DEPARTMENT OF THE ARMY CORPS OF ENGINEERS

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

SAND MOVEMENT BY WIND ACTION
(ON THE CHARACTERISTICS OF SAND TRAPS)

TECHNICAL MEMORANDUM NO. 119

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FOREWORD

Sand movement along the coast by wind action can be a major factor in some areas, yet very little is known about the basic mechanisms of movement by wind, or even as to the relative quantity of material moved. With the growing use of artificial placement of sand material for beach restoration and protection, movement by wind of sand in the area shoreward of the waterline has become more and more a matter of concern - particularly for areas in which extreme storms and hurricane conditions can occur. The first step towards study of the mechanisms and effect of sand transport by wind is to obtain and calibrate the necessary instrumentation. This report presents the results of a study of several types of sand traps, leading to the development of a particular type with very nearly 100% efficiency.

This report was prepared at the Wave Research Laboratory of the Institute of Engineering Research at the University of California in pursuance of contract DA-49-055-Eng-17 with the Beach Erosion Board which provides, in part, for the study of sand movement by wind. The authors of this report, Kiyoshi Horikawa, and H. W. Shen were Assistant Research Engineer and Graduate Research Engineer, respectively, at the University during the time this work was carried out. During this time Professor Horikawa was in this country on a Fulbright scholarship. Professor Horikawa is currently assistant professor at the University of Tokyo in Japan, and Mr. Shen is a graduate student at the University of California.

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Views and conclusions stated in the report are not necessarily those of the Beach Erosion Board.

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SAND MOVEMENT BY WIND ACTION

- ON THE CHARACTERISTICS OF SAND TRAPS -

By

Kiyoshi Horikawa and H. W. Shen

ABSTRACT

The movement of sand by wind action along the coast has long been a problem of importance to the coastal engineer engaged in the design and maintenance of shore protection works. Many research workers have studied this subject in the laboratory and/or in the field, but the mechanism of the sand movement as yet has not been solved completely. In particular more field data are required to formulate a relationship between the rate of sand movement, the sediment characteristics and the wind conditions. Prior to a program of field observation, one of the most important problems to investigate is the characteristics of sand traps and the selection of the most effective one for detaining a representative amount of sand transported by wind. Therefore in this report the main effort is devoted to the study of available sand traps and to development of a suitable type if needed.

INTRODUCTION

The estimation of the annual amount of sand transported along a coast is important for planning and constructing coastal structures. One of the motive forces for transporting sand along the coast is the well-known littoral current generated by wave action, and the other is by wind.

The sand movement by wind action has been treated by several research workers. Their theories can be classified into two groups; one is based on the diffusion theory, and the other is based on the assumption that the sand particles move down stream with bouncing motions near the sand surface. The Exner theory[10]* is a representative of the former, and Bagnold's[1] is of the latter.

According to Bagnold,[1] the sand movement is classified into (1) surface creep, (2) saltation, and (3) suspension. But it is quite clear through the visual observation of sand movement in the wind tunnel that most of the sand particles do not move in suspension due to the large difference of density between the sand particles and the air. This is one of the great differences of sand movement in air from that in water.

In the following sections the factors related to the subject, "Sand Transport by Wind", will be briefly discussed.

Wind Velocity Above Sand Surface

The shear stress, τ_0, at the sand surface due to the wind is one of the most important factors in investigating the sand movement by wind action. When the shear stress (or tractive force) exceeds some critical value, the sand particles start to move.

The equation which is most commonly used for obtaining the wind velocity distribution is the Prandtl equation,

$$U = \frac{U_*}{K} \log \frac{Z}{Z_0}, \qquad (1)$$

where U is the wind velocity at an elevation Z above the sand surface, K is the Karman constant which is about 0.40, Z_0 is the roughness of the surface, and $U_* = \sqrt{\frac{\tau_0}{\rho}}$ is the shear velocity in which ρ is the density of air. By using the above equation with the assumption of K = 0.40, the records of velocities at several elevations may be used to determine the shear velocity and the roughness immediately.

Recently several measurements of the shear values due to wind have been conducted by meteorologists [21] [9] and engineers [26] [27] in order to investigate the variation of the value of K. The results show that the value of K seems to vary with the surface condition. (see Table 1), but there was not sufficient evidence to establish

*Numbers in parentheses pertain to the reference list at the end of the report.

a deviation from the value of 0.40.

Table 1

	Surface Condition	Mean Value of K
Rider, N. E.	Grass Land (Field)	0.43
Zingg, A. W.	Sand Surface (Laboratory)	0.375

On the other hand Vanoni,[24] and Einstein and Chien[8] show that in water the concentration of sediment has a great deal of effect on the value of K which varies from 0.2 to 0.4. From the above investigation, it appears that from the engineering point of view the assumption of $K = 0.40$ may be satisfactory for our present problem.

Concerning the roughness factor, Z_o, Zingg[27] proposes the following equation,

$$Z_o = 0.081 \log \frac{d}{0.18} \tag{2}$$

with Z_o and d (the sand grain diameter) expressed in millimeters. This equation contains both the results of Bagnold ($Z_o = d/30$) for small grain sizes and that of White ($Z_o = d/9$) for large grain sizes.

The Prandtl equation holds good within the condition of wind strength which is not large enough to move sand particles; but if the wind velocity is large enough to move sand particles, the wind velocity profile will be affected by the sand movement. The influence region penetrates into higher elevations with the increase of wind velocity due to the increase in flying height of sand particles. Here is a quite interesting fact; that is, all the straight lines of the velocity distribution on the semi-log paper concentrate on a certain point, which is called a "focal point" by Bagnold. There must be some reason why such a definite point is obtained for each condition of bed material. The reason for such a phenomenon is still unsolved.

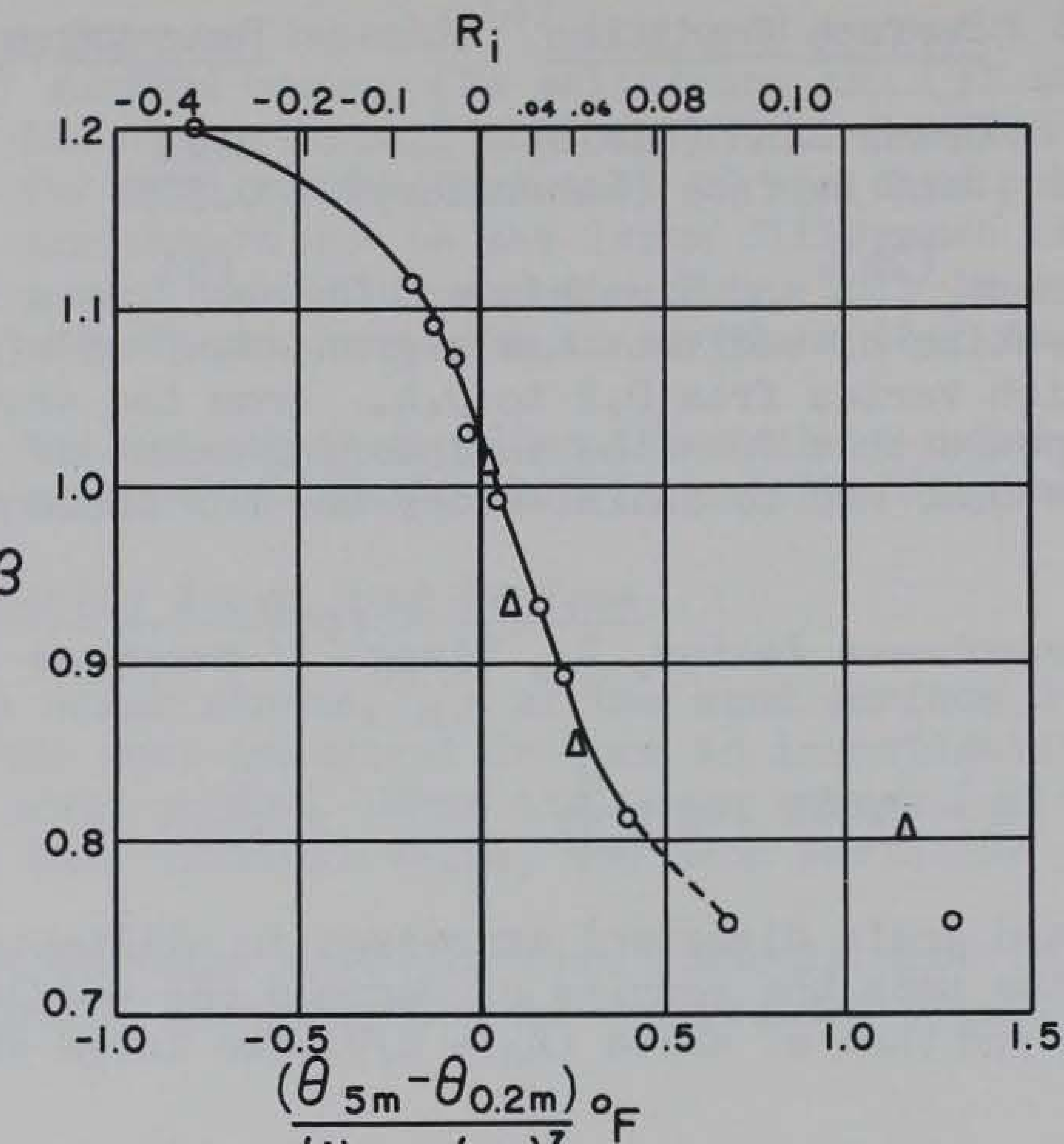
The equation of wind velocity distribution is modified into the following form,[1]

$$U = 5.75\, U_* \log_{10} \frac{Z}{Z'} + U' , \tag{3}$$

in which Z' and U' show the condition at the focal point. According to experiments by Zingg[27] the predicted focal point is expressed by

$$\left.\begin{array}{ll} Z' = 10\ d & \text{in mm,} \\ U' = 20\ d & \text{in mile/hour,} \end{array}\right) \tag{4}$$

where d is the grain diameter being measured in mm with the condition of K = 0.375 determined by Zingg's measurement.



o Short grass surface: Z_o = 0.27 cm

Δ From Sverdrup's observations over snow: Z_o = 0.25 cm

FIGURE I. THE VARIATION OF β WITH STABILITY
(after Deacon, 1949)

Another factor which must be considered is the effect of temperature gradient on the velocity distribution. Deacon(6) proposed one empirical formula for expressing the general wind velocity profile, in which a stability index β , is introduced. The equation is

$$\frac{U}{U_*} = \frac{1}{K(1-\beta)} \left[\frac{Z}{Z_o}^{(1-\beta)} - 1 \right] , \tag{5}$$

in which β is given by the graph shown in Figure 1. Here R_i, the Richardson Number, is defined as

$$R_i = g \frac{d \log_e \theta}{d Z} \Big/ \left(\frac{dU}{dZ}\right)^2_{Z = Z_1} \qquad (6)$$

where θ is a temperature. Therefore the varying thermal stratification can be expressed by the varying values of β. That is,

$\beta > 1$	for thermal instability,
$\beta = 1$	for neutral conditions,
$\beta < 1$	for thermal stability.

Expanding the right hand side of Equation (5), the profile expression becomes

$$\frac{U}{U_*} = \frac{1}{K} \left[\log_e \frac{Z}{Z_o} + \frac{(1-\beta)}{2!} \log_e^2 \left(\frac{Z}{Z_o}\right) + \cdots \right] \qquad (7)$$

Hence under the neutral condition, $\beta = 1$, the above equation reduces to the well-known logarithmic relationship for aerodynamically rough flow.

In the field the effect of the temperature gradient on the wind profile should be considered, but the field observations at Hanford[23] show that the wind profile is logarithmic about 93% of the time during daylight hours. At night the logarithmic formula is less applicable owing to the thermal stratifications of the air.

Woodruff and Lyles[26] concluded from the results of field observations in the Great Plains that:

(1) A large percentage (about 70 percent in this study) do conform to the modified logarithmic law employing the zero plane displacement, d';

$$\frac{U}{U_*} = \frac{1}{K} \log \left(\frac{Z + d'}{Z_o} \right) \qquad (8)$$

(2) Direct shear measurements verify use of the modified log equation for shear computation during steady winds. The Deacon equation was found to represent the velocity profile very well for gusty winds.

From the above investigation the best way to determine the shear stress or shear velocity is from the measurement of the wind velocity from one velocity reading at some special elevation. Here we have two examples, which have been established by Japanese engineers in the field. These are:

$$U_* = 0.053\ U_{100} \qquad \text{(Kawata)}^{(16)} \tag{9}$$

$$U_* = 0.0572\ U_{446.5} - 17.1 \qquad \text{(Hamada, Okubo, and Hase)}^{(12)} \tag{10}$$

in which the unit of velocity is cm/sec and U_{100} and $U_{446.5}$ are velocities at the heights of 100cm and 446.5cm above the sand surface, respectively. Assuming that if (1) the temperature is instable, (2) Zingg's results are applicable for determining the projected focal point, and (3) the grain diameter is 0.3 mm, the following relationships are obtained directly from the above equations;

(1) if $K = 0.375$,

$$U_* = 0.0647\ U_{100} - 17.3, \tag{11}$$

$$U_* = 0.0514\ U_{446.5} - 13.7, \tag{12}$$

(2) if $K = 0.40$,

$$U_* = 0.0690\ U_{100} - 18.4 \tag{13}$$

$$U_* = 0.0548\ U_{446.5} - 14.7. \tag{14}$$

All of the above equations are shown in Figure 2. From this result the assumptions made here seem to be fairly reasonable.

Usually the wind velocity is determined as the mean value from a five or ten minute record. As pointed out by Woodruff and Lyles[26] the gustiness or the fluctuation of wind velocity affects the velocity readings, and therefore the calculations of shear. An examination of wind records shows that they can be grouped into three classes, (1) almost steady, (2) fluctuating, and (3) fluctuating considerably. In this aspect we must consider the effect of gustiness on the shear velocity and on the sediment transportation.

