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Chapter 3

Portable Wind Tunnels for Field Testing of Soils and Natural Surfaces

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Additional information is available at the end of the chapter

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1. Introduction

Wind erosion of soils refers to the detachment, transport, and subsequent deposition of sediment or surface soils by wind. This process is sometimes termed aeolian movement and is responsible for the formation and migration of dunes, soil degradation in agricultural areas, and formation of deep loess deposits in areas downwind from major sediment sources. From cross-bedding in ancient sandstones, it has been determined that aeolian movement of soils and sediments has been occurring for eons and is a natural geomorphic process. Wind erosion affects over 500 million ha of land worldwide and is responsible for emitting between 500 and 5000 Tg of fugitive dust into the atmosphere annually [1]. These fugitive dust emissions contain a disproportional amount of soil organic carbon and plant nutrients and the winnowing and loss of these materials degrades the soil [2, 3].

Much of what we know about aeolian processes comes from wind tunnel-based investigations. The seminal work of Ralph Bagnold was largely conducted in a stationary suction-type wind tunnel 9 m in length [4]. Wind tunnels allow control over the wind and surface factors controlling aeolian movement and thus much more definitive investigations can be conducted in a shorter period of time than in the natural environment where these factors are highly variable in time and space. Other early aeolian researchers used wind tunnels to assess the erodibility of soil surfaces without plant residues based on the texture of the soil and relative abundance of aggregates too large to be entrained by the wind [5]. Large stationary wind tunnels have allowed sufficiently detailed understanding of the physical processes of aeolian movement that predictive models such as the Wind Erosion Equation [6] and the Wind Erosion Prediction System [7, 8] have been developed.

Stationary wind tunnels continue to be used for aeolian research at scales from single grain movement [9] through soil surface scale [10] to landscape scale [11]. The ability to control

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the humidity of the atmosphere has enabled scientists to study such sensitive processes as the electrostatic interactions between particles and electrical fields generated during aeolian activities [12]. Stationary wind tunnels have also been used to study abrasion effects of wind-driven sands on building materials [13], crop plants [14], bare crusted soil surfaces [15], and soil surfaces with microphytic crusts [16] as well as to compare and calibrate instrumentation for aeolian filed studies [17, 18].

Fugitive dust is perhaps the most visible product of aeolian activity and stationary wind tunnels have been used to study fugitive dust emissions from eroding soils. From wind tunnel testing of crusted soils and aggregates, it has been determined that sandblasting of these otherwise non-erodible features is responsible for much of the dust generated during aeolian events [19, 20]. Soluble salts such as $CaCO_3$ effects on dust emissions have also been investigated in stationary wind tunnels [21] as have complex and vegetated surfaces [22] and specific soils from Death Valley, a major dust source area in North America [23]. Although stationary wind tunnels have great utility, they are limited to testing disturbed soil surfaces that have been removed from their natural setting. The development of field portable wind tunnels has greatly expanded our ability to investigate aeolian processes in the field under controlled conditions.

2. Portable wind tunnels

Over the last six decades, portable wind tunnels have been developed and used on natural soil surfaces to measure the effects of soil surface characteristics and protective cover on soil erodibility and dust emissions [24]. In their simplest form, portable field wind tunnels must have at least three components: 1.) a self contained or at least portable power source such as an internal combustion engine, 2.) a fan or blower to induce air movement and create an artificial wind, and 3.) a working section that trains the wind from the blower over a finite area of soil surface. Portable wind tunnels in which the fan or blower pushes air through the working section are called pusher-type tunnels and if the fan or blower pulls the air through the working section they are called suction-type wind tunnels. Other components may include transition sections between the blower and the working section including a flow conditioning section and instrumentation to measure the wind speed in the working section and/or to capture sediment at the mouth of the working section. A typical portable field wind tunnel is presented in Figure 1.

