Chapter 24

SAND LOSSES FROM A COAST BY WIND ACTION

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INTRODUCTION

Sand supplied to a coast by streams, cliff erosion, and other sources generally is moved in one particular direction along the shoreline as a littoral drift by the prevailing wave conditions in the area (3). When this drift encounters a partial obstruction, such as a prominent natural headland or a major engineering structure, a condition is realized which is conducive to sediment deposition. Such littoral compartments eventually become filled and some sand is carried past the obstruction. If the topography back of the area of deposition is relatively low and the prevailing winds are onshore, considerable quantities of sand may be moved inland to create a dune system. This loss of material from the coast may affect the stability of the downcoast shoreline. A measure of the annual loss of sand from a particular section of coast by wind action is necessary in many instances. A method of estimating this loss of sand involves the use of a suitable transport equation along with a knowledge of the sand characteristics and the duration and velocity of the wind in the area under study.

SAND TRANSPORT EQUATION

Numerous laboratory investigations on sand transport by wind action have been made over the years. Recently these various studies were critically reviewed and additional laboratory measurements made by Belly (2). The results of these studies indicated that the Bagnold equation (1), when supplemented by data by other investigators, best defined the rate of sand transport by wind action. The basic Bagnold equation for the rate of sand movement, q, per unit width and unit time is

$$q = c\sqrt{\frac{d}{D}}\ \frac{\gamma}{g}\ U_*^{\,3} \qquad (1)$$

where D is the grain diameter of standard 0.25 mm sand; d is the grain diameter of the sand under study; γ is the specific weight of air; g is the acceleration of gravity; U_* is the shear velocity, and c is a coefficient with a value of: 1.5 for nearly uniform sand, 1.8 for a naturally graded sand, and 2.8 for a very wide range of grain diameter.

The shear stress, τ , produced at the sand surface by wind is one of the most important factors in the movement of sand by wind. When the shear stress exceeds a certain critical value, the sand particles start to move. As long as there is no sand movement, the wind velocity distribution is described by the general equation

$$U = c \log \frac{Z}{Z_o} \qquad (2)$$

in which U is the velocity at height Z above the sand surface and Z_o is a reference parameter. In experiments where sand movement occurs, it was developed by Zingg (6) that

$$U = 6.13 U_* \log \frac{Z}{Z'} + U'$$

or

$$U_* = \frac{U - U'}{6.13 \log (Z/Z')} \qquad (3)$$

where Z' is the height where the velocity profiles for different wind speeds appear to meet at a point which is termed a "focus" and U' is the wind speed at this elevation. The height of the focus, Z' appears to be associated with the height of the ripples on the surface. Zingg (6) found that the value of Z' and U' is given by the expressions

$$Z' = 10\ d, \text{ in millimeters} \qquad (4)$$

$$U' = 20\ d, \text{ in miles/hour} \qquad (5)$$

where the grain diameter, d, is expressed in millimeters.

Equation (1) gives the transport in pounds per second per footwidth. In a more general way this equation can be written as

$$Q = c \cdot \ell \cdot T \sqrt{\frac{d}{D}}\ \frac{\gamma}{g}\ U_*^3 \qquad (6)$$

where

Q = total transport in pounds per year
c = Bagnold constant
ℓ = length of reach in feet perpendicular to direction of wind considered
d = average grain diameter of sand considered (d_{50} mm)
D = average grain diameter of standard 0.25 mm sand

γ = specific wt of air = (0.076 lbs/ft^3)
U_* = shear velocity in ft/sec
T = duration of wind of a particular speed in seconds per year
g = acceleration due to gravity = 32.2 ft/sec^2

Now substituting the values of γ, g, and choosing c = 1.8, since the sand considered has a natural grading, we obtain,

$$Q = (1.8) \cdot (\ell) \cdot (t \cdot 3.6 \cdot 10^3) \sqrt{\frac{d}{D}} \cdot \frac{0.076}{32.2} \cdot U_*^3$$

$$Q = 15.20\, t \cdot \ell \sqrt{\frac{d}{D}}\, U_*^3 \text{ in pounds per year} \qquad (7)$$

where t is in hours per year.