Sand Movement By Wind

In the previous section the wind velocity profile and the shear velocity, which are the primary motivating forces in initiating and sustaining sand movement, were discussed. Consider now the problem of sand movement. The initiation of sand movement has been investigated by Bagnold [1], who gave the following equation for the threshold value of the shear velocity, U_{*t}, that is

$$U_{*t} = A\sqrt{\frac{\sigma - \rho}{\rho}\, gd}, \tag{15}$$

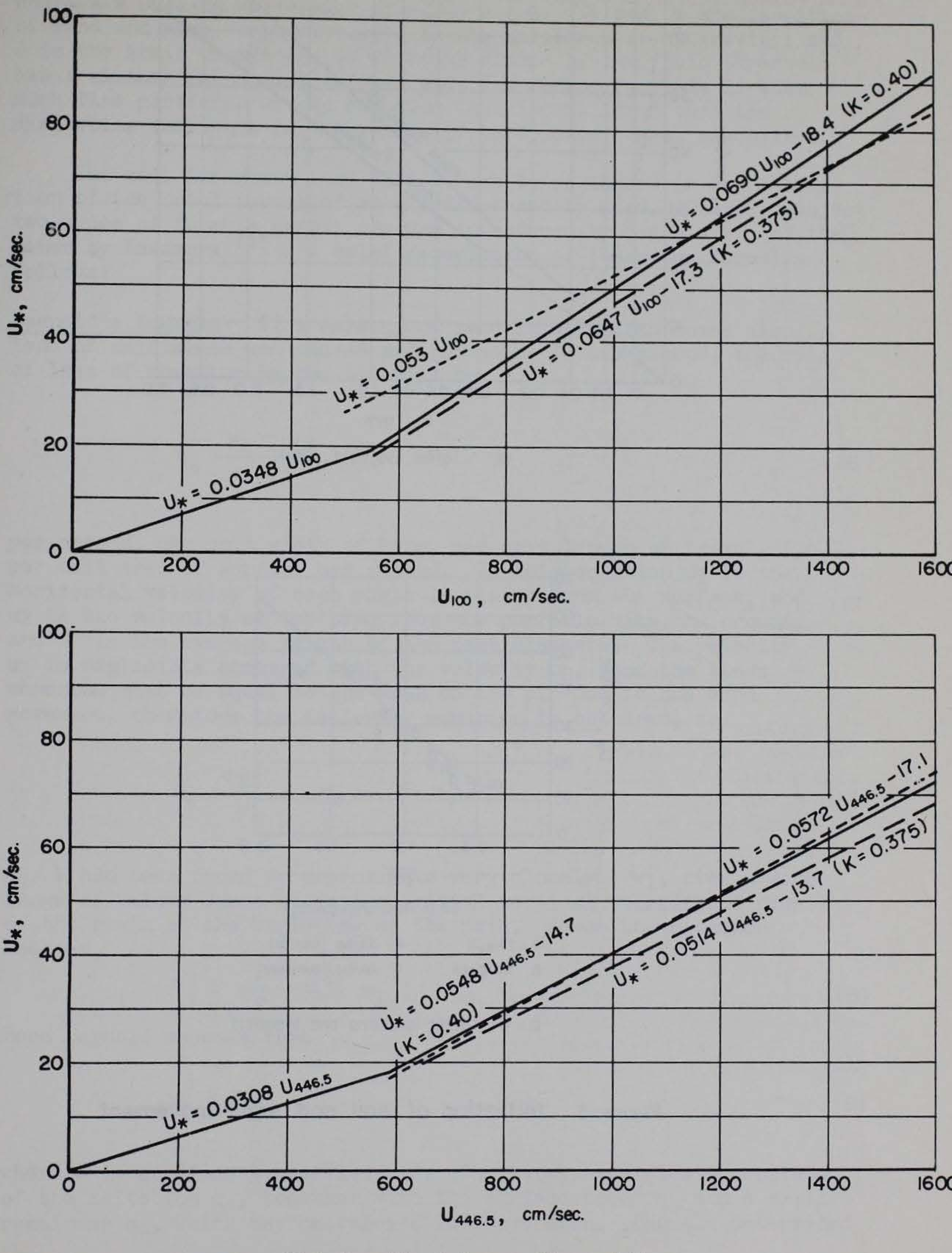
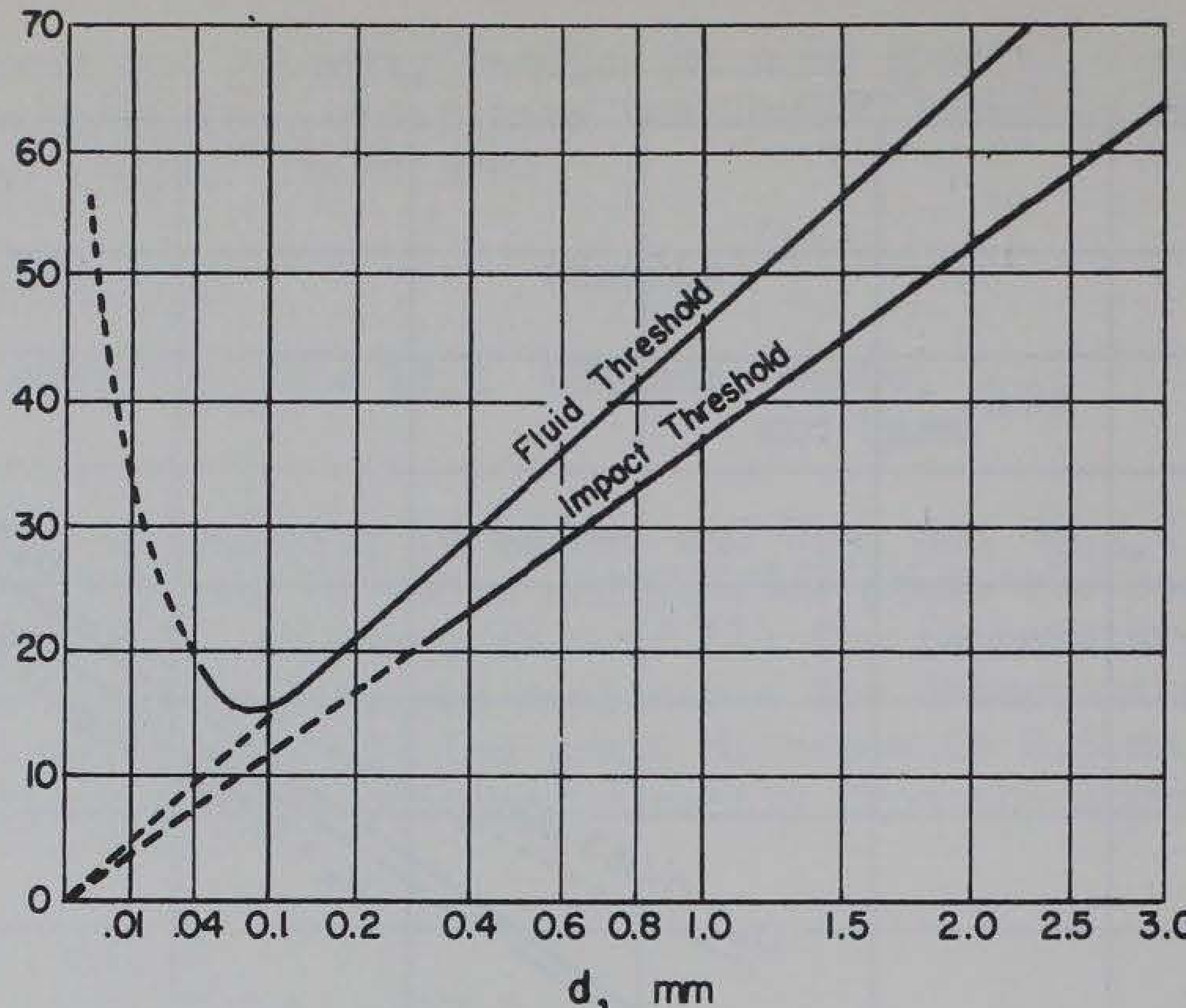
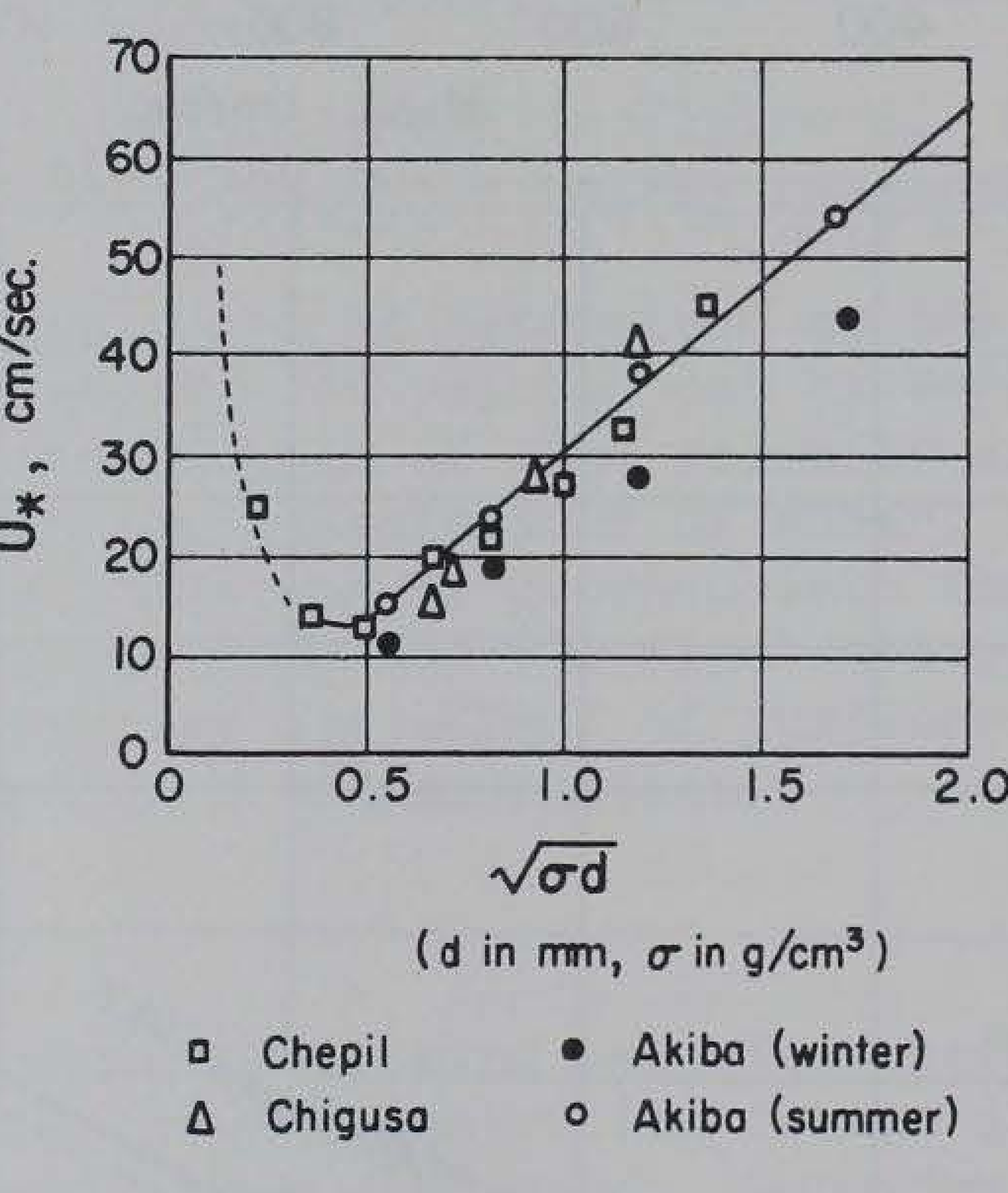


Figure 2. **Relationship between U_* and U_z**



a. (after Bagnold, 1954)



b. (after Ishihara and Iwagaki)

Figure 3. **Initiation of soil and sand movement**

where A = 0.1, in the region of $\frac{U_* d}{\nu} > 3.5$; σ and ρ are densities of sand and air, respectively; g is the acceleration of gravity; and d is the grain diameter. As shown in Figure 3, the fluid threshold has a minimum value at d $\doteqdot$ 0.08 mm. The reason for this is that such fine particles are so far into the viscous layer that the disturbing influence of the eddies of turbulence cannot reach them.

The most important item of interest to engineers is the estimation of the total amount of sand transported by wind. On this subject two types of formula exist; one was introduced by Bagnold(1) and the other by Kawamura.(15). A brief description of these two formulas follows:

Bagnold's Formula: If a mass q_s of sand in saltation moves along a lane of unit width and passes a fixed point in one second, the rate of loss of momentum by the air will be,

$$q_s \frac{u_1 - u_2}{l} \tag{16}$$

per second, per unit width of lane, per unit length of travel, i.e. per unit area of surface per second. In this equation u_1 is the horizontal velocity of each particle rising from the surface, and u_2 is the velocity at the time when the particle hits the ground, and l is the average length of the particle path. The velocity u_1 is negligible compared with the velocity u_2, and the above momentum must be equal to the drag on the air due to the sand movement, therefore the following equation is obtained, as

$$q_s \frac{u_2}{l} = \tau_0 = \rho \ U_*^2 \tag{17}$$

u_2/l has been found to approximate very closely g/w_1, over a wide range of values where w_1 is the initial vertical velocity of rise of the grain at the beginning of the path. Hence the equation becomes,

$$q_s = \frac{\rho}{g} \ U_*^2 \ w_1 \tag{18}$$

Here Bagnold assumes that

$$w_1 = BU_* \tag{19}$$

where B is an "impact coefficient". The total sand flow q consists of the saltation q_s, together with the surface creep q_c and a small remainder q_o, which may be carried in suspension. Bagnold determined that q_c is approximately equal to a quarter of the whole sand flow q. Therefore he obtained

$$q = \frac{3}{4} B \frac{\rho}{g} U_*^3 \quad . \tag{20}$$

In order to include the effect of grain size, Bagnold uses D, the grain diameter of a standard 0.25-mm sand, in the following equation,

$$q = C \sqrt{\frac{d}{D}} \frac{\rho}{g} U_*^3 \quad , \tag{21}$$

C being an empirical coefficient which varies with the uniformity of sand, as shown in Table 2.

