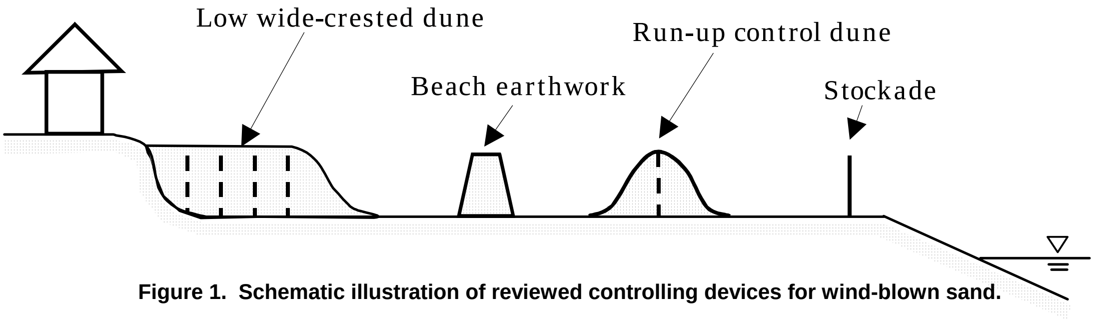


Figure 1. Schematic illustration of reviewed controlling devices for wind-blown sand.

Photo 1. A low dune formed on the beach surface at Atlantic City.

Yoneshiro-Seibu Forestry Office (2001) reported a unique type of works for protecting foredunes. Photo 2 shows a stockade installed at the berm crest that is employed to protect foredunes from wave attack. The stockade functions in a similar manner to the run-up control dune, although it is installed closer to the shoreline than the run-up control dune. The ability it has to decrease the generation of wind-blown sand at the downwind side can be utilized for controlling blown sand

Photo 2. Stockade to protect foredune from wave attack.
(Copied from photo No. 59, Yonesiro-Seibu 2001)

Freestone and Nordstrom (2001) reported on useful multi-row fencing works for a nourished beach. Two rows of sand-trapping fences 5 m apart were first placed at the landward end of a nourished beach (backbeach). Subsequently, two rows of fences were buried and a low dune was formed. Fences were then placed on the seaward side of the dune to encourage horizontal rather than upward growth in order to retain views of the sea for residents(Weggel 2004). The landward side of the dune was fixed in its position using a sand fence so the residential areas were not inundated by blown sand. This example implies that we can prevent intruding blown sand and retain sand at beach when the blown sand on the seaward side of the formed dune can be adequately treated. Hereafter the dune formed as described above is referred to as a "the low wide-crested dune" (See Fig. 1).

Fence Arrangement

Kawate (1940) employed a complex plan fence arrangement consisting of two rows of main fences placed parallel to the shoreline and auxiliary wing fences arranged normal to the predominant wind direction at a beach where a moderately strong wind blew obliquely. The arrangement successfully functioned to construct a foredune and to provide afforestation behind the foredune by using auxiliary covering works by straw. Photo 3 displays a part of the fencing work carried out from 1930 to 1940 on the beach, and Figure 2 a plan view of the fence placement (showing the posts) for obliquely incident wind.

Photo 3. A view of the fencing works.
(Copied from a post card issued by the Tokyo Forestry Bureau)

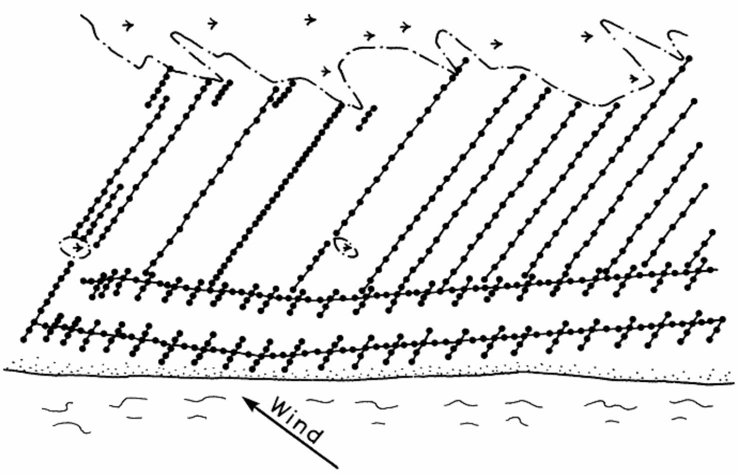


Figure 2. A plan view of the fence placement (showing the posts).
(Partially redrawn and modified from Fig. 22, Kawata 1940)

