The Use of Spheres to Measure Lift and Drag on Wind-Eroded Soil Grains[1]

W. S. CHEPIL[2]

ABSTRACT

Experiments were conducted to determine the relative magnitude of lift and drag on small spheres, similar to soil grains, at different heights in a fluid boundary surface and to determine if these forces are related to movement of soil grains in saltation.

Lift on the average was about 75% that of drag when a sphere was at zero height. Lift decreased with height and virtually ceased a short distance above ground. The greater the ground roughness and drag velocity, and therefore the steeper the velocity gradient, the higher lift extended. It is concluded that lift is caused by a steep wind velocity gradient near the ground.

Drag on the spheres was generally much greater than lift. Drag increased directly with an increase in wind velocity and was apparently due to direct pressure of the wind against the sphere.

It is evident from these experiments that lift alone is too small to cause the saltating grains to rise, as they do, essentially vertically. The predominantly vertical rise apparently is the way the saltating grains rebound from the ground.

PREVIOUS INVESTIGATIONS[3 4] have indicated that in a windstream the forces of lift, drag, and gravity act on the soil grains resting on the ground and just about to be moved by wind. The equilibrium among these forces at the threshold of grain movement by wind were found to be influenced by the diameter, shape, and density of the grains, the angle of repose of the grains with respect to the mean drag level of the wind, the closeness of packing of top grains on the sediment bed, and the lift and drag impulses of fluid turbulence.

A further investigation was undertaken to determine the relative magnitude of lift and drag on small spheres similar to soil grains carried by wind at different heights above the ground. Information of this nature has not been available for water nor for air so far as the author is aware. Results of this investigation are presented here. These results may have some bearing on the design of measures to control soil erosion.

Design of Experiments and Procedure

A previously described wind tunnel[5] was used to measure lift and drag on small spheres entrained in a fluid boundary layer. Measurements were made at various heights and for different drag velocities of the wind 50 feet downstream in the wind tunnel working section. At this location the fluid boundary layer was about 25 to 40 cm. deep, depending on the roughness of the ground surface.

The drag velocity V_* within the boundary layer was equal to

$$\frac{v_z}{5.75 \log (z/k)}$$

where v_z is velocity at height z above the average ground surface and k is the height at which the velocity is zero. Height k defines an aerodynamic surface and is constant for a given ground surface at all fluid velocities but varies with height, shape, and arrangement of the ground roughness elements.

The ground surface was composed of gravel 0.3-cm. average diameter. The gravel surface was smoothed with a straightedge when a 0.3-cm. sphere was used. When a sphere > 0.3 cm. was used, gravel mounds of the same diameter as the sphere arranged 3 diameters apart in a hexagonal pattern were formed. At zero elevation, the poles of the sphere shown in figure 1 were level with the bottom of the mounds. The bottom half of the sphere was embedded in the gravel at this height. The gravel bed was highly porous and presented no difficulty of measuring pressure below its average surface.

The sphere was mounted on one end of a long, tubular shaft as indicated in figure 1. An opening continuous with that of the shaft entered the sphere at one of the poles, made a one-quarter circle through it, and entered the outside at a position directly over its equator. The opposite end of the tubular shaft was connected by rubber tubing to the impact end of an incline-tube alcohol manometer outside the tunnel. The static end of the manometer was connected to a small opening s in the ceiling of the tunnel directly above the sphere. Position s served merely as a reference point from which the pressure differences between the numbered positions of figure 1 could be determined. For example, a pressure difference $P_1 - P_2$ between position 1 and 2 on the sphere is equal to $(P_1 + P_s) - (P_2 + P_s)$ where P_s is the static pressure at the tunnel ceiling.

The end of the tubular shaft was clamped to the bottom of a point gauge for convenient positioning of the sphere at different heights above the gravel surface.

Beginning with zero elevation of the sphere and with the tubular shaft remaining horizontal on the lee of the sphere and parallel with the wind, the sphere was rotated so that the mouth of the opening on its surface was positioned as indicated by numbers in the lower left hand side of figure 1.

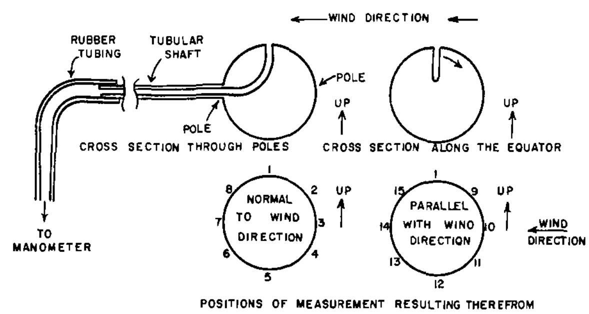

Figure 1—Diagrammatic representation of the method of determining air pressure at different positions on a sphere mounted on the end of a tubular shaft positioned parallel with and normal (at right angles) to wind direction and rotated to give positions of measurement as shown by numbers.