Table 2

C:	Sand Condition:
1.5	Nearly Uniform Sand
1.8	Naturally Graded Sand
2.8	A Sand of a Very Wide Range of Grain Size

Kawamura's Formula: The shear stress on the sand surface τ_0 consists of τ_s due to the impact of sand particles and of τ_w caused by the wind directly, that is

$$\tau_0 = \tau_s + \tau_w \quad . \tag{22}$$

In the equilibrium state the shear τ_w is found to be equal to τ_t, the critical shear value by Kawamura. Therefore the above equation is expressed by

$$\tau_s = \tau_0 - \tau_t \quad . \tag{23}$$

On the other hand τ_s is equal to the loss of momentum in the x direction when the sand particle hits the surface, hence

$$\tau_s = G_0 \overline{(u_2 - u_1)} \quad , \tag{24}$$

where G_0 is the amount of sand falling on the unit area of sand surface during unit time, and the bar above the term of velocity difference shows the mean value. At this point Kawamura assumes,

$$G_0 \overline{|u_2 - u_1|} = \xi G_0 \overline{|(w_2 - w_1)|} \tag{25}$$

which generally holds good in the case of non-elastic impact. ξ is a coefficient. On the other hand since $w_2 - w_1 = -2\overline{w}_1$, therefore

$$\tau_s = 2 \xi G_0 \overline{w}_1 . \tag{26}$$

From Equations (23) and (26),

$$2 \xi G_0 \overline{w}_1 = \tau_0 - \tau_t = \rho (U_*^2 - U_{*t}^2) . \tag{27}$$

According to the experimental result,

$$G_0 = K \rho (U_* - U_{*t}) \tag{28}$$

has been obtained. From the above two relations, (27) and (28),

$$\overline{w}_1 = K_1 (U_* + U_{*t}) \tag{29}$$

is obtained and in which K_1 is a constant. By using the above result Kawamura determined the expression for the average particle path length as

$$\overline{L} = K_2 \frac{(U_* + U_{*t})^2}{g} \tag{30}$$

where K_2 is another constant.

The total amount of sand, q, passing through a vertical plane with a unit width can be approximately expressed by the following equation,

$$q = G_0 \overline{L} \tag{31}$$

Therefore the final result is

$$q = K_4 \frac{\rho}{g} (U_* - U_{*t})(U_* + U_{*t})^2, \tag{32}$$

where K_4 is a constant which should be determined by the experiment.

The basic ideas of the above formulas are almost the same, but Bagnold's equation has the disadvantage that even when $U_* = U_{*t}$, q cannot be zero. From this point of view Kawamura's formula is more reasonable, but in the case of the strong wind, in which we are most interested, both relationships give approximately the same result.

In either case one empirical constant should be determined by measurement in a wind tunnel or in the field. In the former case the experiments will be conducted without much difficulty, but in the field the observations are fairly difficult because of several reasons, mainly in the design of a reliable sand trap.

Bagnold determined his coefficient according to his tests as described previously (see Table 2). Kawamura obtained the value of K_4 = 2.78 in a wind tunnel. In his papers and book Bagnold gave only five measurements of the total amount of sand transported. These were obtained by wind tunnel tests and are quite different from Kawamura's data (Fig. 4). From the above fact, it is obvious that further laboratory studies are required to establish a more reliable formula.

We have the formula obtained by O'Brien and Rindlaub [20], as a result of field observations at the mouth of the Columbia River. These tests (See Fig. 5) gave

$$G = 0.036\ U_5^3 \quad (\text{for } U_5 > 20 \text{ ft/sec}) \tag{33}$$

where G is the rate of movement in pounds of dry sand per day passing an imaginary line 1 foot in length drawn perpendicular to the wind, and U_5 is the wind velocity 5 feet above the beach surface in ft/sec.

For convenience of comparison with other results Equation (33) has been rewritten in the following form assuming that Equation (3) is applicable, and that the mean grain size is 0.20 mm.:

$$q = 9.96 \times 10^{-7} (U_* + 10.8)^3 \tag{34}$$

where q is in g/cm. - sec. and U_* is in cm./sec.

Chepil[4] has studied the movement of soil and found that the coefficient C in the following furmula,

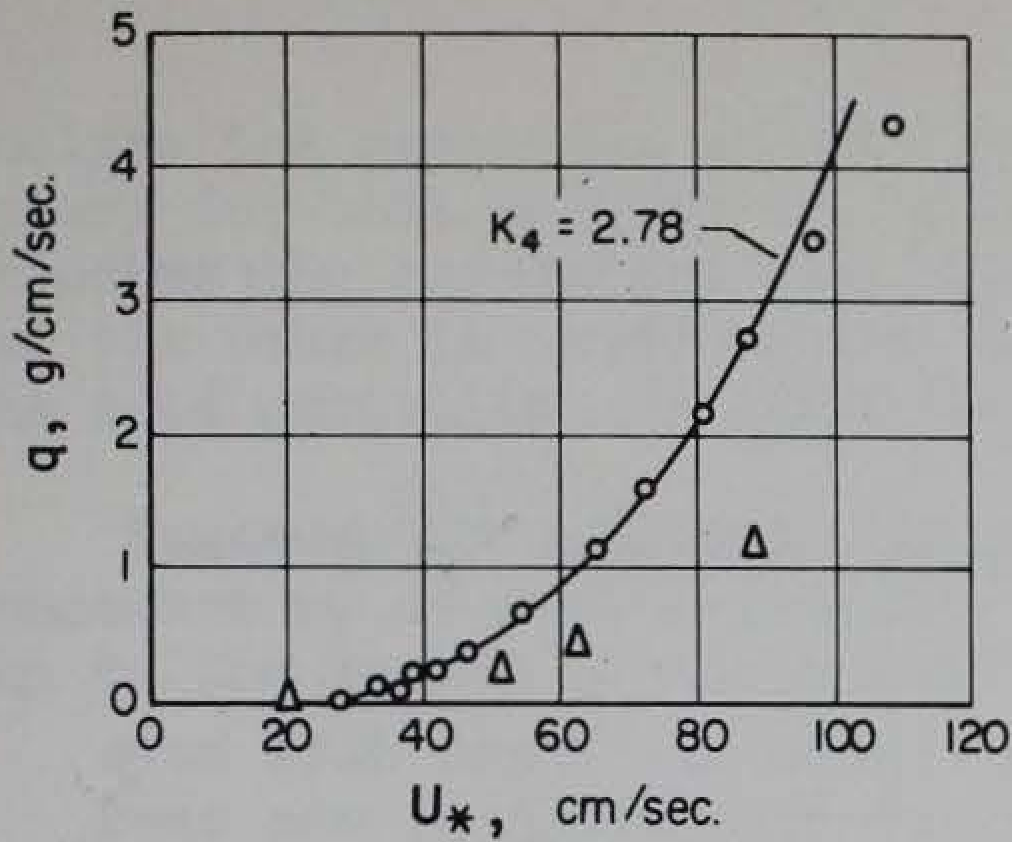


Figure 4. **Total amount of sand transported** (comparison between Kawamura's and Bagnold's result). (after Kawamura, 1951)

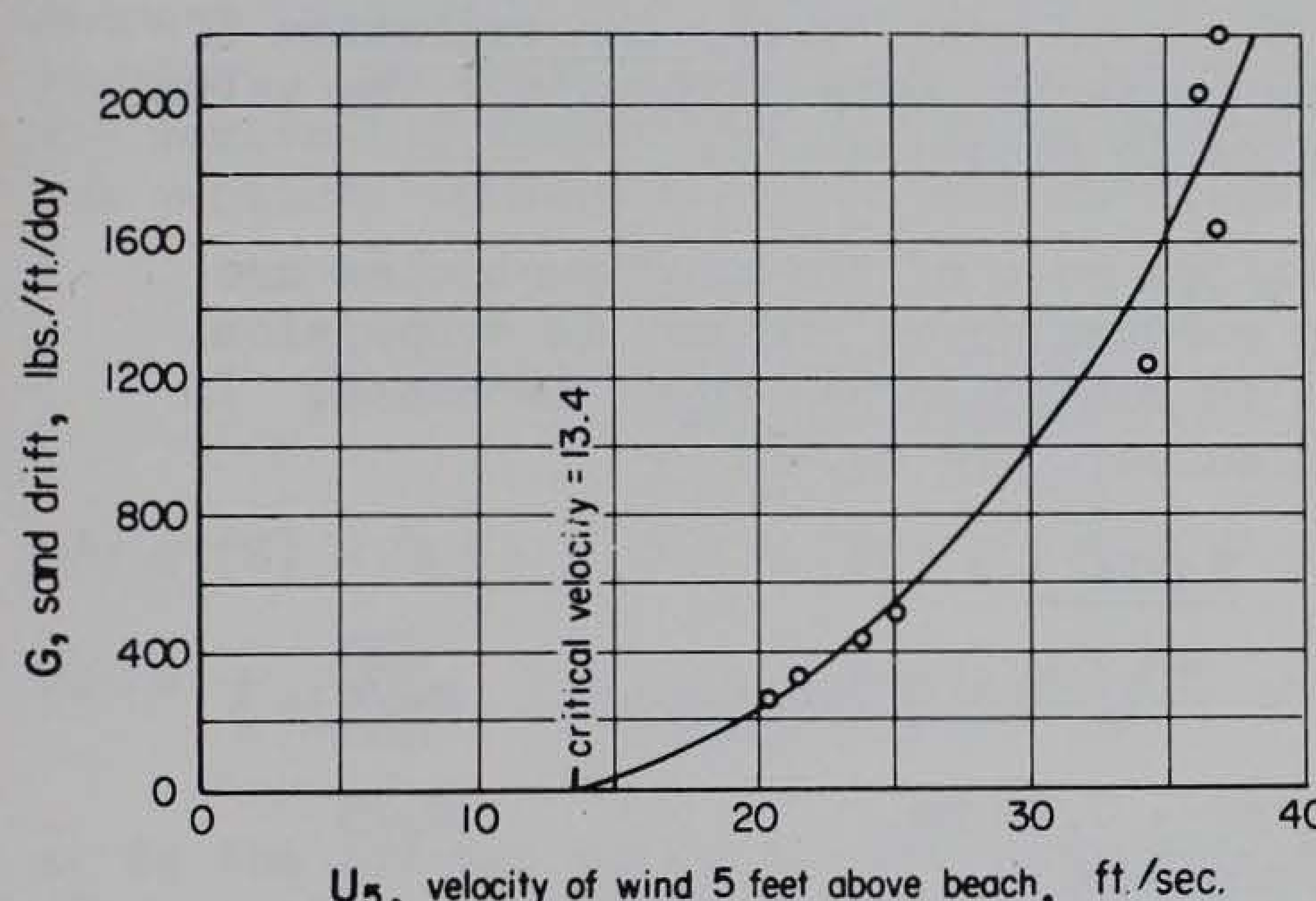


Figure 5. **Relation between wind velocity and rate of sand movement** (after O'Brien and Rindlaub, 1936)

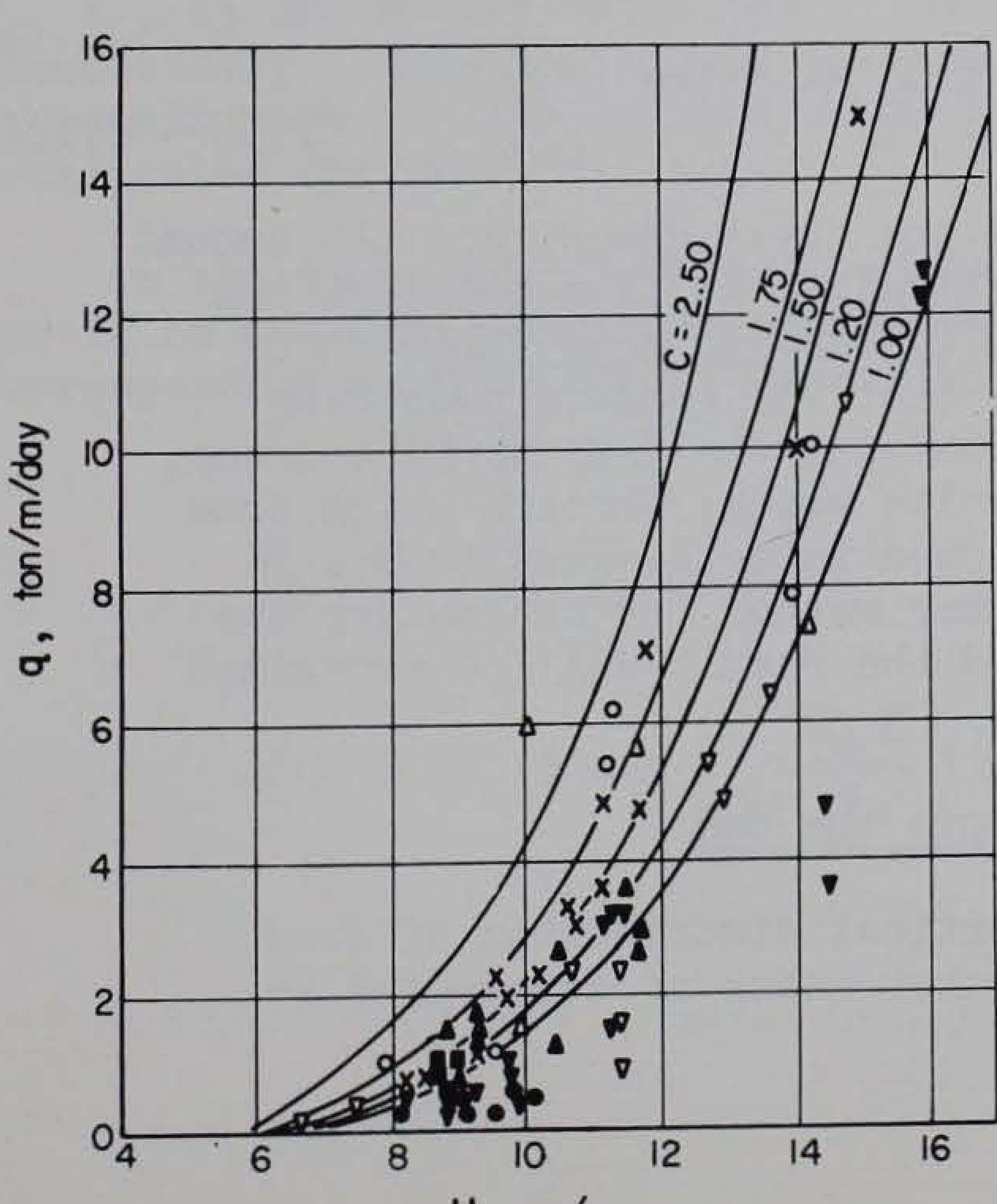


Figure 6. **Relation between wind velocity and rate of sand drift** (after Ishihara and Iwagaki, 1952)

$$q = C \frac{\rho}{g} U_*^3 , \qquad (35)$$

varied widely for different soils, the range recorded being from 1.0 to 3.1.