The use of portable field wind tunnels has been traced back as far as the early 1940s, but the designers and builders did not publish retrievable documentation of their efforts. Austin Zingg, a mechanical engineer with the US Department of Agriculture, was the first to document the design and construction of a portable wind tunnel [25]. This wind tunnel was used to test the erodibility of crop field surfaces [26] and to assess the effects of roughness and drag based on pressure differentials across the soil surface tested [27]. Other early researchers built a portable wind tunnel to test the susceptibility of field-grown crops to abrasion from saltating particles [28]. A small suction-type tunnel was successfully used to test the

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threshold wind velocity necessary for particle movement on natural surfaces compared with disturbed surfaces and sieved soil [29]. Another very small suction-type portable wind tunnel has been used in Australia to determine the relative dust emission rates for a range of iron ores and road surfaces [30].

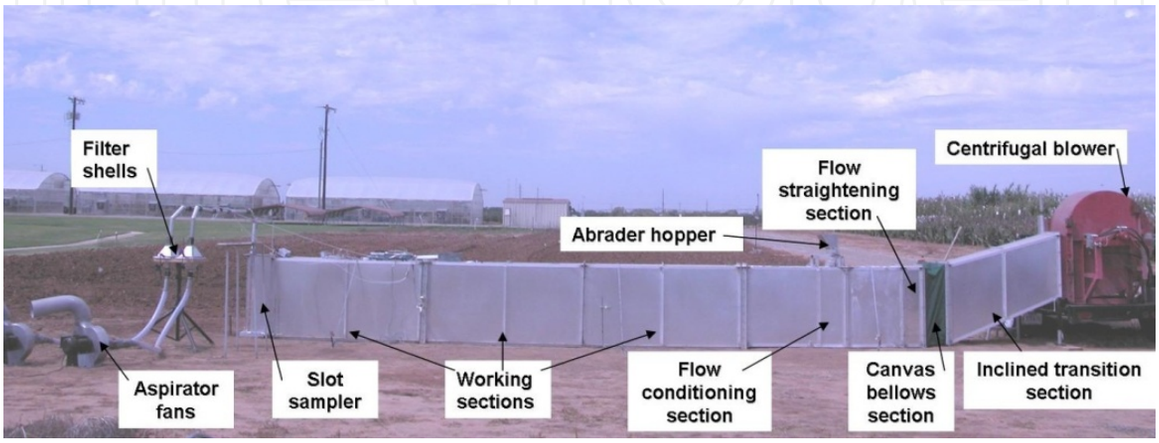


Figure 1. A Typical portable field wind tunnel showing component parts and sampling devices

Australians have also built a truck-mounted portable wind tunnel, tested rectangular and triangular working sections, and determined that the rectangular cross section was superior to the triangular one [31]. These same researchers noted the importance of wind flow conditioning upstream of the working section. Their wind tunnel has been used to assess the erodibility of bare cultivated and uncultivated soil [32], the effects of disturbance on the erodibility of cryptogamic crusts [33], and the sandblast injury and subsequent growth of narrow-leaf lupine [34].

In North America, a pusher-type wind tunnel was built to test the effects of oriented and random surface roughness elements on soil erodibility [35, 36]. This wind tunnel needed a small tractor and a secondary transmission for its power source and was transported using a large truck and 16 m long trailer. Another large portable wind tunnel built in North America was a suction-type wind tunnel that had a 12 m long working section. This wind tunnel was used to determine the erodibilities of natural crusted surfaces in North America and Africa [37-40]. A pusher-type wind tunnel with the power source and blower mounted on a truck bed and the working section lifted from the truck bed and lowered into place on the soil surface by hydraulic arms has been successfully employed to assess dust emissions from loess soils with and without surface cover in the Pacific Northwest of North America [24, 41-44] (Figure 2).



Figure 2. A large wind tunnel working section being lowered into place by a hydraulic arm.

Although large portable wind tunnels requiring mechanical devices to install may be powerful and allow testing of relatively large surface areas, the logistics of transporting them and finding a suitable footprint of level ground to test limit their utility. Examples of medium-size tunnels that may be installed by human power include a German tunnel that was field calibrated [45], a portable boundary layer wind tunnel with a working section formed of three 2 m long elements that fits on a 5 m trailer [46], and another German design that incorporates a rainfall simulator to induce wind-driven rain splash [47]. A summary of portable field wind tunnels, the dimensions of their working sections, maximum wind velocities developed, and reported boundary layer depths is presented in Table 1.