A specific arrangement of sand fences to be used in the formation of foredunes for controlling wind-blown sand was carried out in the eastern part of the Enshunada Coast more than 150 years ago. This method is based on the idea of “making the wind-blown sand flow turn aside”. Figure 3 demonstrates the idea of the oblique foredunes employed, where α is the azimuth of the shoreline. When the wind blows from the west, the wind-blown sand generated on the beach surface sweeps into the sea if α is smaller than 90 degrees, and the blown sand is transported towards the inland if α is greater than 90 degrees. In the case α is greater than 90 degrees, the obstacle forces the wind-blown sand flow to turn aside in the downward direction (to the sea) and the flow of blown sand sweeps into the sea, if the obstacle shown as a foredune in Fig. 3 is positioned obliquely to the normal of the wind direction on the beach surface. The predominant wind direction on the Enshunada Coast is west in the winter and the azimuth of the shoreline on the eastern part of the Enshunada Coast ranges between 90 and 135 degrees. By using repeated placement of sand fences foredunes with heights of 5-10 m successfully formed in the direction of the dune crest from 120 to 135 degrees in azimuth and the foredunes functioned well (Shizuoka Pref. 2001). It is often observed on natural beaches that the blown sand runs down on and along the dune slope when dunes with relatively steep slopes are positioned obliquely to the wind direction. This method to make the blown sand direction change can be effectively used for controlling blown sand on beach surfaces, if the blown sand transported on the slope surface at the downwind end can be properly guided.

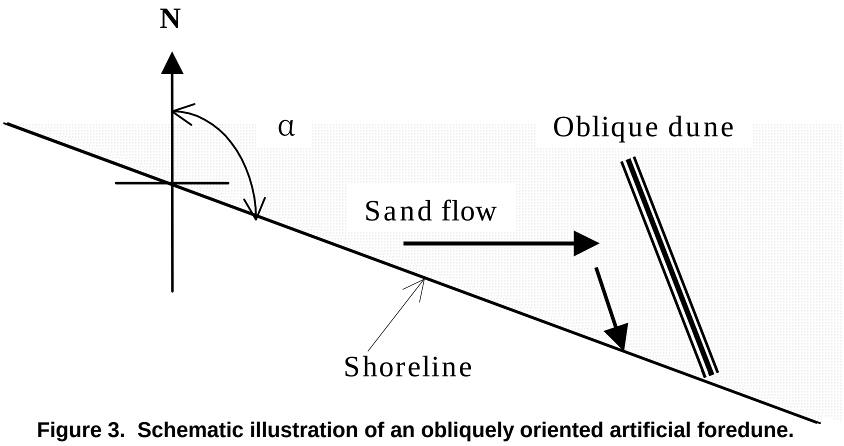


Figure 3. Schematic illustration of an obliquely oriented artificial foredune.

Photo 4 shows a fencing work at the Shonan beach where the wind blows normal to the shore. Four rows of sand fences are installed on the landside covering about half of beach width, resulting in a decrease of the region where the blown sand is generated. The first row facing the sea is fully buried and the trapping ability has been lost. The remaining three rows are not buried and are still functioning for sand trapping. In order to maintain the trapping function of the fence, it is required that the trapped sand is periodically removed

Photo 4. Working sand fences on the beach surface at Shonan Beach.