Another set of results is shown in Figure 6. These data have been obtained in the field by several Japanese engineers, who used different types of sand traps (14). The scattering of the data is due to the facts (1) that the characteristics of the various sand traps were greatly different from each other, and (2) that the surface conditions, such as the mean grain size, the variation of grain sizes, and the moisture contents, were different. The value of C in Figure 6 is the same as in Equation (35).

As has been discussed before most of the sand particles are transported in saltation and surface creep and not in suspension. How much sand is transported in surface creep is of interest. In Table 3 some results on this subject are shown:

Table 3

Authority:	Grain Size:	q_c/q:
Bagnold	Mean Diameter - 0.25 mm.	0.25
Chepil	(1) Fine Dune Sand	
	54.2% of total is 0.15-0.25 mm.	0.157
	(2) Sceptre Heavy Clay	
	79.6% of total is 0.25-0.83 mm.	0.249
Ishihara(13) and Iwagaki	(Field observation at Ajiro Harbor, Japan)	0.065 - 0.166

In the above table, q and q_c are the total amount and the amount of surface creep of sand, respectively. It is noted that the ratio of q_c/q varies greatly and appears to be a function of grain size. The writer believes that the various measuring methods were not accurate for obtaining the true surface creep; that is, the sand traps had a finite width, through which some amount of sand flying can be dropped into the sand traps. Therefore, the writer tried another method for estimating the surface creep. The procedure and the result will be explained in a later section.

Distribution of Sand Movement Above the Bed

The investigation of the vertical distribution of sand movement above a sand bed is another means of attempting to analyze the mechanism of sand movement. In order to establish a theory for this problem two methods have been applied. One is based on the assumption that the sand particles move as projectiles, and the other is based on the theory of diffusion by assuming that the sand particles are suspended in air.

Kawamura[15] assumed that the distribution of the vertical component w_1 of sand particles, rising up from the sand surface due to the impact of other sand particles, is expressed by:

$$\phi\ (w_1)\ \alpha\ e^{-\mu w_1}, \tag{36}$$

where $\phi\ (w_1)$ is a probability density in regard to w_1, and μ is a constant. He finally obtained the following equations; one is for the vertical distribution of concentration, and the other is for the vertical distribution of sand movement above the bed:

$$\Psi\ (Z) = \frac{2G_o}{\sqrt{gh_o}}\ K_o\left(\sqrt{\frac{2Z}{h_o}}\right) \tag{37}$$

$$\text{and } q'(Z) = G_o\left[2\sqrt{2\lambda}\left\{K_o(\xi) - \beta\sqrt{\frac{h_o}{g}}\,\xi\,K_1(\xi)\right] + \frac{1}{2}\,\frac{a\beta\sqrt{0.75\,h_o}}{g}\,\xi^2\left\{K_o(\xi)+K_2(\xi)\right\}\right], \tag{38}$$

where $\xi = \sqrt{\frac{2Z}{h_o}}$, $\lambda = \frac{\bar{u}_1}{\sqrt{2gh_o}}$, $\beta = \frac{3\pi\mu d}{m}$, and $U = a\ \sqrt{Z}$ (assumed).

$\bar{u}_1$ is the average value of the horizontal velocity components of sand particles jumping out from the sand surface, m is the mass of a sand particle, h_o is the average value of the maximum height h of the saltant path of the sand particles, a is a constant, and K_o, K_1, K_2 are Bessel functions of zero, first and second order, respectively. Kawamura's experimental results show a very good agreement with the above theory, but the expressions are fairly complicated for practical use.

On the other hand Ishihara and Iwagaki[14] assume that sand particles are suspended, and introduce the following relations corresponding to Equations (37) and (38):

$$\Psi = \Psi_o\ \exp\left(-\ \frac{W_o Z}{\eta}\right), \tag{39}$$

$$q' = C\ \Psi_o\ U\ \exp\left(-\frac{W_o Z}{\eta}\right) \tag{40}$$

where W_0 is the fall velocity of a sand particle; η , the coefficient of eddy viscosity; Ψ_0 is the mass of sand particles contained in a unit volume at $Z = 0$; U is the wind velocity; and C is a coefficient.

Some results obtained by Kawamura[15] (in the laboratory and the field), and Ishihara and Iwagaki[14] (in the field) are shown in Figure 7.

Zingg[27] establishes another type of expression (Fig. 8) from an analysis of his experimental results; that is:

$$q'(Z) = \left(\frac{a}{Z + C}\right)^{1/n} \tag{41}$$

where a, c, and n are constants which should be selected to fit the experimental results. According to Zingg's experiments the value of C is a function of grain size only, and the values of a and n vary with both the grain size and the wind velocity. From this he establishes the following equation for estimating the total quantity of sand transported as:

$$q = C\left(\frac{d}{D}\right)^{3/4} \frac{\rho}{g} U_*^3 \tag{42}$$

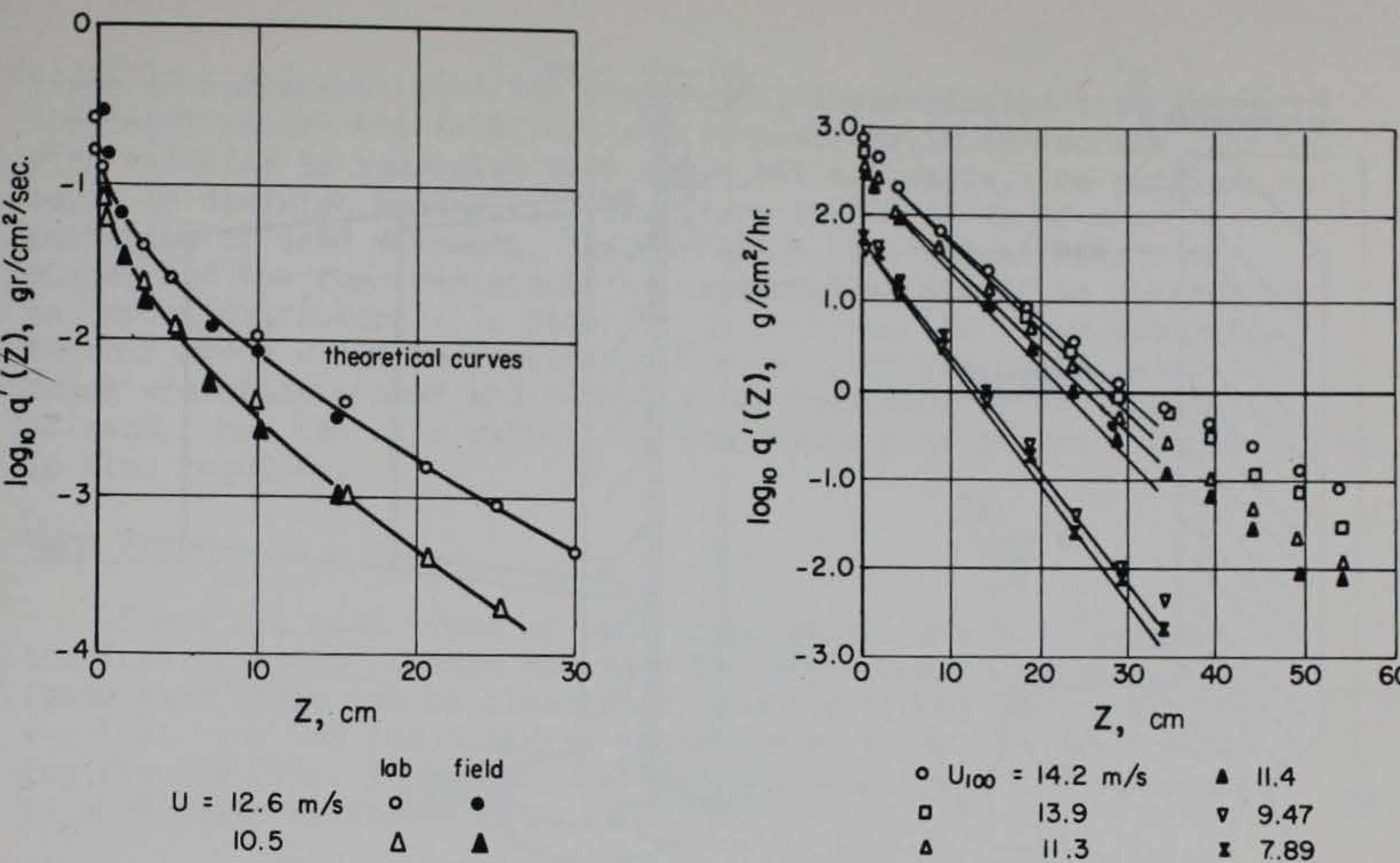
The above equation differs from Bagnold's Equation (2) only in the effect of grain size.

Beach Sand

The size of the sand particle is one of the most important factors in the transportation of sand by wind. The specific gravity of sand is almost always equal to the constant of 2.65. According to the mechanical analysis of sand by Twenhofel[22] (5), from the Oregon Coast, particles between 0.5 and 0.125 mm. are quite predominant. This is similar to that obtained in the desert by Bagnold[1]. On the other hand, Mason and Folk[18] show that by analyzing the sand sizes statistically, we can determine their relative locations, such as near beach, mid-beach, dune, and aeolian flat. Their reason is that the coarse end of the normal size distribution lags selectively behind because the wind cannot carry the coarser grains as easily. Therefore the skewness should be considered as an important factor.

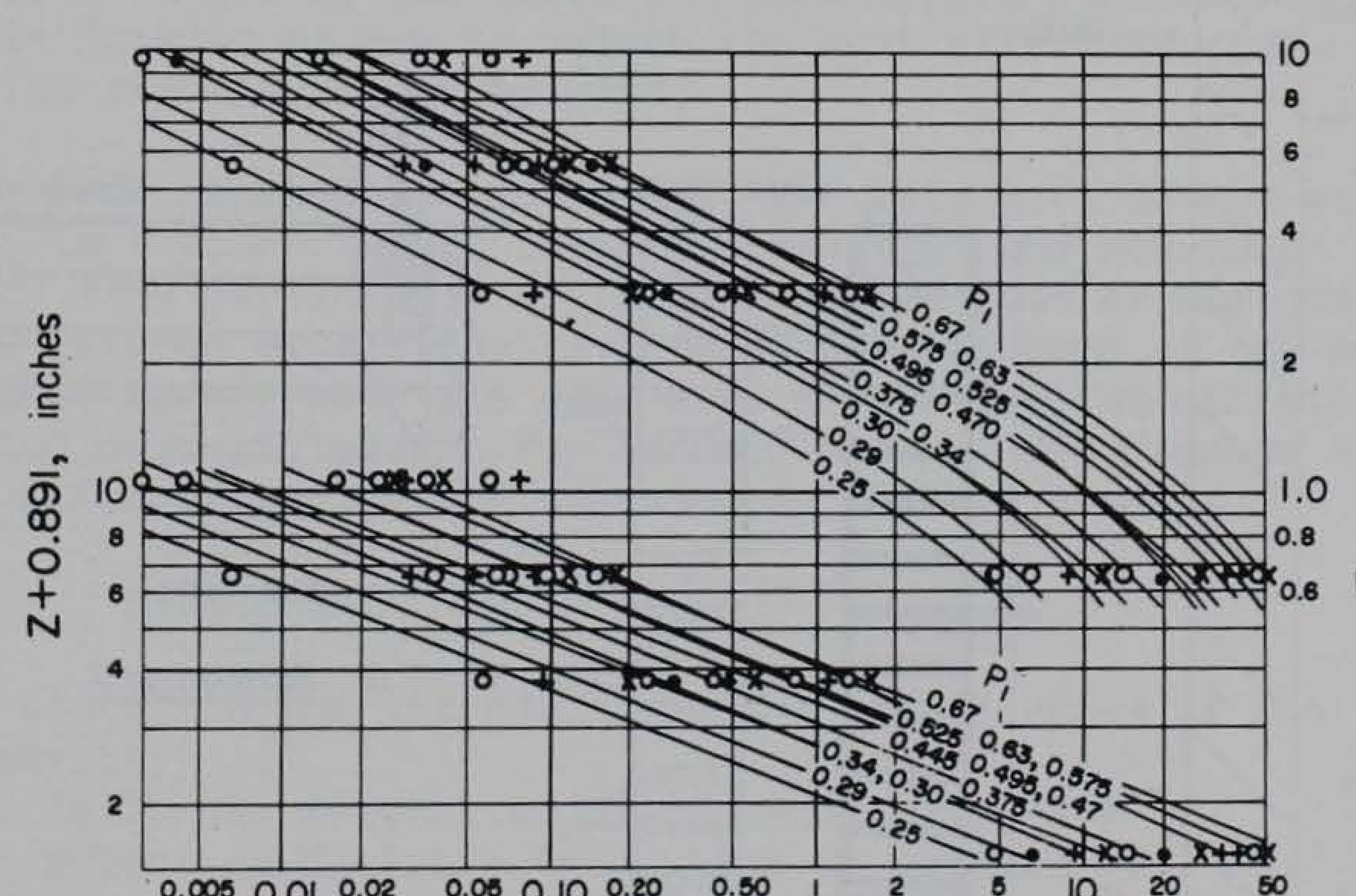
Sand Ripples

In the above discussion, we have assumed that the sand surface is smooth, but actually in some range of wind velocity sand ripples are almost always formed on the sand surface. As the ripples have a certain length and height, which are fairly



a. (after Kawamura) b. (after Ishihara and Iwagaki)