ESTIMATES OF TRANSPORT FROM NATURAL BEACHES

As an illustration of the application of the above equations to calculating the annual transport of sand from a beach, Salmon Beach in Northern California was selected (Fig 1) (Kadib, (4). As discussed by Zeller (5), this is a typical condition for the establishment of a major sand dune area--namely, (1) a supply of sand from streams upcoast from the area, (2) a prominent headland where sediment over the centuries has accumulated, and (3) low topography back from the beach where the prevailing onshore winds can easily move the sand inland from the region of accumulation at the beach.

In the calculations to follow it is assumed that the sand size at the mid-tide level on the beach face is a measure of the sand being blown inland from the beach by wind action. Consequently, sand samples were taken at the mid-tide level for eight localities along the coast as shown in Fig. 2. These samples were subjected to mechanical analyses and the 50% grain diameter (d_{50}) determined. These mean diameters are shown in Fig. 2. For calculations the coastline was divided into eight reaches whose characteristics are shown in Table 1.

The wind duration in hours of winds of various speeds from various directions was compiled from wind observations taken nearby at the Pacific Marine Station, Dillon Beach, California. A year of observations (September 1, 1962 to August 31, 1963), in which both wind speed and direction were obtained from an anemometer located at 18 ft above the ground surface, are summarized in Table 2. As indicated in this table, the anemometer recording system was inoperative a portion of the time; consequently, the computed rate as indicated below perhaps is on the low side, but the computation procedure is valid. In Table 2 wind speeds below 10 mph were considered as "calm," since their contribution to transport can be considered as small. The choice of the uneven values

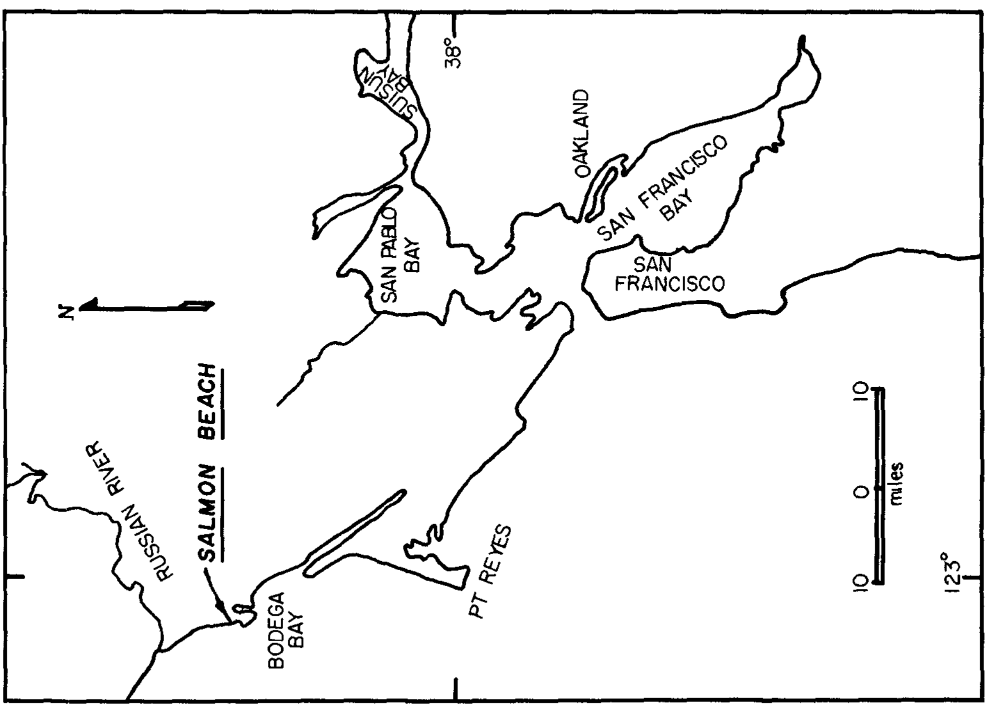

FIG. 1. --VICINITY MAP: SALMON BEACH NEAR BODEGA BAY, CALIF.