---

[1]Contribution from Soil and Water Conservation Research Division, ARS, USDA, with the Kansas, Agr. Exp. Sta. cooperating. Department of Agronomy Contribution No. 715. Presented before Div. I, Soil Science Society of America, Dec. 5, 1960, at Chicago, Ill. Received Dec. 19, 1960. Approved Feb. 13, 1961.

[2]Soil Scientist, Western Soil and Water Management Research Branch, SWCRD, ARS, USDA, Manhattan, Kans.

[3]Chepil, W. S. The use of evenly spaced hemispheres to evaluate aerodynamic forces on a soil surface. Trans. Am. Geophys. Union 39:397-404. 1958.

[4]Chepil, W. S. Equilibrium of soil grains at the threshold of movement by wind. Soil Sci. Soc. of Am. Proc. 23:422-428. 1959.

[5]Zingg, A. W. and Chepil, W. S. Aerodynamics of wind erosion. Agr. Eng. 31:279-282, 284. 1950.

The pressure differences between each of these positions and position 1 were recorded. Then, without shifting the elevation of the sphere and without changing the wind velocity, the shaft was placed horizontal and at right angles to wind direction and the sphere was rotated again so that the mouth of the opening was positioned as indicated by numbers in the lower right hand corner of figure 1. The pressure differences between these positions and position 1 were recorded.

The pressure differences were determined in like manner for different elevations of the sphere above the ground surface, for different sizes of spheres ranging from 0.3 to 5.1 cm. in diameter, and for different drag velocities of the wind.

Drag per unit of horizontal area on the sphere was taken directly as a pressure difference on the hemispherical surface facing against and away from the wind. It was found by geometric computation that the two circular caps lying around positions 10 and 14 (figure 1) with their boundaries extending half way toward positions 9 and 11 and 13 and 15, respectively, each occupy 0.39 of the largest cross-sectional area of the sphere. The zone lying outside each cap down to the equator occupies 0.61 of the largest cross-sectional area of the sphere. Hence the drag per unit of the largest cross-sectional area of the sphere is approximately equal to

$$0.61\,\frac{(P_{11} - P_{13}) + (P_9 - P_{15})}{2} + 0.39\,(P_{10} - P_{14})$$

in which P_1, P_2, etc. are pressures at positions 1, 2, etc.

Lift on the sphere was taken as a pressure difference on the hemispherical surfaces facing against and away from the ground surface. Same as for computing drag, the circular caps lying around positions 1 and 2 and the zones outside each cap to the greatest circumference of the sphere were taken as 0.39 and 0.61 of the largest cross-sectional area, respectively. Therefore, lift on the sphere is approximately equal to

$$0.61\,\frac{(P_{11} - P_9) + (P_{13} - P_{15}) + (P_6 - P_8) + (P_4 - P_2)}{4} + 0.39\,(P_{12} - P_1).$$

Positions 12 and 5 are one and the same.

Table 1—Measured drag velocity and forces of lift and drag on spheres at different heights above the ground surface.

Drag velocity V_*	Height of ground roughness	Diameter of sphere	Height of sphere above average ground	Lift on sphere†	Drag on sphere	Ratio lift to drag
cm./sec.	cm.	cm.	cm.	dynes/cm.^{2}	dynes/cm.^{2}	%
76	2.55	5.1	0	24	45	53
76	2.55	5.1	1.27	18	93	19
76	2.55	5.1	2.54	7	128	5
76	2.55	5.1	5.08	tr	189	tr
76	2.55	5.1	10.16	tr	273	tr
109	2.55	5.1	0	72	105	69
109	2.55	5.1	1.27	48	166	29
109	2.55	5.1	2.54	24	220	11
109	2.55	5.1	5.08	tr	356	tr
109	2.55	5.1	10.16	tr	510	tr
146	2.55	5.1	0	188	249	76
146	2.55	5.1	1.27	197	286	69
146	2.55	5.1	2.54	117	379	31
146	2.55	5.1	5.08	69	636	11
146	2.55	5.1	10.16	tr	934	tr
188	2.55	5.1	0	393	594	66
188	2.55	5.1	1.27	442	598	74
188	2.55	5.1	2.54	278	729	38
188	2.55	5.1	5.08	83	1096	8
188	2.55	5.1	10.16	tr	1646	tr
98	0.4	0.8	0	34	35	97
98	0.4	0.8	0.25	33	78	41
98	0.4	0.8	0.51	33	144	23
98	0.4	0.8	1.02	20	318	6
98	0.4	0.8	1.52	21	408	5
98	0.4	0.8	2.03	9	476	2
98	0.4	0.8	2.54	tr	530	tr
75	0.15	0.3	0	22	25	88
75	0.15	0.3	0.25	14	60	23
75	0.15	0.3	0.51	27	140	19
75	0.15	0.3	1.02	7	313	2
75	0.15	0.3	1.52	5	408	1
75	0.15	0.3	2.03	tr	481	tr
75	0.15	0.3	2.54	tr	535	tr
99	0.15	0.3	0	68	97	70
99	0.15	0.3	0.25	57	248	23
99	0.15	0.3	0.51	23	484	5
99	0.15	0.3	1.02	11	868	1
99	0.15	0.3	1.52	tr	1062	tr
99	0.15	0.3	2.03	tr	1222	tr
99	0.15	0.3	2.54	tr	1350	tr