Figure 7. **Vertical distribution of sand drift**



$$q' = \left(\frac{a}{Z+C}\right)^{1/n}$$

Figure 8. **Vertical distribution of sand drift**
(after Zingg, 1952)

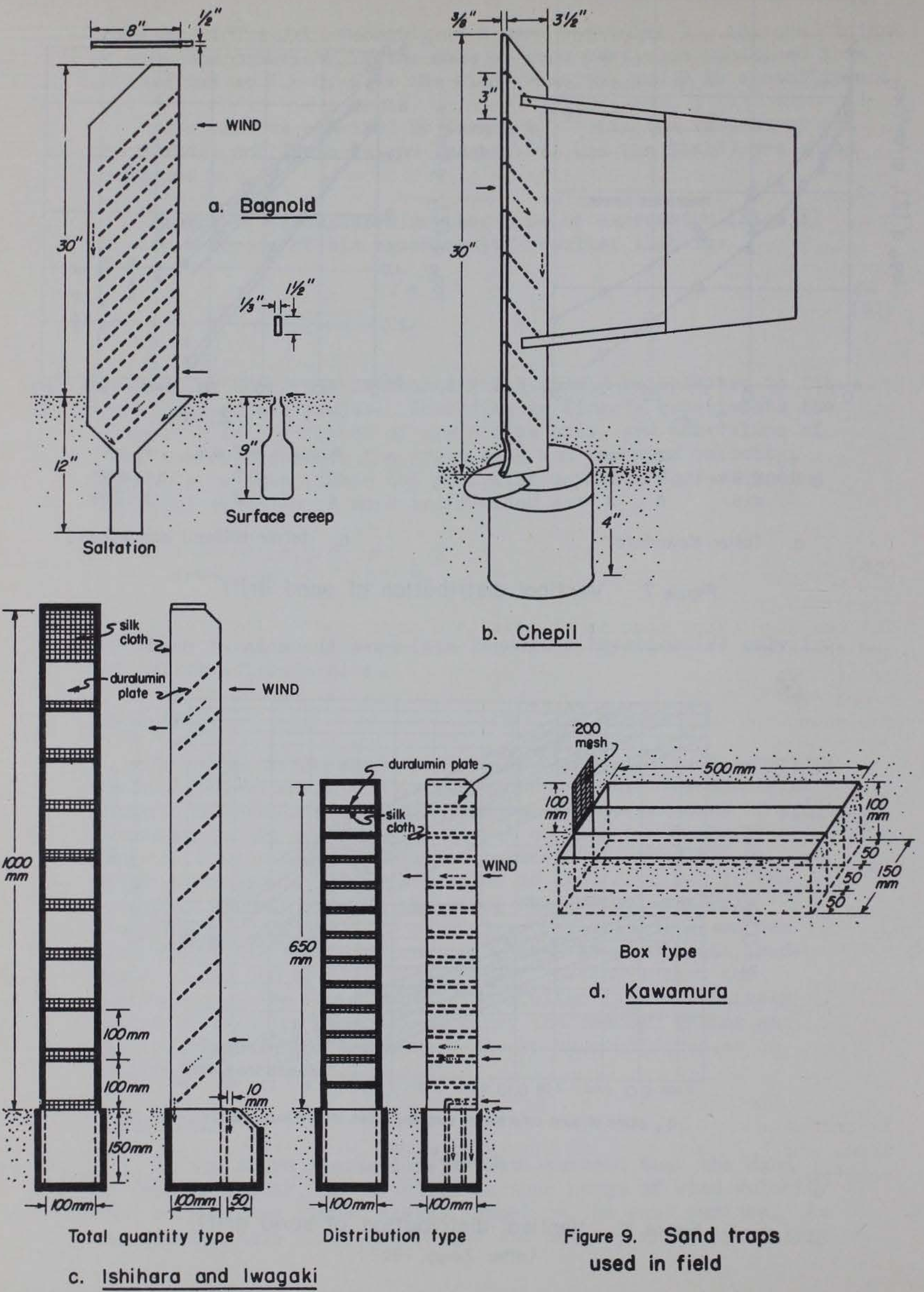


Figure 9. **Sand traps used in field**

large in comparison with the grain size, these ripples increase the total resistance as a form resistance. But whenever the wind velocity is increased over some critical value, the ripples begin to diminish gradually. Therefore in the study of the mechanism of sand movement, the formation, the geometrical shape, and the form resistance of sand ripples should be considered as important factors. In order to investigate the above subject, further study would be required. Moreover, in the field, sand dunes are often caused and have a great influence on the movement of sand, thus the observation of the movement of the sand dunes is also required.

Sand Traps

There are many types of sand traps which have been used in the investigation of sand movement by many research workers. These sand traps can be classified into two types; one is a vertical type and the other is a horizontal type. In the following figures (Fig. 9) examples of several sand traps are summarized to show their different principles.

Einstein(7) has calibrated some sand traps which have been used in the water and found that the efficiency is a function of grain size. Recently Vinckers, Bijker & Schijf(25) and Novak(19) presented some new ideas on sand traps for catching bed load. But the sand traps used in the air have never been calibrated and therefore it is quite difficult to compare the data of sand transportation caught by the different sand traps. Information therefore is lacking on how to select the most effective trap for measuring sand transport by wind.

It has been commonly accepted that the main part of the sand in movement is transported in saltation and that the momentum held by each sand particle is so large that the path of the particle will not be altered significantly by the back pressure of the sand trap. If that is correct, the sand trap should have an efficiency of almost 100 percent, except for surface creep. The purpose of this study is to determine the correctness of that concept.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

As is stated in the Introduction, the main purpose of the present study is,

(1) To calibrate several types of sand traps, and

(2) To select or design a trap which is suitable for measuring the total sand transport.

Experiments were conducted in a wind tunnel, 1 foot wide, 60 feet long, and 1.28 feet high as shown in Figure 10. The channel was constructed of wood, with one side made of plate-glass for observation