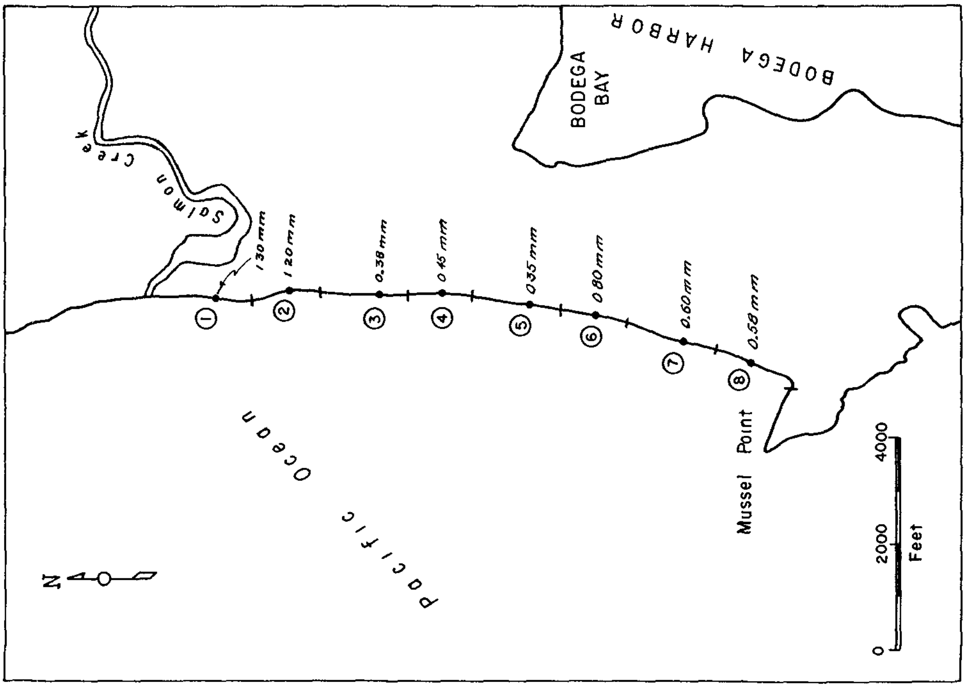

FIG 2 --NUMBER AND LOCATION OF REACHES AND SAND SAMPLES (SALMON BEACH, CALIF.)

Table 1

Physical Characteristics of Salmon Beach

Reach No.	Length along the coastline (ft)	d_{50} (mm)	$\sqrt{\frac{d_{50}}{D}}$	Remarks
1	2200	1.30	2.29	Naturally graded sand
2	1350	1.20	2.20	"
3	1700	0.380	1.24	"
4	1200	0.450	1.35	"
5	1700	0.355	1.22	"
6	1350	0.800	1.80	"
7	1800	0.600	1.55	"
8	1800	0.580	1.53	"

Table 2

Duration of Wind Per Year for Different Wind Speeds
(Pacific Marine Station)

		Duration of Wind (Hours per Years)							
Speed ft/sec.	Speed mph	N	NW	W	SW	S	SE	E	NE
14.7	10	4	45	3	5	2		1	1
16.5	11.2	20	83	13	12	18	2	38	2
18.2	12.4	3	50	1	7	2		1	2
18.8	12.8	10	23	6	4	5	6	20	
20.	13.6	5	24	1	1	3			2
21.02	14.3	12	39	5	5	6	7	24	
21.8	14.8	1	33	4				1	1
22.9	15.6	14	35	5	5	2	9	10	1
23.2	15.8		28	1		1		1	2
24.7	16.8	10	53	2	3	4	6	8	
26.2	17.8	1	25	1					1
26.6	18.1	4	28			1	5	12	
27.6	18.8		15			1			1
28.4	19.3	6	14	2	2	4	10	5	
29.1	19.8		18	4					
30.3	20.6		14	2	1	4	5	3	
32.	21.7	6	13			3	7	1	1
33.2	22.6	5	8		3	3	8	4	
34.7	23.6	8	10	1	1	2	7		
36.3	24.6	2	14		3	1		2	
37.8	25.7	8	3				4	2	
39.3	26.7	8	5		3		3	1	
40.7	27.7	3	2				5	2	
> 41.2	>28.0	5	1				2	16	

Total hrs - 1135 hrs. of wind > 10 mph
Calm - 3555 hrs.
No records - 4070 hrs.

of wind speeds resulted from the reduction of wind data from the anemometer chart and the calibration curve of the anemometer.