Niigata Port and Airport Office have carried out a series of field experiments for controlling wind-blown sand on a nourished beach on the Niigata-West Coast facing Japan Sea, where a strong wind blows from the WNW in the winter. Several patterns of fence arrangements have been tested during more than ten years. The arrangement concluded to be the most effective is to have two rows of fences along the shore with isolated wing fences placed normal to the predominant wind direction, as shown in Fig. 4 (Tanaka et al. 2007). Photo 5 shows the fences viewed on the crest of the dune, indicating that the fences have trapped all the blown sand. However, it was observed that a small amount of sand was transported to the landside beyond the two rows of fences in suspension during strong winds. Ugi et al.(2005) reported that sand fences placed on the beach surface induced a local disturbance around the fences that ejected blowing sand grains to high elevations of about 10 m. This phenomenon can explain the fact that sand was transported beyond the two rows of fences (to be further discussed later in the paper).

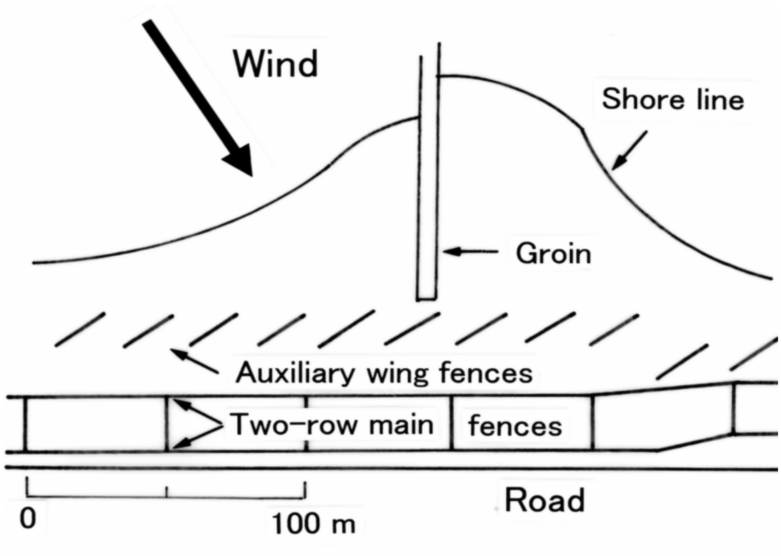


Figure 4. Plan view of fence arrangement in Niigata West Coast.
(Partially redrawn and modified from Fig. 5 in Tanaka et al. 2007)

Photo 5. A rear view of the fence arrangement.
(Courtesy of the Niigata Port and Airport Office)

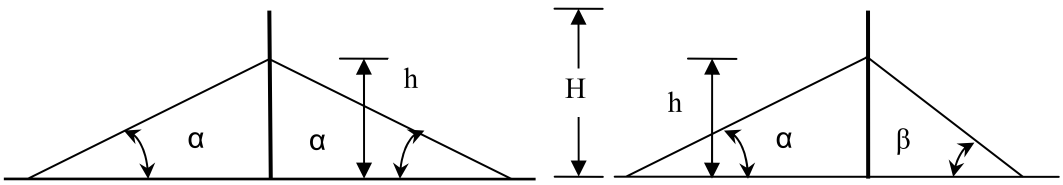
Small Artificial Embankments

On beaches in the Hokkaido Island small embankments have often been used where sand is piled up at the site to a height of about 1 m, having a crown width of 0.5 m (Higashi 1975). Hereafter, such embankments will be denoted as the beach earthwork for convenience. Beach earthworks were successively employed at the early stage of afforestation works to protect seedlings from the wind and the wind-blown sand. The coast of Hokkaido in winter is windy, snowy, and cold, and frequent snow and frozen ground surfaces decreases the generation of wind-blown sand. On beaches with considerable amounts of wind-blown sand, the employment of the beach earthworks for afforestation purposes will be limited use. The beach earthworks can be considered to act as a non-permeable fence. Thus, the beach earthworks may be utilized instead of solid fences on ordinary beaches.