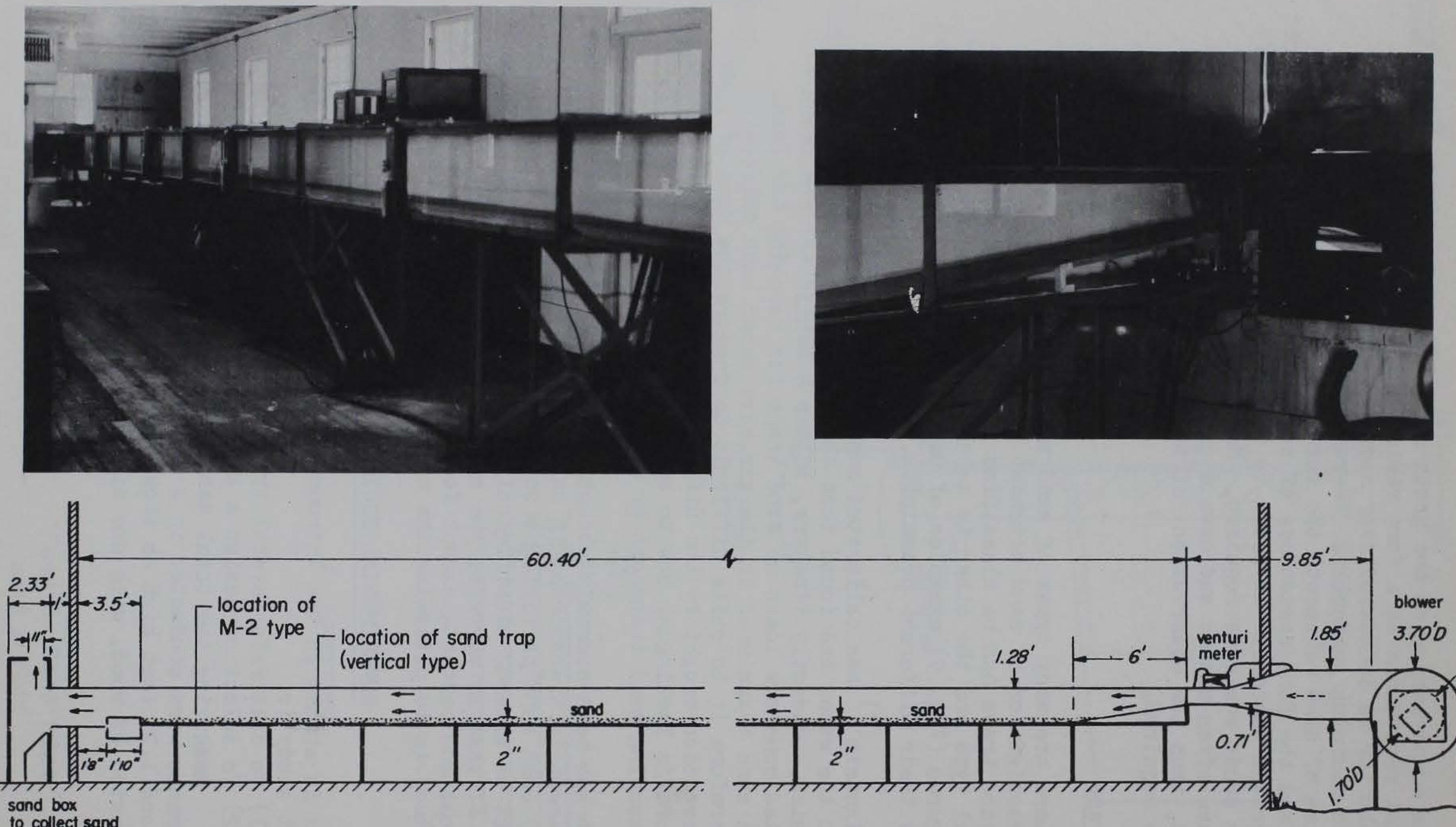


Figure 10. Wind tunnel

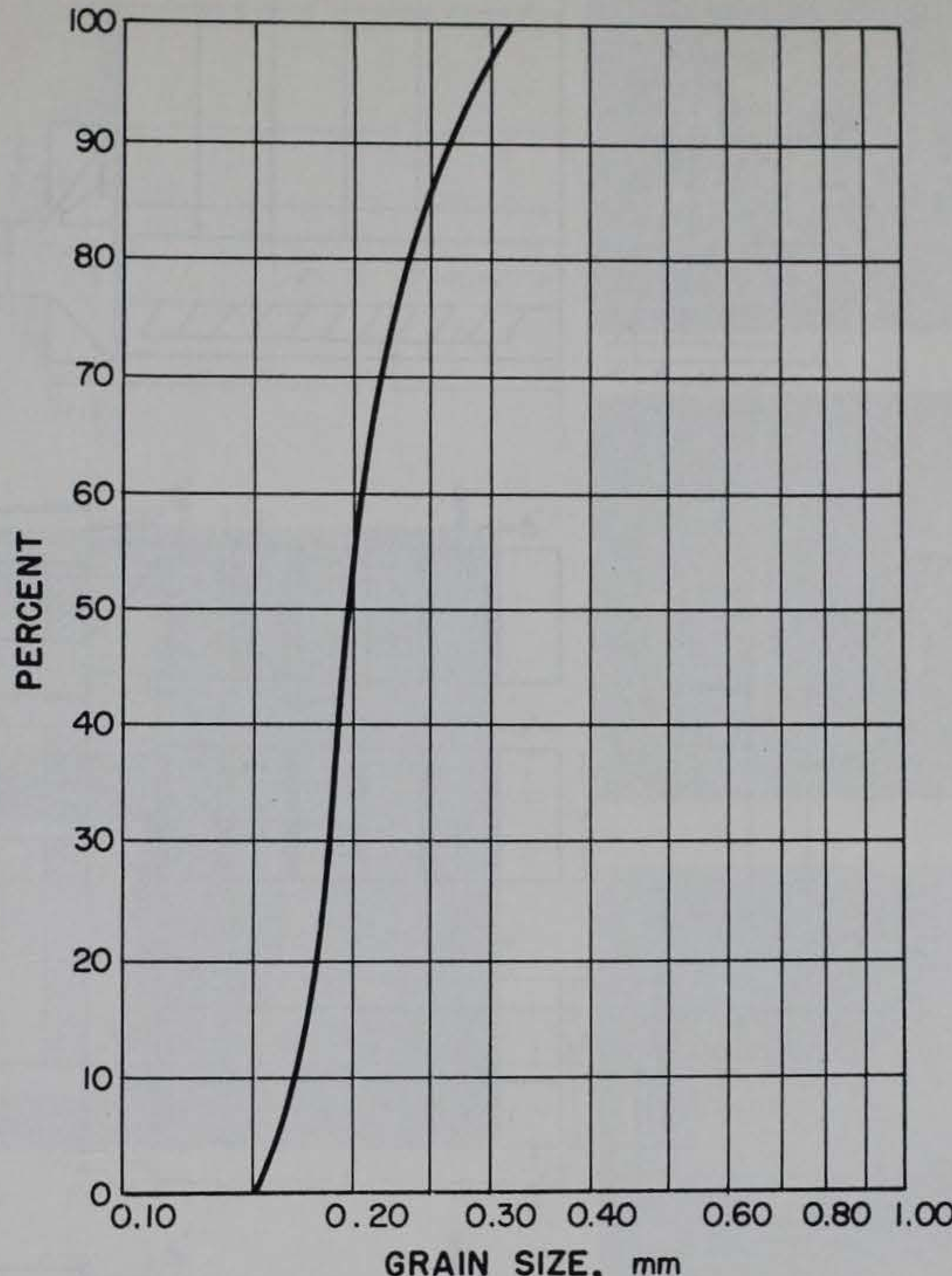


Figure 11. **Mechanical analysis of sand used**

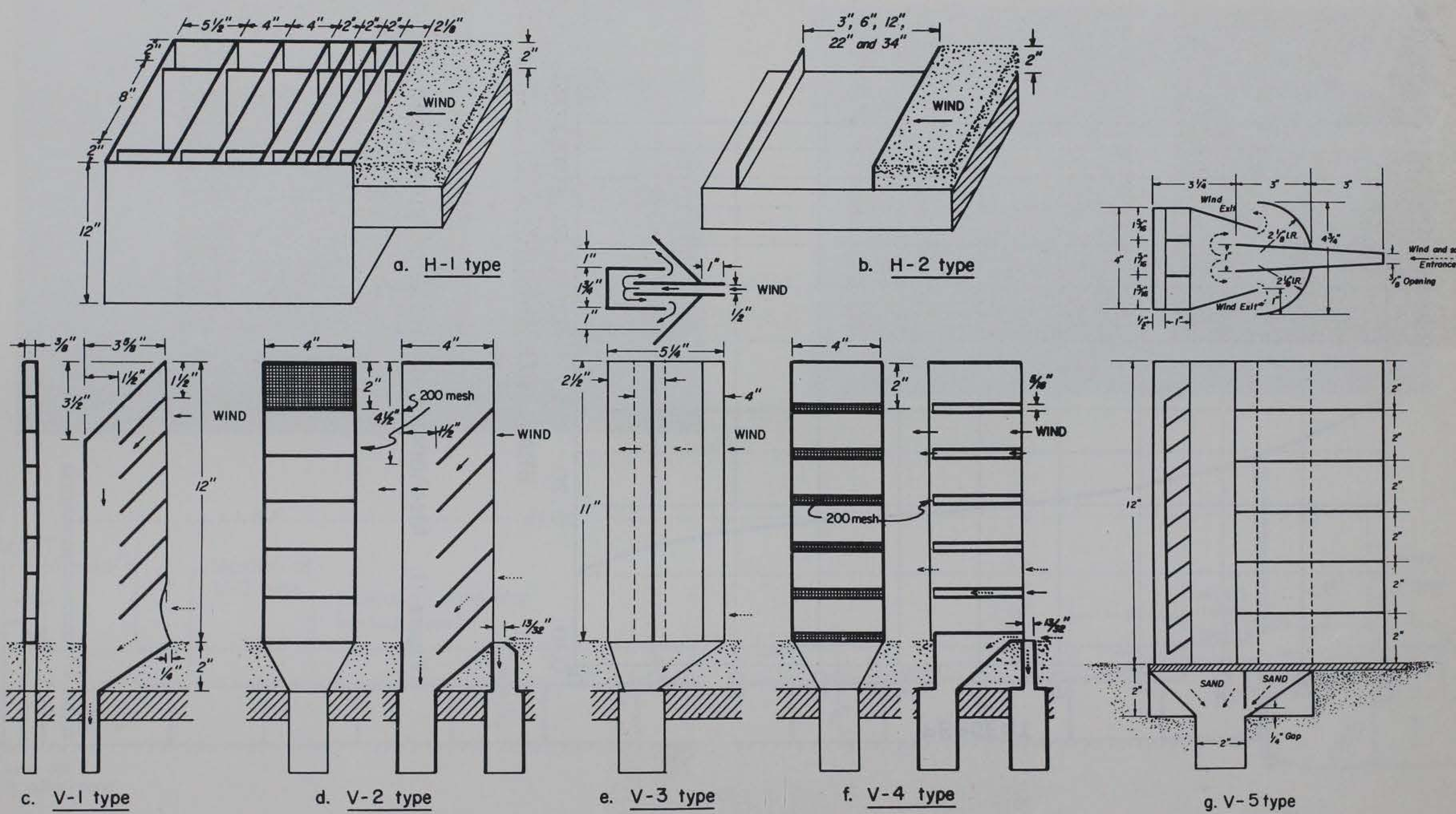
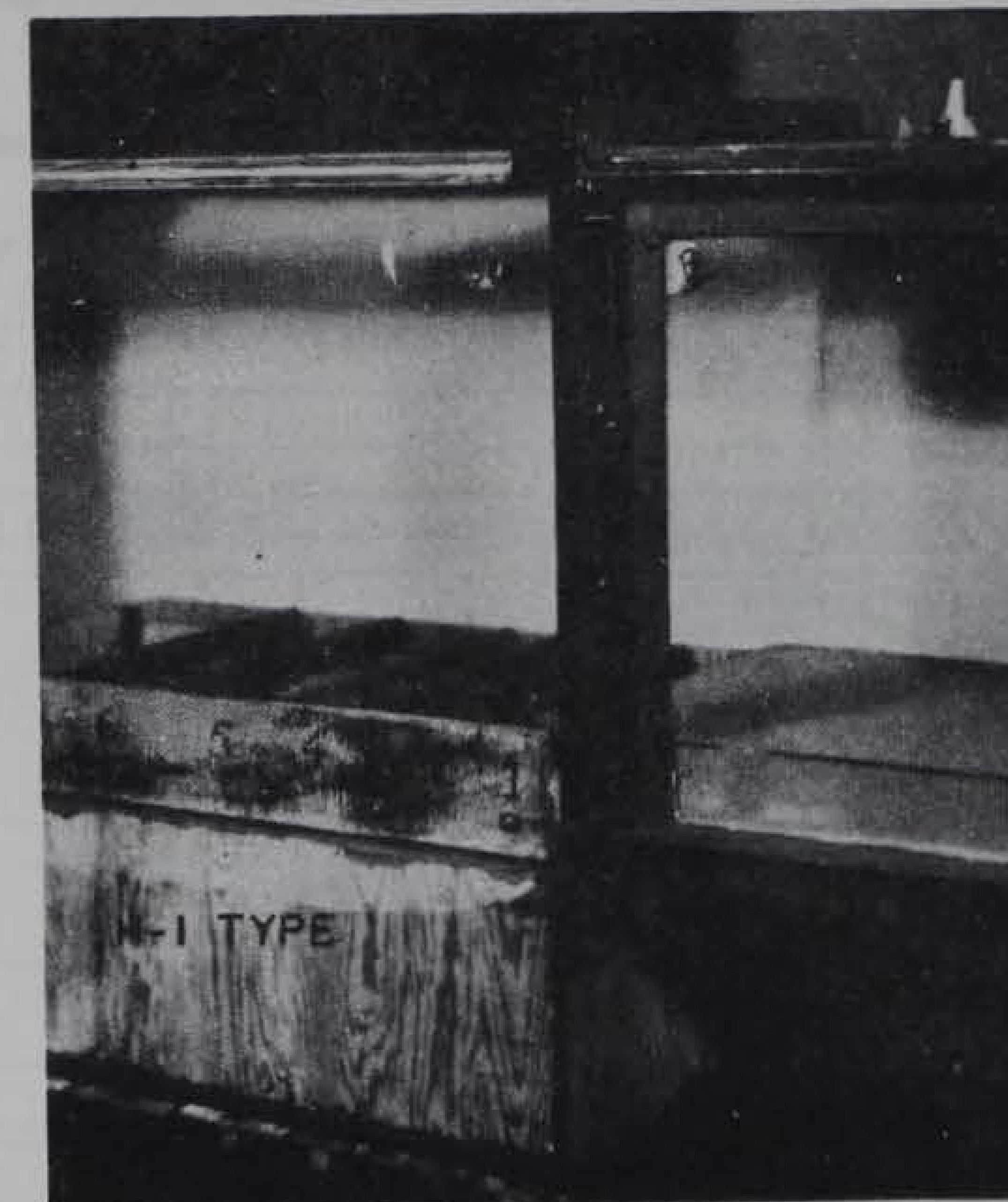
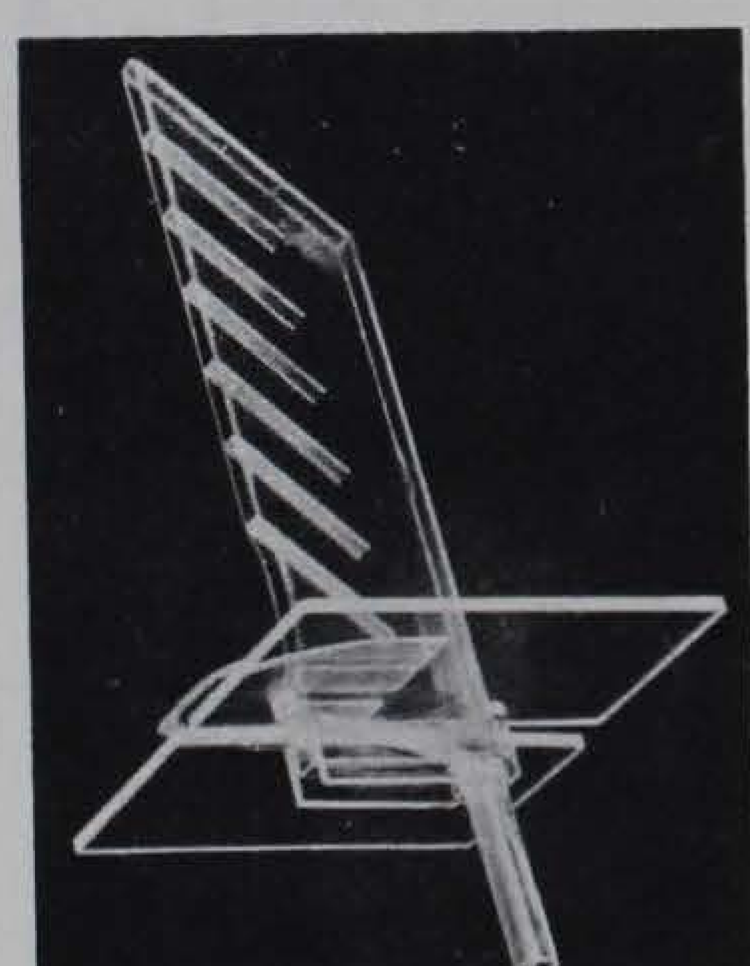