Although it is noted from Table 2 that winds may blow from practically all directions, it is evident from Fig. 2 that winds from only a few directions will cause an inland transport of sand from the beach. Thus, considering the different possible wind directions to give inland transport, it appears that only four directions need be considered at Salmon Beach. These directions are N, NW, W, and SW. The perpendicular projections ℓ_2, ℓ_4, ℓ_1, and ℓ_3, respectively, of these directions (Fig. 3) were measured and presented in Table 3. These lengths represent ℓ in equation 7 for total transport calculations.

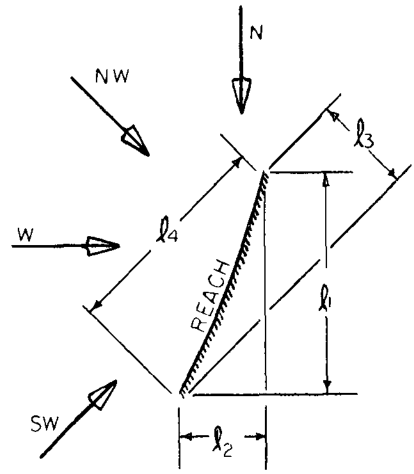

Fig. 3

The shear velocity, U_*, in equation 7 is calculated from equation 3 with the values of Z' and U' being evaluated by equations 4 and 5, respectively, from the mean grain diameter, d, for each reach. Values of Z' and U' for each reach are presented in Table 4. The value of Z in equation 3 was 18 ft, the anemometer height. Using the data in Table 4 the shear velocity for various wind speeds U observed at an elevation Z of 18 ft was calculated for each reach and is summarized in Table 5. A sample calculation for the data summarized in Tables 4 and 5 is as follows:

For Reach (4)

$$d_{50} = 0.45$$

From equation (4), $Z' = (10)\,(0.45) = 4.5$ mm or 0.0147 ft. and from equation (5), $U' = (20)\,(0.45) = 9$ mph or 13.20 ft/sec. Considering a wind speed of 27.7 mph (40.70 ft/sec) the shear velocity from equation (3) is

$$U_* = \frac{U - U'}{6.13 \log(Z/Z')} = \frac{40.70 - 13.20}{6.13 \log (18/0.0147)} = 1.44 \text{ ft/sec}$$

Table 3

Perpendicular Projections for Different Wind Directions*

Reach No.	Length ℓ (ft)	Representing grain dia. d_{50} (mm)	ℓ_1 (ft)	ℓ_2 (ft)	ℓ_3 (ft)	ℓ_4 (ft)
1	2200	1.30	1900	200	1400	1450
2	1500	1.20	1400	200	900	900
3	1700	0.38	1600	150	1150	1300
4	1200	0.45	1150	150	850	800
5	1700	0.355	1500	400	1100	1400
6	1350	0.80	1300	300	700	1000
7	1800	0.60	1700	500	900	1500
8	1800	0.58	1400	900	500	1700

* South, SE, E and NE winds do not contribute to inland movement

Table 4

Calculations for the Focal Point Using the Zingg Formula

Reach No.	d_{50} mm	Z' = 10 d mm	Z' (ft)	U' = 20dm (m/h)	U' ft/sec
1	1.30	13.0	0.0427	26.00	38.00
2	1.20	12.0	0.0394	24.0	35.00
3	0.38	3.8	0.0125	7.6	11.30
4	0.45	4.5	0.0147	9.0	13.20
5	0.355	3.55	0.0116	7.10	10.40
6	0.80	8.0	0.0262	16.00	23.50
7	0.60	6.0	0.0197	12.00	17.60
8	0.58	5.80	0.019	11.60	17.00