Publication	Tunnel Design	Width (m)	Height (m)	Length (m)	U_{max} (m s^{-1})	Bdy. Lyr. (m)
Zing [25]	Pusher	0.91	0.91	9.12	17	0.23
Armbrust and Box [28]	Pusher	0.91	1.22	7.32	18	----
Gillette [29]	Suction	0.15	0.15	3.01	7	----
Fryrear [34, 35]	Pusher	0.60	0.90	7.00	20	0.15
Nickling and Gillies [37]	Suction	1.00	0.75	11.90	15	>0.2
Raupach and Leys [31]	Pusher	1.20	0.90	4.20	14	0.40
Pietersma et al. [24]	Pusher	1.00	1.20	5.60	"/>20	>1.0
Leys et al. [30]	Suction	0.05	0.10	1.00	19	----
Maurer et al. [45]	Suction	0.60	0.70	9.40	15	----
Van Pelt et al. [46]	Pusher	0.50	1.00	6.00	19	0.50
Fister and Ries [47]	Pusher	0.70	0.70	3.00	8	0.2

Table 1. Summary of previous and present portable wind tunnel designs, dimensions, maximum wind speed reported, and boundary layer thickness.

3. Wind tunnel design

In an engineering paper on wind tunnel design [48], the author stated that "the design of blower-driven air tunnel…is a combination of art, science, and common sense, the last being the most essential. It is difficult and unwise to predict firm rules for tunnel design." In addition to the power source, fan or blower, flow conditioning section, and working section, flow tripping fences and spires are often used to deepen the boundary layer thickness [49, 50], abrader feeders and regulators are used to initiate a saltation cloud, and sediment samplers to quantify the rate of erosion and dust emissions are often included in the design. Instrumentation such as anemometers of many designs and particle impact sensors are often used to monitor wind tunnel performance and to set operating parameters. In almost all cases, portable field wind tunnel designs are somewhat unique and highly influenced by their intended use.

3.1. Practical design criteria

When Zingg published the design and operation of his first portable field wind tunnel [25], he offered seven practical criteria to consider. These practical criteria are listed below;

1. The wind tunnel must be capable of producing an air stream free of general rotation and of known and steady characteristics.
2. It must provide easy and positive control of a range of wind velocities and forces common to the natural wind.

3. It must be durable.
4. It must be safe to use.
5. It should have sufficient size to afford free movement and representative sampling of eroding materials over field surfaces.
6. It must have ready portability.
7. It should be light in weight and amenable to quick and positive assemblage and dismantling.

Another criterion that he used but did not list was the use of commercially available equipment when available.

3.2. Aerodynamic design criteria

Mike Raupach and John Leys [31] suggested six aerodynamic criteria that should be considered in addition to the seven practical criteria proposed by Zingg. These aerodynamic criteria are listed below:

1. The flow must reproduce the logarithmic wind speed profile in the natural atmosphere, thus ensuring realistic aerodynamic forces on saltating grains.
2. The surface shear stress must scale correctly with the wind speed above the surface so that realistic aerodynamic forces act on grains of all sizes at the surface.
3. The vertical turbulence intensity and scale in the region close to the ground must be realistic, ensuring that vertical turbulent dispersion of suspended grains is properly modeled.
4. The flow must be spatially uniform to avoid local scouring by anomalous regions of high surface stress.
5. Gusts should be simulated in the tunnel due to the fact that higher shear stress is required to initiate erosion than to sustain it.
6. A portable wind tunnel simulation of erosion should allow for the introduction of saltating grains at the beginning of the working section if more than the very upwind area of an eroding field is to be simulated.

They noted that criteria 1 to 4 are satisfied if the air flow near the ground surface is a well developed equilibrium boundary layer sufficiently deep to contain particle motion in the inner region where the mean wind speed profile is logarithmic and uniform over the eroding area. The logarithmic wind speed profile for neutral atmospheric stability has been described by:

$$U_z = \left(u^*/k\right) ln\left(z/z_o\right) \tag{1}$$

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where U_z is the wind speed at height z above the surface, u^* is the friction velocity, z_o is the aerodynamic roughness length of the underlying surface, and k is the von Karman constant, usually assigned a value of approximately 0.4.