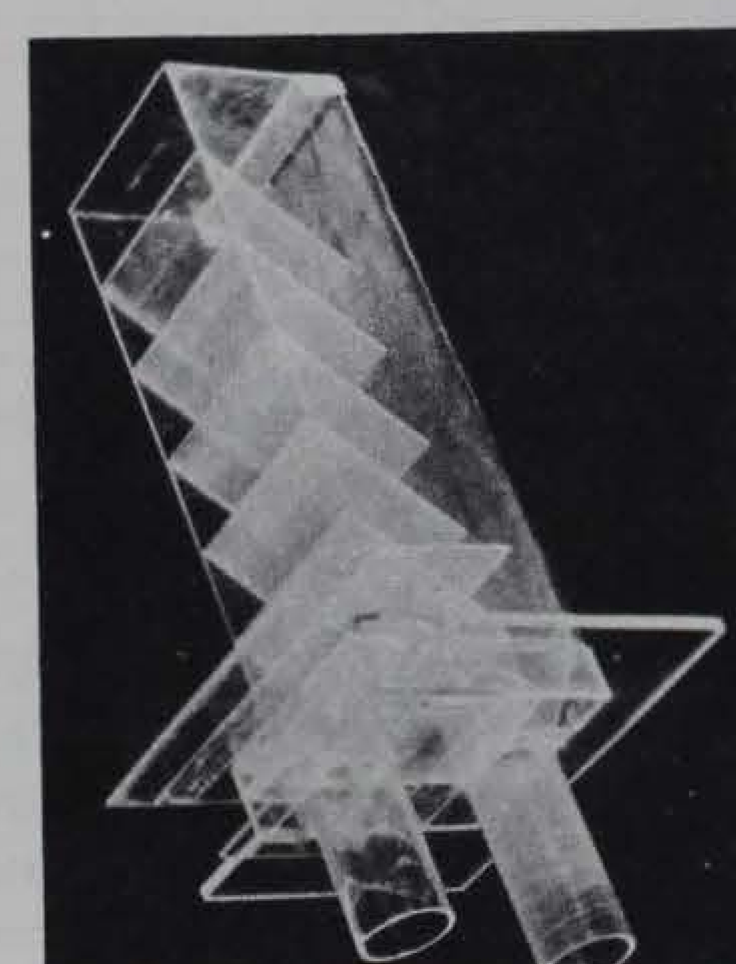
Figure 12A Sand traps tested



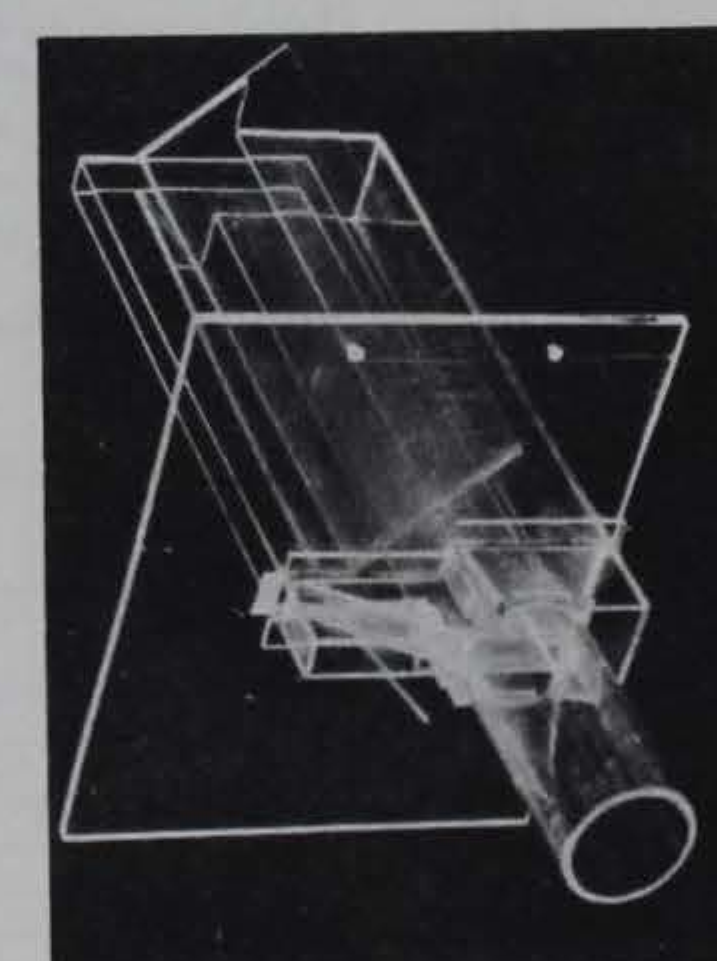
TYPE H-1



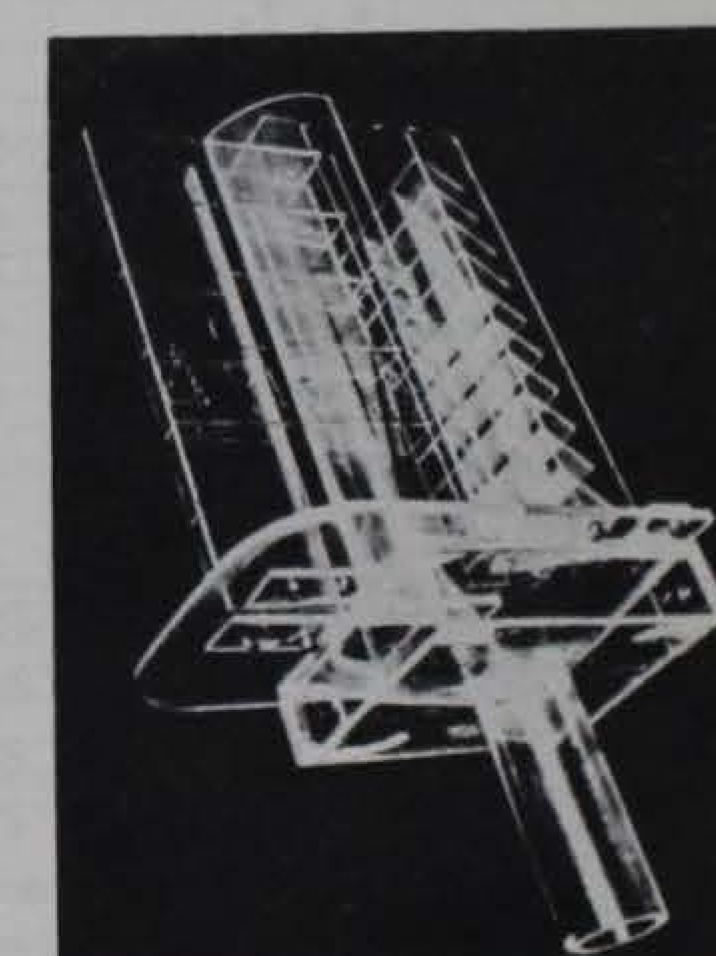
TYPE V-1



TYPE V-2

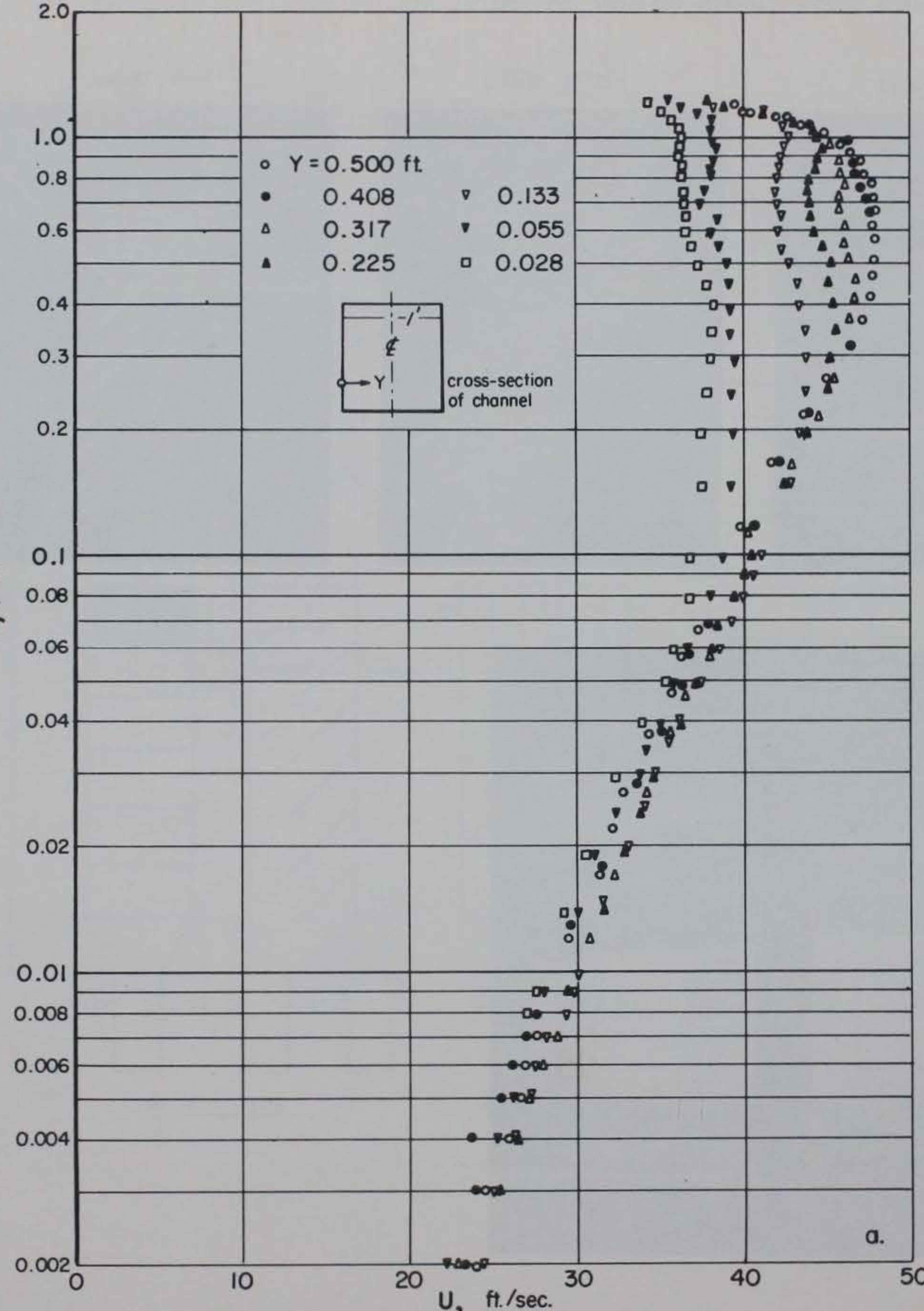


TYPE V-3



TYPE V-5

Figure 12-B Sand traps (Photos)



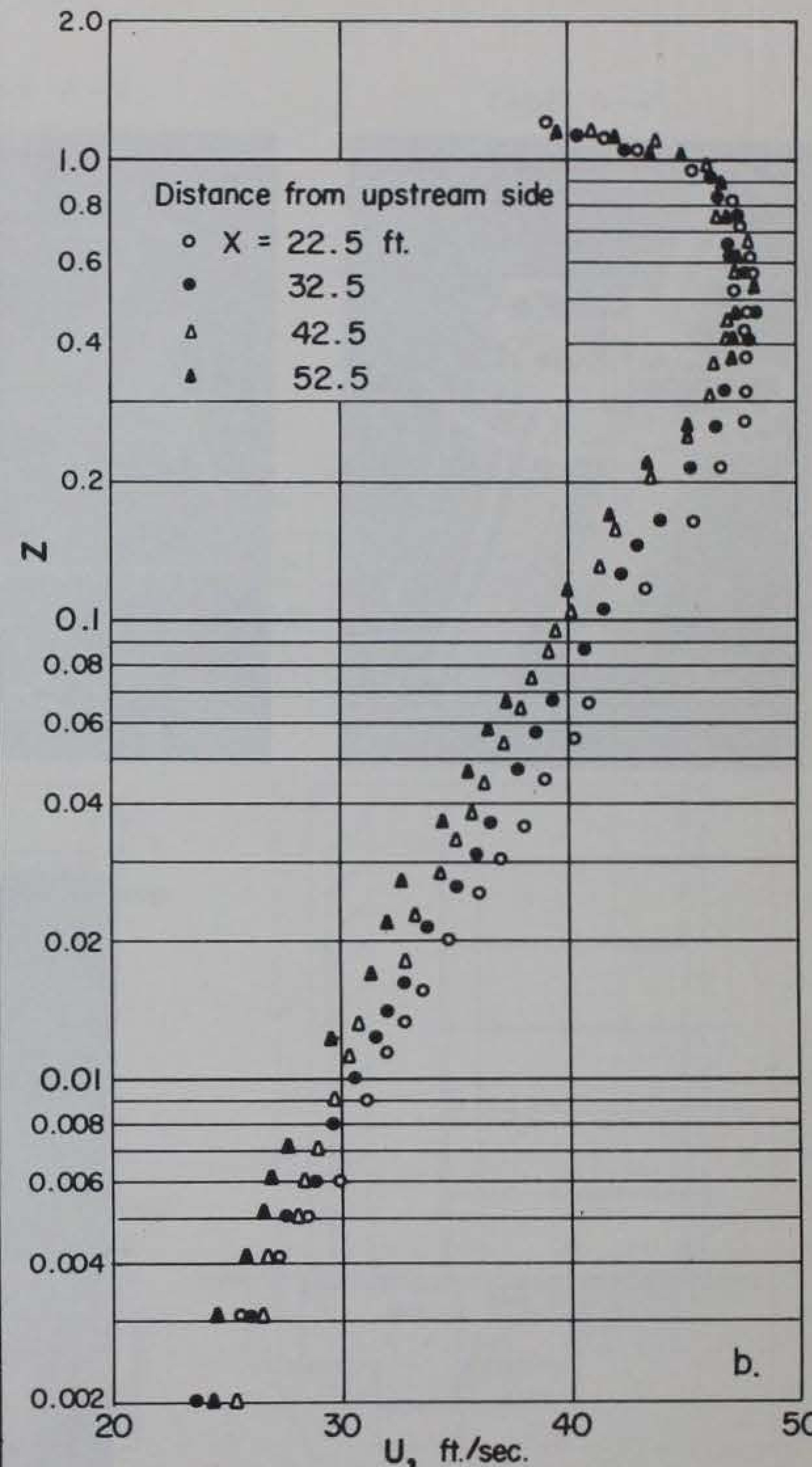


Figure 13. a. Velocity distribution at X = 52.5 feet (without sand); b. velocity distribution at center of each section.