Table 5

Calculation of U_* for Different Reaches and Wind Speeds

U_{18} ft/sec	$U_* = \frac{U_{18} - U'}{6.13 \text{ Log } Z/Z'}$ ft/sec							
	Reach No. 1	Reach No. 2	Reach No. 3	Reach No. 4	Reach No. 5	Reach No. 6	Reach No. 7	Reach No. 8
14.70	-	-	0.175	0.079	0.22	-	-	-
16.50	-	-	0.268	0.175	0.310	-	-	-
18.20	-	-	0.356	0.264	0.40	-	0.033	0.065
18.8	-	-	0.385	0.286	0.428	-	0.066	0.098
20.0	-	-	0.45	0.358	0.49	-	0.130	0.164
21.02	-	-	0.50	0.410	0.55	-	0.19	0.22
21.8	-	-	0.54	0.450	0.58	-	0.23	0.26
22.9	-	-	0.61	0.510	0.635	-	0.29	0.32
23.2	-	-	0.615	0.53	0.64	-	0.31	0.34
24.7	-	-	0.690	0.605	0.73	0.069	0.39	0.42
26.2	-	-	0.780	0.695	0.815	0.167	0.48	0.51
26.6	-	-	0.795	0.710	0.825	0.180	0.49	0.525
27.6	-	-	0.840	0.760	0.88	0.235	0.55	0.58
28.4	-	-	0.88	0.800	0.92	0.29	0.59	0.621
29.1	-	-	0.918	0.84	0.954	0.328	0.63	0.66
30.3	-	-	0.98	0.90	0.97	0.40	0.694	0.73
32.0	-	-	1.07	0.99	1.06	0.494	0.73	0.81
33.2	-	-	1.13	1.053	1.12	0.56	0.80	0.882
34.7	-	-	1.15	1.13	1.20	0.65	0.88	0.964
36.3	-	0.074	1.24	1.22	1.28	0.74	0.97	1.05
37.8	-	0.172	1.32	1.29	1.35	0.83	1.05	1.19
39.3	.082	0.265	1.39	1.37	1.43	1.00	1.13	1.27
40.7	0.168	0.31	1.464	1.44	1.50	1.10	1.207	1.35
>41.2								

Using the above equations and the data presented in Tables 1-5, inclusive, the total annual transport can be calculated for each reach for all winds contributing to the movement of sand. The procedure in these calculations is presented in Table 6 where Reach 4 is considered as an example. Winds in excess of 10 mph from the critical directions of N, NW, W, and SW are considered. The application of the various data in the calculation of the annual rate of transport in Reach 4 by equation 7 is self-explanatory. Similar calculations for the other reaches along the beach under investigation show a total estimated annual rate of transport inland of approximately 11,000 cubic yards; however, as previously stated this quantity perhaps is on the low side since the anemometer was inoperative for an appreciable percentage of the time. It should be noted that no