From the above review of the selected examples, a brief summary may be given as follows. Using different protective measures, such as the run-up control dune, the stockade, the low wide-crested dune, the oblique dune, and beach earthworks, wind-blown sand can be controlled in the region from the shoreline to the landward end of the beach. However, in order to maintain proper functioning of these measures, their trapping ability must be ensured, which implies the need for management and implementation of a suitable plan arrangement of multi-row sand fences and wing fences that increases the capacity for trapping sand and decreases the areas where blown sand is generated.

Accumulation Around Sand Fences And Their Burial Time

In managing sand fences an important matter is to know the time elapsed until the fence will be buried. Kawata (1949, 1951) offered a simple model to predict the time period, T, required to bury a fence with the fence height, H.



(a) Isosceles triangular form. **(b) Triangular form.**

Figure 5. Schematic diagram of assumed model dune forms.

Kawata assumed that a dune formed around a fence has the shape of an isosceles triangle, as shown in Fig. 4(a), and that the dune grows while keeping the same shape. When the dune grows from h to $h + dh$ within a small time period, dt, the sand mass increase per unit length along the dune crest, dM, is given by Eq. (1),

$$dM = d\{ \rho\, h^2 \cot \alpha \} = 2\, \rho\, h \cot \alpha\, dh = q\, dt \qquad (1)$$

where ρ is the apparent density of the sand and q is the sand transport rate. Then, dt is:

$$dt = \{ (2\, \rho\, h \cot \alpha) /q \}\, dh \qquad (2)$$

The time elapsed, T, during which the dune grows from the level 0 to the height of fence, H, is given by Eq. (3), obtained by integrating Eq. (2) and substituting boundary conditions with the upper limit as H and the lower limit as 0:

$$T = (\rho\, H^2 \cot \alpha)/ q \qquad (3)$$

The unit of time will be decided from the unit of the transport rate. Thus, the unit of time will be hour if we use the unit time of hour for the transport rate (kg/hr). Wind tunnel and field studies have shown that the trapping efficiency of sand fences depends on the fence porosity and wind speed and that the trapping efficiency decreases with an increase in the dune height (Hotta et al. 1987, 1991). To take this into account, an empirical coefficient, E, smaller than 1.0 was introduced,

$$q' = E\, q \tag{4}$$

where q' is the adjusted transport rate. When we substitute Eq. (4) instead of q into Eq. (3), $T' = T / E$. Kawata(1949) gave a numerical model to estimate the value of E, but preferably it should be determined by field or wind tunnel studies.

Other authors have modified the model for certain conditions. Sand mainly, and rapidly, accumulate in front of the fence for fence porosities less than about 30 %, and the leeside slope angle of the formed dune become approximately the angle of repose for sand, β (see Fig. 4(b), Hotta et al. 1987, 1991). When considering this fact, Eqs. (1), (2), and (3) will be replaced by Eqs. (5), (6), and (7), yielding:

$$dM = d\{ \rho\, h^2 \,(\cot \alpha + \cot \beta) \} = \rho\, h\, (\cot \alpha + \cot \beta)\, dh = q\, dt \tag{5}$$

$$dt = \{ \rho\, h\, (\cot \alpha + \cot \beta) / q \}\, dh \tag{6}$$

$$T = \{ \rho\, H^2 \,(\cot \alpha + \cot \beta) \} / 2\, q \tag{7}$$

Field studies have given α = 7 - 8 degrees and the angle of repose for beach sand ranges from 30 – 35 degrees. The density ρ varies from about 1300 kg/m^3 – 1600 kg/m^3. Now we can calculate T for a given height of the fence, or conversely, H for a given sand volume to be accumulated when a time series of the wind data is available.

