Integration of trend surface, entrainment, and grain size analysis on the Oregon Dunes National Recreation Area, Oregon

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Abstract

The origin of the Oregon Dunes National Recreation Area sand sheet is still under investigation. It has recently been learned that the paleowind direction vectors in the time of believed dune emplacement (~40,000 radiocarbon years before present) were oriented at 33° NE (Micks, personal communication). The analysis of grain size data though trend surfacing and entrainment analysis supports this recent research. The entrainment trend surface plot displays a northerly decreasing critical shear velocity. This supports the idea that as the wind blew sand in from the south, over an increasing amount of land and a corresponding decreased wind velocity. It is also supported by sand showing an increased thickness trending northward.

Background

The Oregon Dunes National Recreation Area is located on the south central coast of Oregon. It is approximately 70 km long and 5 km wide, and situated between Florence, OR to the north and Coos Bay, OR to the south. The sand dunes are periodically stabilized by European Beachgrass and other native and introduced species, with the result being paleosols and related characteristic soil horizons. These paleosols create localized perched aquifers, which are still not fully understood.

The dunes provide a large recreation area, specifically for off-highway vehicles. The large open sand dunes provide expansive areas for the drivers of these vehicles. There are also multiple camping areas and hiking trails in the dunes.

Figure 1: Map of Oregon Coast showing the ODNRA, between Florence to the north and Coos Bay to the south.

The origin of the dunes is still under study (Stock et al., in progress). There has been two hypotheses suggested, both of which involve sea level fluctuations. The high sea level hypothesis entails the rising sea level forcing the sand on shore in beach environments, and subsequently the sand being blown onto the terrace and up to the foothills of Oregon's Coast Range. The low stand theory involves sand being blown from the exposed continental shelf during low stands. This would also allow loess to be blown in, while the high stand theory would not allow this due to the high-energy environment of the beach forcing. These two ideas would produce different ^{14}C (the only ones obtained thus far) dates, and the latter idea is supported due to the oldest date being ^{14}C dead at ~40,000 radio carbon years before present, with other dates not expected to be significantly older. This date corresponds to low sea level stands.

Definition of Problem

The most recent information on paleo-wind direction indicates that the winter winds during the suspected time of emplacement of the initial sand were approximately three times stronger than winds today and the direction of wind was towards 33° NE (Micks, personal communication). It is suspected that the dunes would exhibit trends that would support these wind patterns. One way that this could be tested would be to examine grain size data for the dunes.

Grain size is proportional to the shear velocity of the transporting medium. Modeling the paleowind strength via analysis of grain size variations over the length dunes would be an acceptable way of doing this. It is believed that the dunes will exhibit trends corresponding to a fining up to the north end of the dunes. The trend would be the result of the sand being blown northward from the south-southwest, over an increasing amount of land, rather than over the sea. The fining up of the grains would be the result of decreasing wind strength over the land.

The trends will be examined by first outlining the initial entrainment of a single quartz grain on equidimensional grains. Second, the entrainment by wind of grains in a saltating system will be examined. A grain-size trend surface analysis will then be performed on sand auger cores dug in the dunes in late 1996. With the grain size data that the trend surface analysis provides, the entrainment equation will be applied.

Unfortunately, the application of trend surface analysis to grain size data could not be found in the literature search. However, the application of trend surfaces in other sedimentological related uses (Boon, 1968; Lammons et al., 1982) has been reported on. This amount of literature is small when comparing it to the amount of work applied to statistical work performed on other grain size uses and parameters (Syvitski, 1991; Cheong and Shen, 1983; Pluis, 1992; Goudie, 1969; Stapor and Tanner, 1975)

Mechanics of initiation of sediment movement

The first step in understanding the initiation of movement is grasping what is happening at the level of the individual grain in relation to the surrounding grains. This is gained through the knowledge of the forces acting on the grain by gravity, surrounding grains, and the force associated with the fluid movement. The variables involved are defined as the equilibrium requirements.

Equilibrium Requirements

The best way to gain an understanding of the forces in to generate a free body diagram of the interacting grains and forces. We must also make assumptions, or place limits on the system. The assumptions in this exercise are as follows: cohesionless, horizontal bed, contact points equidistant from each other, and equidimensional grains. A free body diagram for this exercise is shown in figure 1.