Table 6

Total Transport Per Year, Reach 4

Reach No. 4, $\sqrt{\frac{d}{D}} = 1.35$

U ft/sec	U* ft/sec	$U*^3$	N t hrs	N ℓ_2 ft	N $U*^3t$	NW t hrs	NW ℓ_4 ft	NW $U*^3t$	W t hrs	W ℓ ft	W $U*^3t$	SW t hrs	SW ℓ_3 ft	SW $U*^3t$
14.7	0.079	.0005	4	150.00	.002	45	800.00	.0225	3	1150.00	..0015	5	850	.0025
16.5	0.175	.0053	20	150.00	0.106	83	800.00	0.440	13	1150.00	.069	12	850	.0635
18.20	0.264	0.0185	3	150.00	0.555	50	800.00	.925	1	1150.00	.019	7	850	.1295
18.80	0.286	0.0234	10	150.00	0.234	23	800.00	0.57	6	1150.00	0.140	4	850	0.0935
20.00	0.358	0.046	5	150.00	0.230	24	800.00	1.10	1	1150.00	.046	1	850	.046
21.02	0.410	0.0685	12	150.00	0.820	39	800.00	2.66	5	1150.00	0.342	5	850	0.342
21.80	0.45	0.090	1	150.00	0.090	33	800.00	2.96	4	1150.00	0.360	0	850	0.000
22.90	0.51	0.132	14	150.00	1.850	35	800.00	4.64	5	1150.00	0.650	5	850	0.650
23.20	0.53	0.148	0	150.00	0.000	28	800.00	4.15	1	1150.00	0.148	0	850	0.000
24.70	0.605	0.220	10	150.00	2.200	53	800.00	11.65	2	1150.00	0.440	3	850	0.660
26.20	0.695	0.335	1	150.00	0.335	25	800.00	8.36	1	1150.00	0.335	0	850	0.000
26.60	0.710	0.358	4	150.00	1.432	28	800.00	10.024	0	1150.00	0.000	0	850	0.000
27.60	0.76	0.440	0	150.00	0.000	15	800.00	6.600	0	1150.00	0.000	0	850	0.000
28.40	0.80	0.510	6	150.00	3.060	14	800.00	7.140	2	1150.00	1.020	2	850	1.020
29.10	0.84	0.590	0	150.00	0.000	18	800.00	10.60	4	1150.00	2.360	0	850	0.000
30.30	0.90	0.712	0	150.00	0.000	14	800.00	10.000	2	1150.00	1.424	1	850	0.712
32.00	0.99	0.980	6	150.00	5.880	13	800.00	12.700	0	1150.00	0.000	0	850	0.00
33.20	1.053	1.160	5	150.00	5.80	8	800.00	9.28	0	1150.00	0.000	3	850	3.48
34.70	1.130	1.45	8	150.00	11.60	10	800.00	14.50	1	1150.00	0.145	1	850	0.145
36.30	1.22	1.82	2	150.00	3.64	14	800.00	25.50	0	1150.00	0.000	3	850	5.46
37.80	1.29	2.15	8	150.00	17.20	3	800.00	6.45	0	1150.00	0.000	0	850	0.00
39.30	1.37	2.55	8	150.00	20.40	5	800.00	12.75	0	1150.00	0.000	3	850	7.65
40.70	1.44	2.96	3	150.00	8.88	2	800.00	5.92	0	1150.00	0.000	0	850	0.000
>41.2	1.80	5.80	5	150.00	29.00	1	800.00	5.80	0	1150.00		0		0.000
					112.815			174.742			7.500			20.456

$\Sigma U*^3 \ell t$ = 16,930 + 139,793 + 8,625 + 17,368

= 182,712

Q_4 = 1.35 x 15 · 2 x 182,716 = 3,758,000 lb/year reduction was made in the calculated rate of transport for sand being in the moist condition--which Belly (2) showed to be an important factor. This factor may be particularly important in localities, such as the section of the California coast discussed above, where high winds may also be accompanied by considerable rain.

SUMMARY

A procedure is outlined for the calculation of the annual rate of transport of sand that might be expected to be carried inland from a natural beach by wind action. The procedure involves the beach composition and alinement, the frequency of winds of various speeds from various directions, and a suitable formula to describe the transport. It is possible that the transport formula may be altered as a result of current research; however, the general procedure as outlined herein should apply.

REFERENCES

1. Bagnold, R. A., The physics of blown sand and desert dunes, William Morrow and Co., New York, 265 pp.

2. Belly, Pierre-Yves, Sand movement by winds, U. S. Army Coastal Engineering Research Center, Tech. Memo. No. 1, Wash., D. C., Jan. 1964.

3. Johnson, J. W., Sand movement on coastal dunes, Federal Inter-Agency Sedimentation Conference, Jackson, Miss., Jan. 1963.

4. Kadib, A. L., Calculation procedure for sand transport by wind on natural beaches, U. S. Army Coastal Engineering Research Center, Misc. Paper 2-64, April 1964, Wash., D. C.

5. Zeller, R. P., A general reconnaissance of coastal dunes of California, Beach Erosion Board Misc. Paper No. 1-62, Wash., D. C., June 1962.

6. Zingg, A. W., Wind-tunnel studies of movement of sedimentary materials, Proc. Fifth Hydraulic Conference, State Univ. of Iowa Studies in Engin., Bull. 34, 1953, pp. 111-135.