Trenches

The sand-trapping trench as a countermeasure against wind-blown sand has been come into practice in Japan. The idea to employ a trench for controlling the wind-blown sand stems from the results of several previous studies (Hotta and Horikawa 1996, Hotta et al. 1998). Horikawa et al. (1984) tried to measure the transport rate on a natural beach using trenches that were 1m deep and 5-8 m wide. The blown sand that fell into the trench was deposited at the upstream slope of the trenches with the deposition progressing in the downstream direction while maintaining the same level with respect to the beach surface and composing a slope angle around the rest angle of dry sand, resembling roughly a parallelogram shape. This characteristic deposition form in the trenches can be explained from the fact that a portion of the blown sand moves with the surface creep motion, the flying distance of sand grains in saltation motion occupying more than 80 % of the total blown sand is rather short, and little amount of blown sand moves in suspension. Based on observations at the site and the results of data analysis Horikawa et al. (1984) concluded that no significant amount of sand was transported beyond the trench and that the trench could trap almost 100 % of the blown sand.

In a series of field experiments for controlling wind-blown sand carried out by the Niigata Port and Airport Office, a 1 m deep and 6 m wide trench was applied twice for measuring the transport rate together with a horizontal total-quantity type trap (Funakoshi et al. 1993, Shiozawa et al. 1993). The trench could trap moving sand effectively and the deposition configuration in the trench was almost the same as described before but a little more complex because of varying wind directions.

In the winter of 2007, a trench used as a controlling device was dug at a beach on the Niigata West Coast (Shimizu et al. 2008). The trench trapped the wind-blown sand and no significant blown sand was transported beyond the trench during a period of 18 days. Twenty-four days after the trench was dug, when it was half full of sand, exceptional high waves attacked the beach and the trench was completely filled in. However, the sand that buried the trench was eroded from the beach area landward of the trench, implying that the trench did not have an overall negative influence on the beach erosion. Photo 6 illustrates the trench after it was dug (a), after 18 days of infilling (b), and after 24 days of infilling (c)

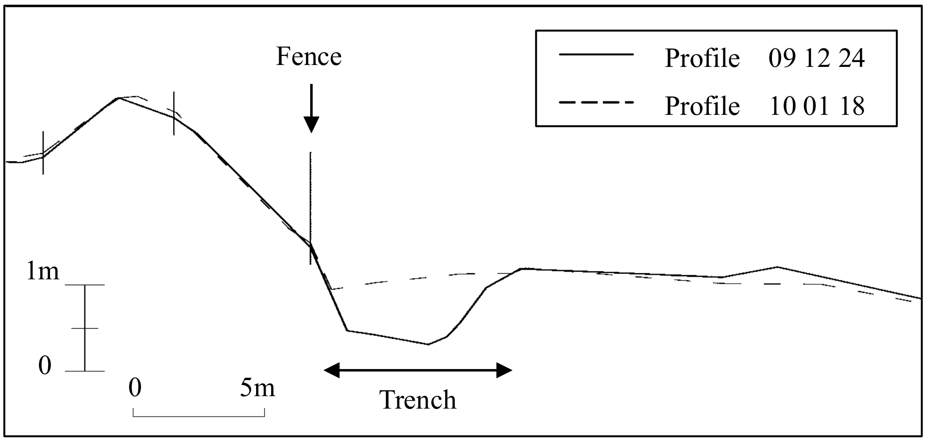
(a) After dug.

(b) After 18 days of infilling.

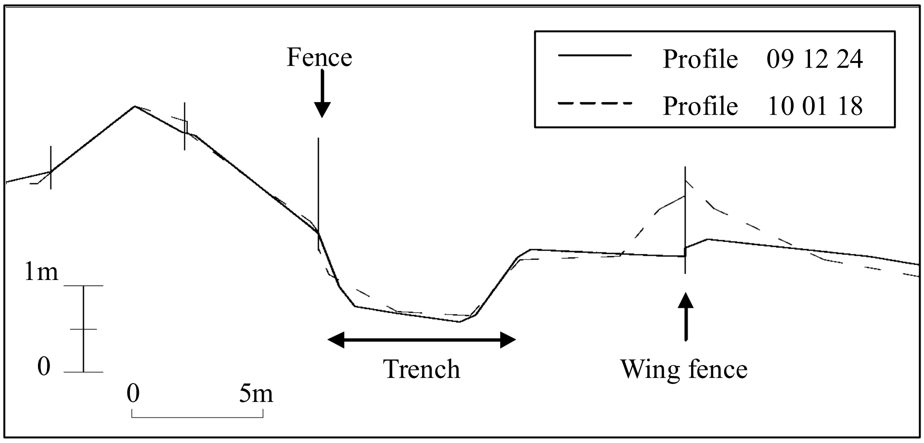
(c) After 24 days of infilling.