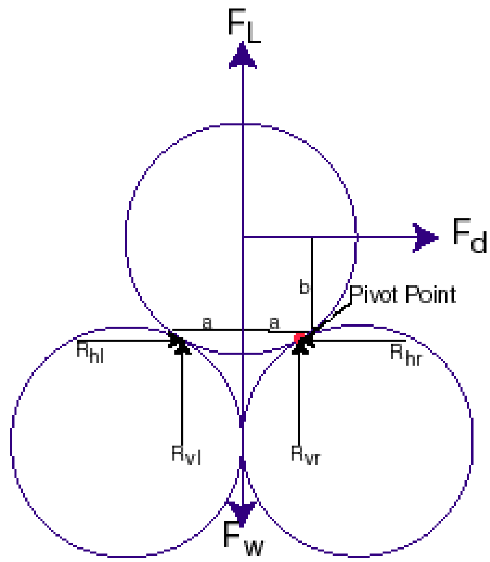
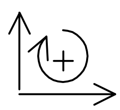


Figure 2: Free body diagram of grains and the related forces.

The equations involved for this section are as put forward below, as well as the solution for the force requires to entrain the grain.

$$\left[\sum F_m = 0\right] \quad \left[\sum F_x = 0\right] \quad \left[\sum F_y = 0\right] \qquad 1.$$



$$\sum F_m = aF_L + bF_D - aF_w + 2aR_{vl} = 0$$
$$\sum F_x = F_D - R_{hr} + R_{hl} \qquad 2.$$
$$\sum F_y = F_L + R_{vr} - F_w + R_{vl}$$

Solve for system of three equations

$$\sum aF_L + bF_D - aF_w + 2aR_{vl} = 0$$
$$\sum F_D - R_{hr} + R_{hl} = 0 \qquad 3.$$
$$\sum F_L + R_{vr} - F_w + R_{vl} = 0$$

Summation in the X direction can be ignored, since that both sides equal one another.

Solve for F_w in the Y direction: $F_w = F_l + R_{vr} + R_{vl}$

Plug into moment equilibrium eq.

Solution: $aF_l + bF_d - a(F_l + R_{vr} + R_{vl}) + 2aR_{vl} = 0$

Solve for F_d:

$$1.)\ F_d = \frac{a}{b}\left(R_{vr} + R_{vl}\right); R_{vr} + R_{vl} = F_{w,}\ \therefore$$
$$2.)\ F_d = \frac{a}{b} F_w \qquad 4.$$

Find parameters for a 1-mm diameter pure quartz spherical sand grain in air, in two dimensional cubic close packing with two other equidimensional sand grains lying on a flat surface. This gives the parameters of:

$F_w = \rho g V$

$\rho = 2.65\ g/cm^3$

Volume of grain = $\frac{4}{3}\pi r^3 = 5.2 \times 10^{-4}\ cm^3$

$g = 980 cm/s^2$

a = 0.5 sin 30° = 0.25 mm

b = 0.5 sin 60° = 0.43 mm

Plug into equation:

$$F_d = \frac{0.25cm}{0.43cm}\left(2.65\ {}^{g}\!/\!_{cm^3} \times 980\ {}^{cm}\!/\!_{s^2} \times \left(5.2 \times 10^{-4}\ cm^3\right)\right)$$
$$F_d = 0.79\ {}^{g\cdot cm}\!/\!_{s^2} \qquad 5.$$
$$F_d = 7.9 \times 10^{-12}\ N$$

Therefore, the force required to move the grain out of equilibrium is 7.9×10^{-12} N.