Criterion 5 requires turbulence with length scales greater than possible within the practical dimensions of portable wind tunnels and cannot be naturally generated by shear forces within either the working sections or flow conditioning sections of a portable wind tunnel. They tried to simulate gustiness using mechanical interruption of air flow in the flow conditioning section of their tunnel but discovered that the turning vane they employed for this purpose reduced the mean wind speed without increasing the vertical turbulence.

3.3. Simulating saltation

Although criterion 6 is not truly aerodynamic, it is very necessary in order to simulate well developed steady state saltation of sand grains over an eroding surface. However, it also raises more questions as to the design and operation of the portable wind tunnel such as how much material to introduce, what the size distribution should be, and how to distribute it realistically in the flow before it strikes the ground surface tested in the working section. An orifice controlled gravity fed saltation initiator that drops the sand abrader into inclined tubes for acceleration before striking a sandpaper surface and bouncing into the flow stream is shown in Figure 3.

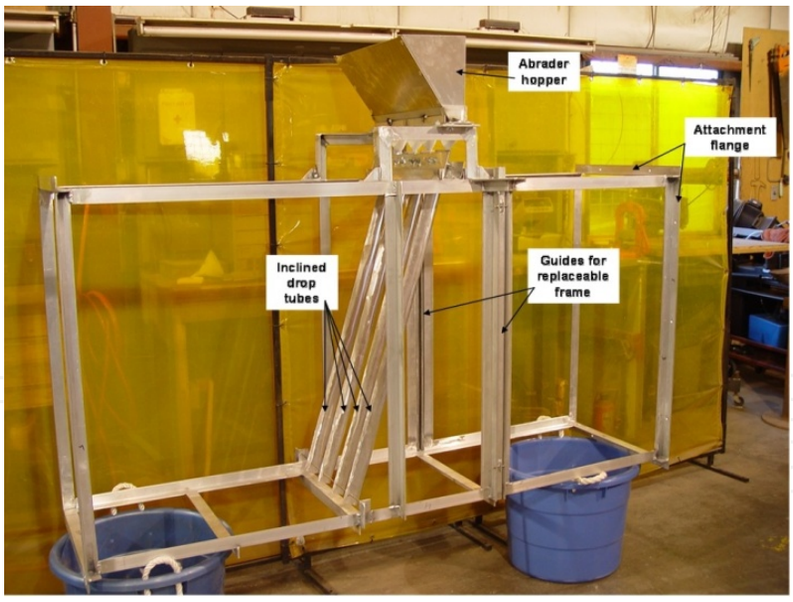


Figure 3. A complex flow conditioning section showing the abrader hopper and inclined tubes used to initiate saltation into the flow stream.

Saltation has been shown to reach a maximum at about 7 m length in wind tunnels [51] and decreases at longer distances, reaching equilibrium at between 10 and 15 m into the working section [45]. Longer working sections have limited utility however due to their lower transportability [47] and require a substantially longer uniform level surface on which to be set

[52]. Working section lengths of portable field wind tunnels have varied from 3 m [19, 47] to almost 12 m [38, 39]. Recently, a small circular device named the Portable In-Situ Wind Erosion Research Laboratory (PI-SWERL) [52] has been used to develop shear stress over a surface and entrain particles using radially induced rather than linearly induced shear stress.

3.4. Power sources

Power sources have ranged from external sources such as the power take-off shaft of a tractor as input to a transmission that output to drive chains [35, 36], to self-contained direct drive internal combustion engines [24, 25, 28, 31, 38-40], self contained internal combustion engines driving hydraulic pumps to provide for a hydraulic drive motor at the blower [46], and electric motors supplied by portable generators [45, 47]. All these power sources are field tested and reliable. The wind speed may be adjusted by varying the engine or motor speed or by changing the pitch of the fan or blower blades.