Photo 6. Trench at Niigata Coast in the winter of 2007.
(Courtesy of the Niigata Port and Airport Office)

In the winter of 2009 the Niigata Port and Airport Office (2009) carried out a field experiment to evaluate the effectiveness of trench and wing fences. Two different configurations, pattern I with a trench only and pattern II with a trench and wing fences were investigated. Trenches with the dimensions 1 m deep, 5 m wide, and 50 m long were dug in front of a low embankment vegetated by beach grass. For pattern II, the wing fences were placed in front of the trench, about 5 m in the seaward direction. Figure 6 shows the arrangement of the trench and the wing fences, the beach profile, and the measured profile change. The trenches were dug about 1.0 m deep, employing a reversed trapezoidal shape with side slopes of about 35 degree, which was nearly equal to the repose angle of dry sand, in order to keep strollers on the beach safe. The figure shows that the wing fences trapped blown sand well and that the trench behind the wing fences was not buried, keeping its trapping ability. In comparison, for pattern I with a trench only, the trench was almost buried.



(a) Pattern I with trench only.



(b) Pattern II with trench and wing fences.

Figure 6. Arrangement of trench and wing fences in the field.
(Drawn from original tabulated data in Niigata Port and Airport Office 2010)

Trenches were dug on December 24th, 2009. Photo 7(a) shows the trench of pattern I on January 23rd, 2010, when the trench was completely filled-in. Photo 7(b) shows the trench of pattern I on January 26th, 2010. The sand trapped was removed and the original shape of the trench was recovered. Photo 7 (c) shows the trench of pattern II on January 26th, 2010, when 33 days had passed since the trench was dug. The trench was not completely filled at that time.

(a) The trench of pattern I after being filled-in completely.

(b) The trench of pattern I after removal of the trapped sand.

(c) Infilling of the trench of pattern II after a period of 33 days.

Photo 7. Trenches at Niigata Coast in the winter of 2009.
(Courtesy of the Niigata Port and Airport Office)

The estimated trapped sand volume from profile changes is approximately the same for both patterns. However, pattern II is better than pattern I in terms of the trapping ability. Using a vertical distribution-type trap the sands in suspension transported over the low vegetated embankment was measured at the downdrift end of the vegetated embankment. The measured transport rate in suspension was less than 1 % of the transport rate estimated at the plan beach surface located seaward. This result implies that both patterns functioned well for trapping blown sand. However, the transport rate in suspension measured for pattern I was less than one order of magnitude lower than for pattern II. Thus, the trench disturbs the wind flow on the beach surface less than the fence, as mentioned before. The expenses for digging a trench by earthmoving machines are less than those for installing fences. Based on the short discussion above, we can conclude that the trench is an excellent controlling device for the wind-blown sand and the present authors recommend the trench for use in practice

CONCLUSION

An important finding from the present study is that almost all devices for controlling wind-blown sand, in terms of stopping and stabilizing the blown sand generated in the seaward region of the beach, have been placed at the landward side of the beach. The number of cases with placement of controlling devices to restrain and stop the generation of blown sand in the seaward region of beach is limited(Hotta and Horikawa 1996). Based on these observations, blown sand may be prevented from intruding into economically important areas from adjacent beaches, if the generation of blown sand can be restrained at the upwind side and trapped and stabilized at the downwind side of the beach.