† "tr" is value too small to be measured.

RESULTS

On the average, lift was equal to only about 75% of drag on a sphere at zero height (resting on the ground) as shown in table 1. Lift decreased with height and, as far as could be measured, virtually ceased to exist a few sphere heights above the ground surface. For the

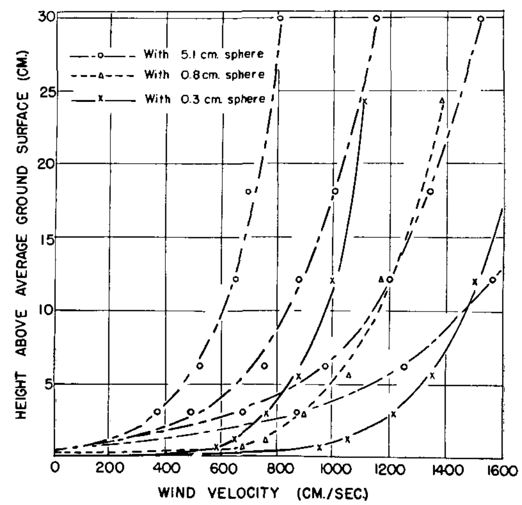

Figure 2—Wind velocity gradients over three different degrees of surface roughness with velocity plotted against the linear scale of height. Height of surface roughness was approximately one-half diameter of sphere used.

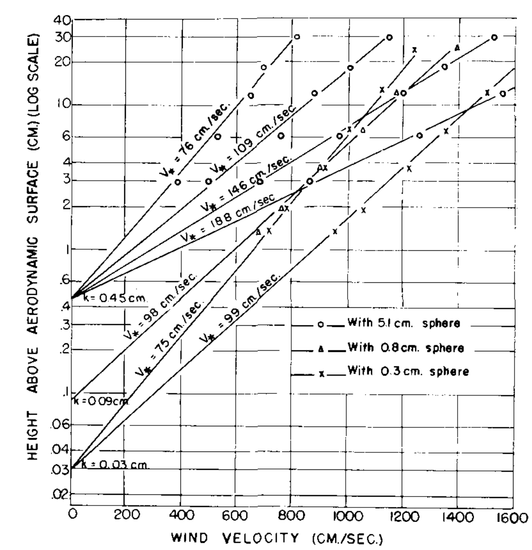

Figure 3—Wind velocity gradients of figure 2 plotted against the logarithm (base 10) of height above the aerodynamic surface Z_0 (a level at which the projected velocity of figure 2 is approximately zero).

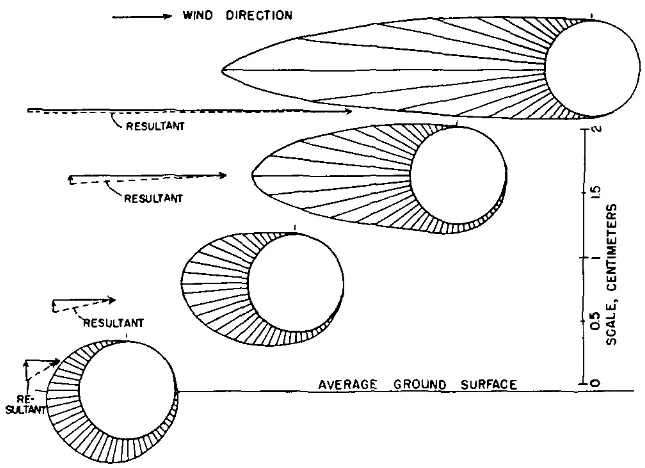

Figure 4—Pattern of approximate pressure differences between position 1 on top of the sphere and other positions on the sphere at various heights in a windstream. Length of lines in the shaded areas outside the circular line (sphere) denote the relative differences in air pressures. The sphere is 0.8 cm. in diameter and the drag velocity is 98 cm. per second.