3.5. Fans and blowers

The fans and blowers employed for wind tunnels are of two primary types. Axial fans (Figure 4a) are composed of fixed or adjustable pitched blades arranged radially around the axis of rotation, which is often aligned with the axis of flow through the wind tunnel. Although axial fans are highly efficient at inducing flow, the flow tends to spiral and this problem must be addressed [53] if the flow conditions of Zingg's first criterion are to be met. Centrifugal blowers (Figure 4b) have fixed pitch blades or impellers that are arranged parallel to the axis of rotation at the circumference of a blower cage. The axis rotation is commonly normal to the axis of air flow down the wind tunnel. Centrifugal blowers tend to be more flexible with respect to design, are more stable and efficient over a variety of flows, and produce less spiraling in the flow than axial fans [53].

Some portable field wind tunnels are too compact for adequate flow conditioning. This shortcoming is very problematic as flow considerations are the most important factor in the successful operation of the wind tunnel [31]. Wind tunnels may not reach true transport capacity or overshoot true transport capacity if flow conditioning upwind of the working section is inadequate [54] and wind tunnel height may limit the amount of upward mixing during strong turbulent diffusion [23]. The height of the working section affects the depth of the boundary layer that may be achieved. Upper limits of the Froude number F have been proposed for wind tunnel design of from 10 [55] to 20 [24]. The Froude number is defined by:

$$F = U^2 / gH \tag{2}$$

Where U is the wind tunnel design wind speed, g is the acceleration due to gravity, and H is the wind tunnel height. A well developed boundary layer at least 50 cm thick is recommended to ensure initiation of vertical particle uplift [45]. For this reason, mini-tunnels and micro-tunnels may be too small to allow results that can be scaled up to field scales [56].

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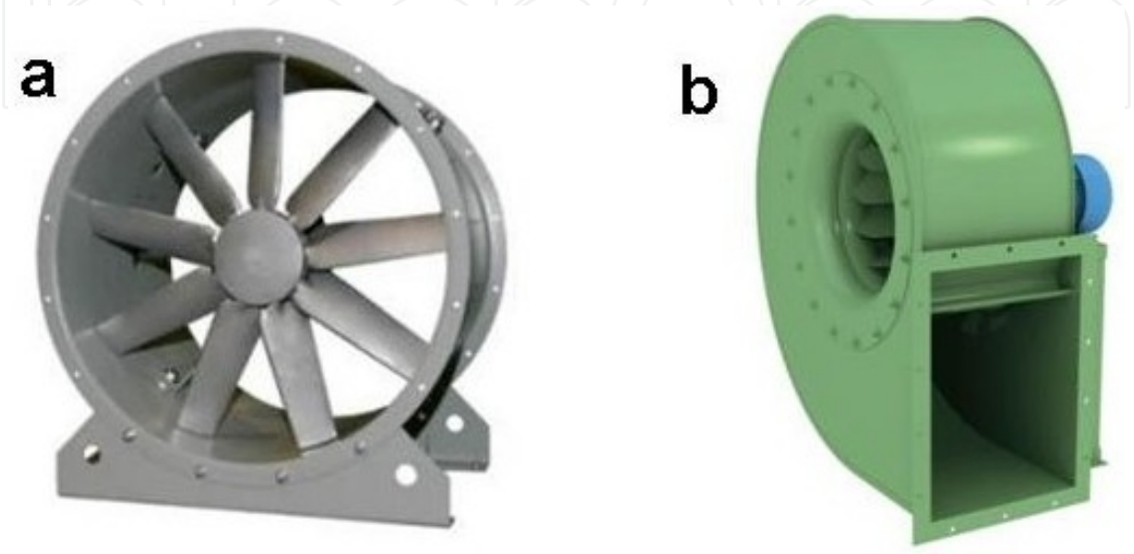


Figure 4. An axial fan (a) and a centrifugal blower (b) typical of those used in construction of portable field wind tunnels.