Considering the characteristics of controlling devices, it may be concluded that the combination and arrangement shown in Fig. 7 can effectively control the blown sand from beach surfaces, although maintenance work to keep the functioning of the sand fences and the trench is requested. Devices that have good trapping and stabilizing functions are placed at the landward side and devices that have restraining function are placed at the seaward side of the beach.

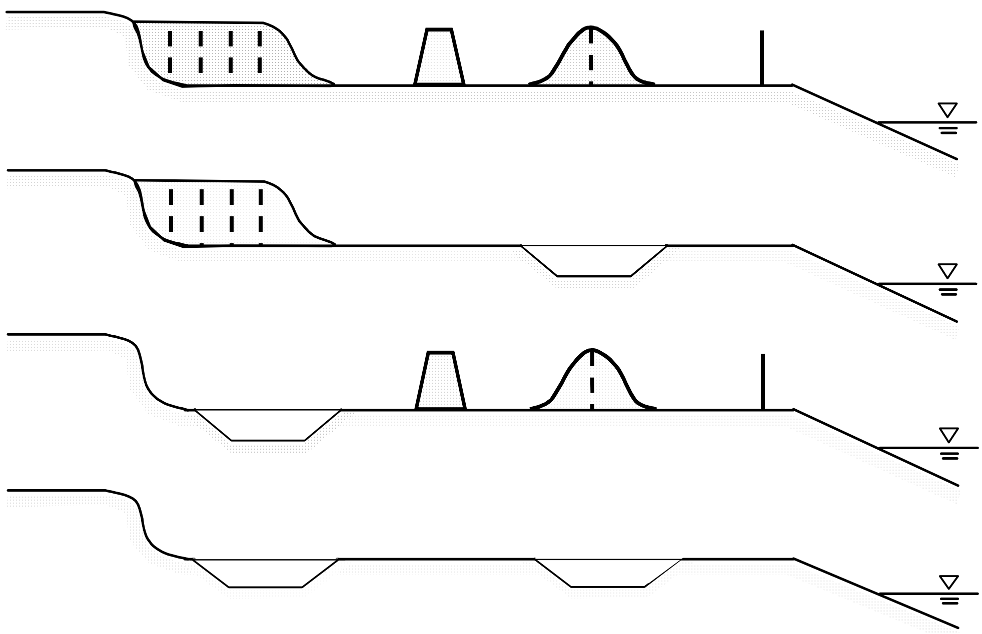


Figure 7. Recommended combination and arrangement of devices controlling wind-blown sand.

Sand fences store the blown sand in the upward direction with respect to the beach surface, whereas trenches store the blown sand in the downward direction to the beach surface. Trenches do not disturb the wind and the blown sand flow more than sand fences and they are economical compared to sand fences. Therefore, utilization of trenches is recommended. Management of installed sand fences is often difficult. Utilization of movable porous fences may be considered (Hotta and Horikawa 1996).

In selection of controlling measures against wind-blown sand on beaches the authors would like to provide the following additional conclusions:

1. In plan arrangement of short trenches and short wing fences, which are 30-100 m long depending on the beach conditions, the zig-zag arrangement is the preferred choice.
2. Depending on the beach width and the wind direction, one suitable measure is beach earthworks. After construction of a beach earthwork (e.g., a dune), having a gentle upwind side slope and a steep downwind side slope, the angle of repose of sand will approximately be formed soon. Then the dune begins to migrate downwind, resulting in the delay of sand movement (Bagnold 1973, Inman et al. 1966). A beach earthwork may also include an obliquely oriented artificial foredune, which makes the wind-blown sand flow turn sideways.
3. The suitable aspect ratio (depth to width) of a trench is 1 to 5-6 (Hotta et al. 1998). A deeper a trench is more effective for storing wind-blown sand. However, a deep trench may be dangerous for strollers on the beach. To avoid such dangers it is necessary not to construct vertical trench walls. A slope smaller than the repose angle of sand is acceptable. Accordingly, depressions may be employed that can trap and store the wind-blown sand.

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