Entrainment by Wind

Bagnold's (1941) description and derived equations of entrainment by wind are still widely accepted and applied today. It is straightforward and simple to apply, yet accurate enough to still be in use for over fifty years after its introduction. The form of the equation is as follows:

$$u_{*t} = A\left(\frac{\rho_p - \rho_f}{\rho_f} \times g \times d\right)^{1/2} \qquad 6.$$

Where

A is a empirical coefficient equal to 0.1 for Reynold numbers >3.5 and with no saltation in progress (0.8 for saltation)

u_{*t} = critical shear velocity

d = grain diameter

g = gravitational acceleration

ρ_f = density of fluid

ρ_p = density of particle

The primary drawback to this equation is that it doesn't give the options of changing important variables of the motion initiation, such as various angles and other relationships of the primary grain in relation to the bed grains. The generalities of this equation would make it a quick way of estimating the critical wind speed required for entrainment of a single grain, and would do well in most cases.

In summary, the critical shear velocity to entrain a 1mm quartz grain by wind with no saltation in progress is 46 cm/s or 16.6 km/h.

Trend surface analysis

For application of trend surfaces to the grain size data, UTM coordinates were used as the x and y variables, while average grain size for the core (subtracting out soil profile data) was the z variable. The equations below were used to find interpolated z values, in the first, second, third, and fourth order trend surfaces (Swan and Sandilands, 1995).

$$Z = A+Bx+Cy$$

$$Z = A+Bx+Cy+Dx^2+Ey^2+Fxy$$

$$Z = A+Bx+Cy+Dx^2+Ey^2+Fxy+Gx^3+Hy^3+Ix^2y+Jxy^2$$

$$Z = A+Bx+Cy+Dx^2+Ey^2+Fxy+Gx^3+Hy^3+Ix^2y+Jxy^2+Kx^4+Ly^4+Mx^3y+Nxy^3+Ox^2y^2$$

The coefficients, A-O, were solved using the least squares method (Swan and Sandilands, 1995) These coefficients attempt to minimize error.

Analysis of variance tables were then formulated to see if the trends displayed were statistically significant. Complete results are attached in the appendix. In summary, only the first order trend surface displayed statistically significant trends, due to the critical f ratio being lower than the calculated f-test value.

Discussion of trend surface

The first order trend surface displayed a fining to the north trend, as expected. What was not expected was the direction of the finest point of the graph. This was on the northwestern corner of the grid, rather than on the northeastern portion as expected. The northeastern corner was expected since that would be the furthest inland portion of the grid. However, this variance could be explained by one or two samples tipping the slope in that direction. Nevertheless, the northward trend of finer grain size is more prevalent than the east-west trends.

Integration of entrainment and trend surface plot

Applying Bagnold's (1941) equation to the grain size trend surface plot will model the critical shear velocity that is required to move the interpolated grain size. This is done simply by using defined variables and the calculated grain size and applying the equation to solve for critical shear velocity. This provides a spatially distributed diagram of modeled critical entrainment velocities. This diagram (attached in the appendix) displays the declining critical velocities needed to entrain the smaller grains in the northern section of the grid. This supports the idea that the wind was coming in from the south, blowing across the shelf, and up against the headlands and accumulating in the northern section. This accumulation idea is also supported by the well logs in the area (one attached in appendix), with the thicker sand sections being in the northern end of the dune field.

Discussion

The analysis of grain size data via trend surfacing and entrainment velocities provides a detailed look at the grain size trends and their implications. The theory of sand being blown in from the south is supported by the trends displayed and additionally by well logs in the northern half of the dunes, where sand thickness reaches 163 feet below surface level. The trends displayed by the analysis displayed a northwesterly fining of loose sediments; the northward trend was expected, while the westward trend was not. The westward trend could be the result of core location, core-averaging procedure, or boundary conditions. The problematic boundary conditions in this case could lie in the fact that the dunes are a long and narrow strip of land, rather than an equidimensional plot. This being the case could make the cores that lie to the east and west of the central axis of core locations more influential than they would otherwise be. Supporting the idea that this is an artifact rather than a true trend is that there is no loose sediment source to the southeast, which is what the plot indicates. If it is not an artifact, it could be the result of the seasonal bi-directional wind regimes, or changes that have occurred since the emplacement of the dunes. Other than that, the trends displayed support the hypothesis that sand was blown in from the south, then accumulated in the north. .

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Appendix

1. ANOVA tables
2. First through fourth order trend surface plots
3. Well log from City of Florence Well Field
4. Entrainment trend surface plot

Full grain size data set available upon request