3.6. Flow conditioning

Flow conditioning sections of various designs have been used to straighten the flow and remove or reduce the scale of eddies in the flow, to initiate a logarithmic wind speed profile and turbulence, and to initiate saltating abrader material into the air flow down the wind tunnels. A typical honeycomb flow straightener with 10 mm screen layers used to create an even logarithmic wind speed profile is presented in Figure 5. If the flow is properly conditioned and the height of the wind tunnel is not limiting the depth of the boundary layer may be estimated from the wind speed profile in the wind tunnel working section [46]. Investigators have stated that although boundary layer thickness is a poorly defined concept, it may be estimated as the height at which the wind speed profile attains 99 percent of its maximum value [57]. Finally, the proper regulation of carefully chosen abrader material allows for saltation clouds representing different rates of erosion and surface abrasion although rates consistent with those noted in the field for natural sand movement [58] are commonly used. Portable field wind tunnel may be used to estimate the threshold wind velocity necessary to initiate particle movement using impact sensors [18] or optically based sensors [59]. The technique of using the percentage of seconds in which moving particles are noted [60] is easily employed in a portable wind tunnel if the wind speed can be slowly and evenly increased.

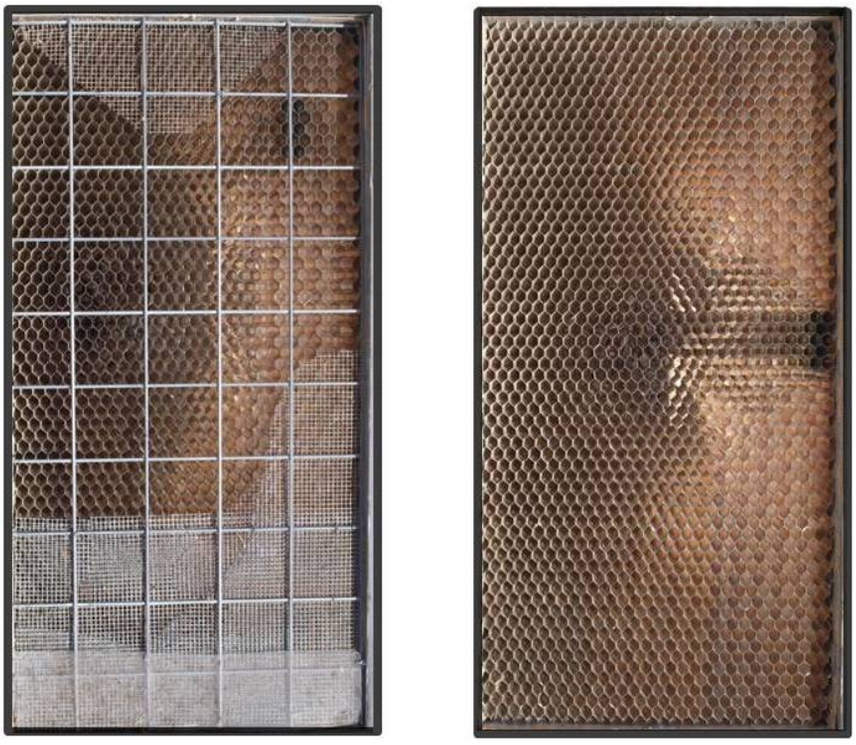


Figure 5. A flow conditioner showing the large cell honeycomb used to break the scale of eddies and straighten flow and also the 10 mm screen layers used to even the flow and create a logarithmic wind speed profile in the wind tunnel.

4. Conclusions

Over the last 6 decades, portable field wind tunnels have been successfully used on several continents to study the controlling processes of aeolian particle movement, assess the erodibility of natural surfaces subjected to different disturbances, estimate dust emission rates for natural surfaces, investigate the partitioning of chemical and microbiological components of the soil on entrained sediment, and to estimate the threshold wind velocity necessary to initiate aeolian particle movement. Although not a perfect replacement for wind in the natural environment due to the absence of turbulent gusts, the forces created by the wind are repeatable and the accuracy of the tunnel is solely dependent on the accuracy of the devices measuring critical operating parameters such as wind velocity and sediment loading. When properly designed, calibrated, constructed, and operated, very useful information can be obtained in a relatively short period of time with these tools.

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Nomenclature of symbols and their units

U– Wind velocity (m s^{-1})

z– Height above the surface (m)

z_o– Roughness length (m)

u* - Friction velocity (m s^{-1})

k– von Karman constant (~0.4)

F– Froude number (dimensionless)

g–Acceleration due to gravity (m s^{-2})

H– Wind tunnel height (m)

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