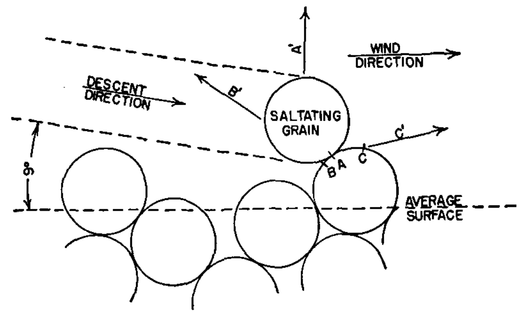

Figure 5—Diagrammatic representation of a saltating grain striking a stationary grain at an average impact point A and rebounding in a vertical direction A′. Possible extreme points of impact are B and C with rebound directions B′ and C′.

drag velocities and roughness of surface used, lift did not extend appreciably beyond 2 inches (10.16 cm.) in height. The greater the ground roughness (and the diameter of the sphere) and the greater the drag velocity of the wind, the higher lift extended.

Increases in ground roughness and drag velocity also increased the velocity gradient at all heights (figures 2 and 3). A velocity gradient is a change in velocity per unit of height. The increases in velocity with height above the ground apparently were associated with the decreases in static pressure (pressure measured transverse to the fluid motion) with height above the ground in accordance with the well-known Bernoulli effect. In other words the higher the wind velocity at any point the lower was the static pressure at that point. It seems logical therefore that the increases in velocity gradient caused the increases in lift. However, no single criterion, such as velocity gradient at some point on the sphere, could be found that would serve as an index of lift.

A diagrammatic representation of pressure on a 0.8-cm. sphere and a drag velocity of 98 cm. per second is given in figure 4 for a more vivid portrayal of the relative magnitudes of lift and drag on the sphere suspended at various heights. It is shown that lift in this case virtually ceased to exist at about 2.5 cm. height. The drag on the sphere, on the other hand, continued to increase all the way up to the height of measurement, just as velocity increased with height. However, as for lift, no single criterion, such as velocity at some point on the sphere, could be found that would serve as an index of drag.

INTERPRETATIONS AND CONCLUSIONS

Pressure differences at various positions on a sphere, such as a soil grain entrained at different heights above the ground, indicate for the first time that lift on the sphere is greatest only when the sphere is on the ground but diminishes rapidly with height and ceases to be measurable a short distance above the ground. This distance is considerably less than the height that many grains jump in saltation.

Drag on the sphere, on the other hand, is least when the sphere is on the ground but increases rapidly with height as long as wind velocity increases with height.

The drag on the grains is generally much greater than lift. After being shot into the air, the grains rise to various heights, and because of the force of gravity, fall at an accelerating velocity. There is at the same time a horizontal acceleration of the falling grain due to the force of drag. The downward and forward accelerations are uniformly proportioned so that the inclined path of the falling grain is almost a straight line. However, the average force of drag is much greater than the force of gravity and therefore the angle of descent is only about 6 to 12 degrees from the horizontal. If the ground were perfectly smooth and there were no lift, the angle of ascent (expressed as deviation from the horizontal) should be the same as of descent. However, grains in saltation rise vertically or nearly so.

It is concluded from results of these experiments that the essentially vertical rise must be due in some measure to the presence of lift near the ground but that lift alone could not possibly be the sole factor involved. Another factor apparently is the surface obstructions from which the saltating grains rebound (figure 5). The obstructions are usually spherical or nearly spherical soil aggregates or other grains resting on or creeping along the ground. The topmost grains that compose the eroding surface occupy on the average about 0.1 of the total surface and are therefore spaced about 3 diameters apart (1, 2), as shown in figure 5. The saltating grains descend at an average angle of about 9 degrees from the horizontal, strike the top portions of spherical ground objects, and then rebound predominantly in a vertical or nearly vertical direction. Because of the particular angle of descent and configurations of the ground surface, as shown diagrammatically in figure 5, the rebounds should tend to be on the average in a vertical direction even if lift did not exist. Lift merely contributes to the vertical rise of soil grains. The vertical momentum of saltating grains carries some of them upward and above the zone of lift.