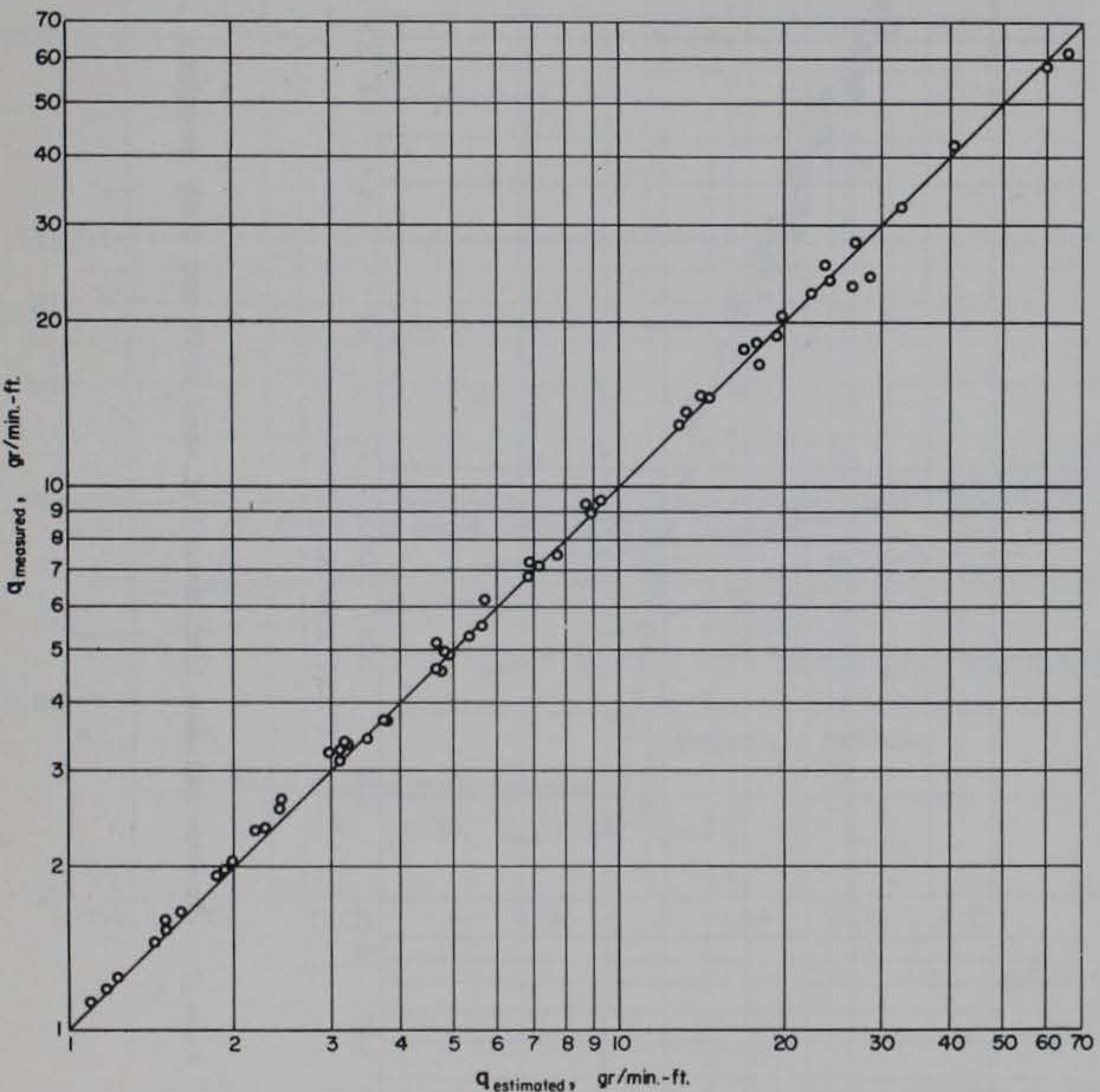


Figure 14. Comparison between $q_{estimated}$ and $q_{measured}$

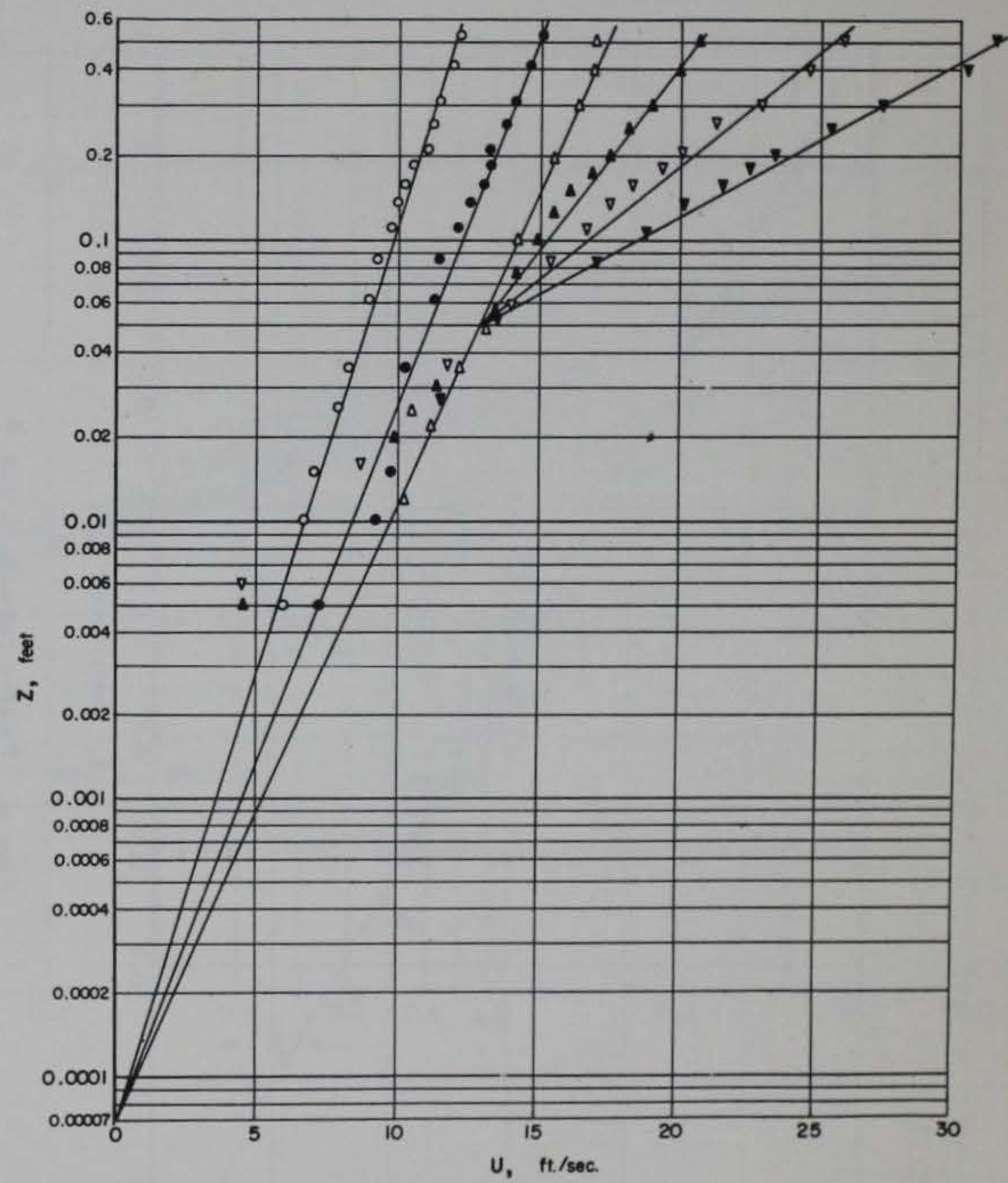


Figure 15. Velocity distribution above sand surface

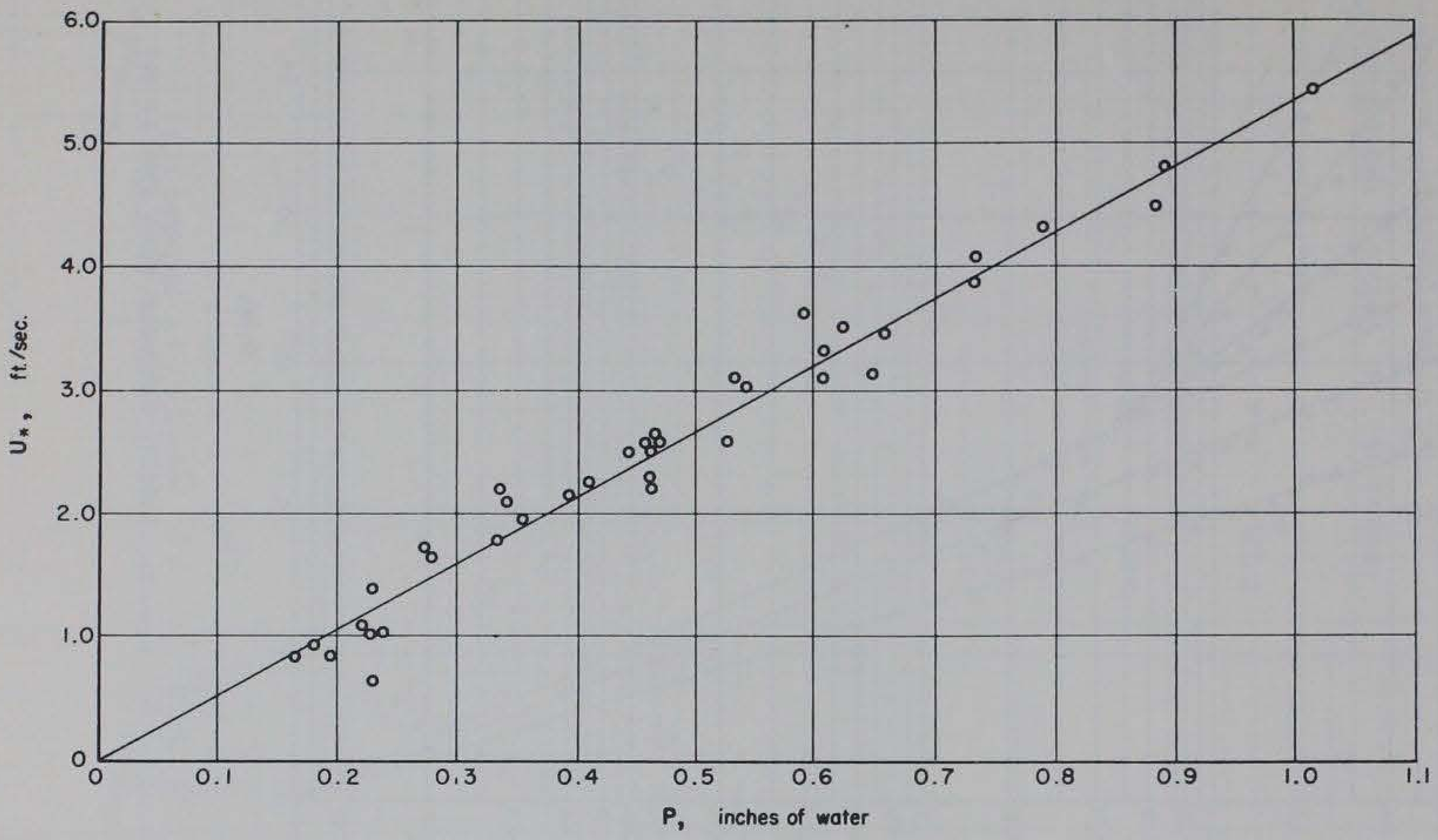


Figure 16. **Relation between U_* and P**

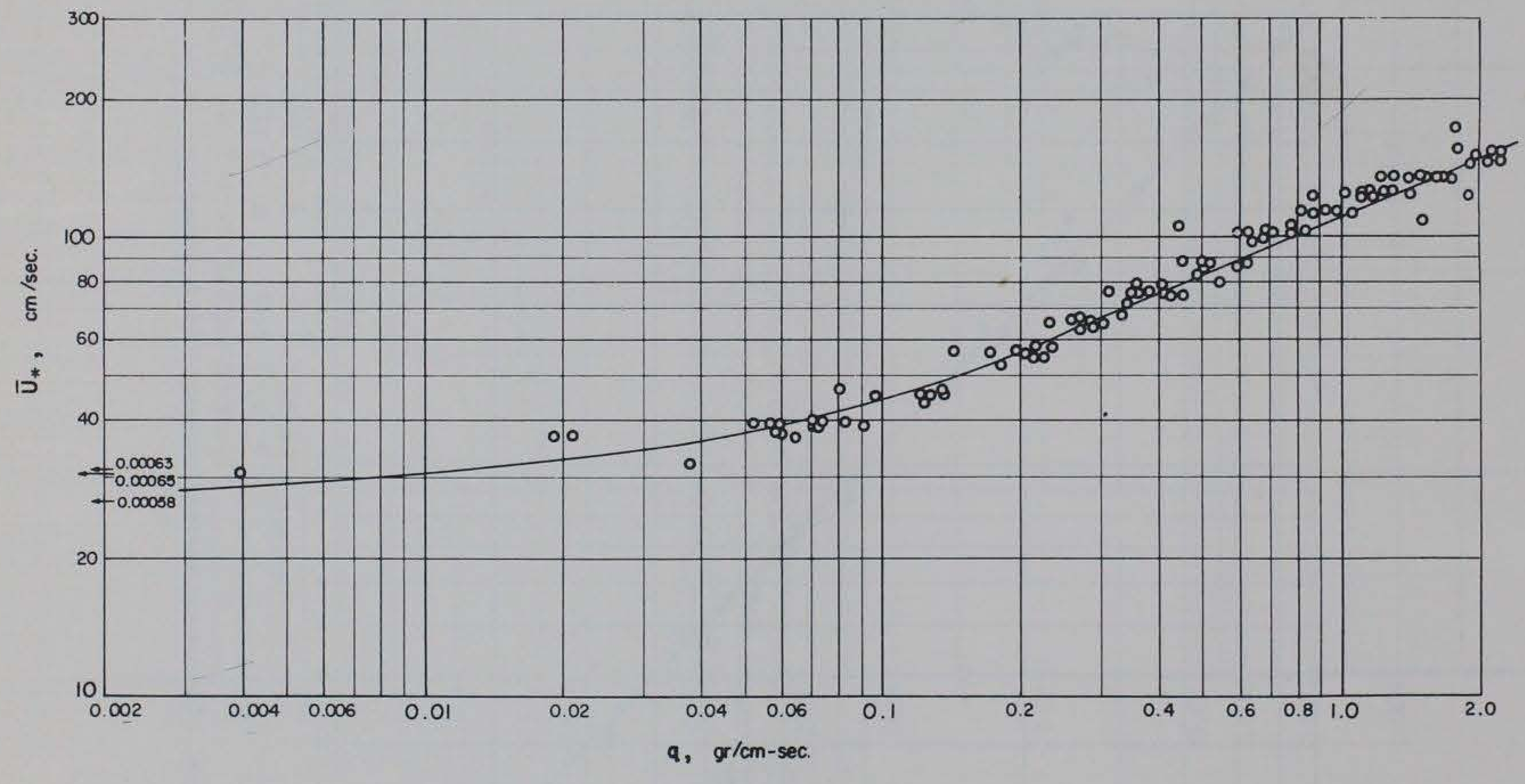


Figure 17. **Relation between total amount of sand drift and shear velocity**

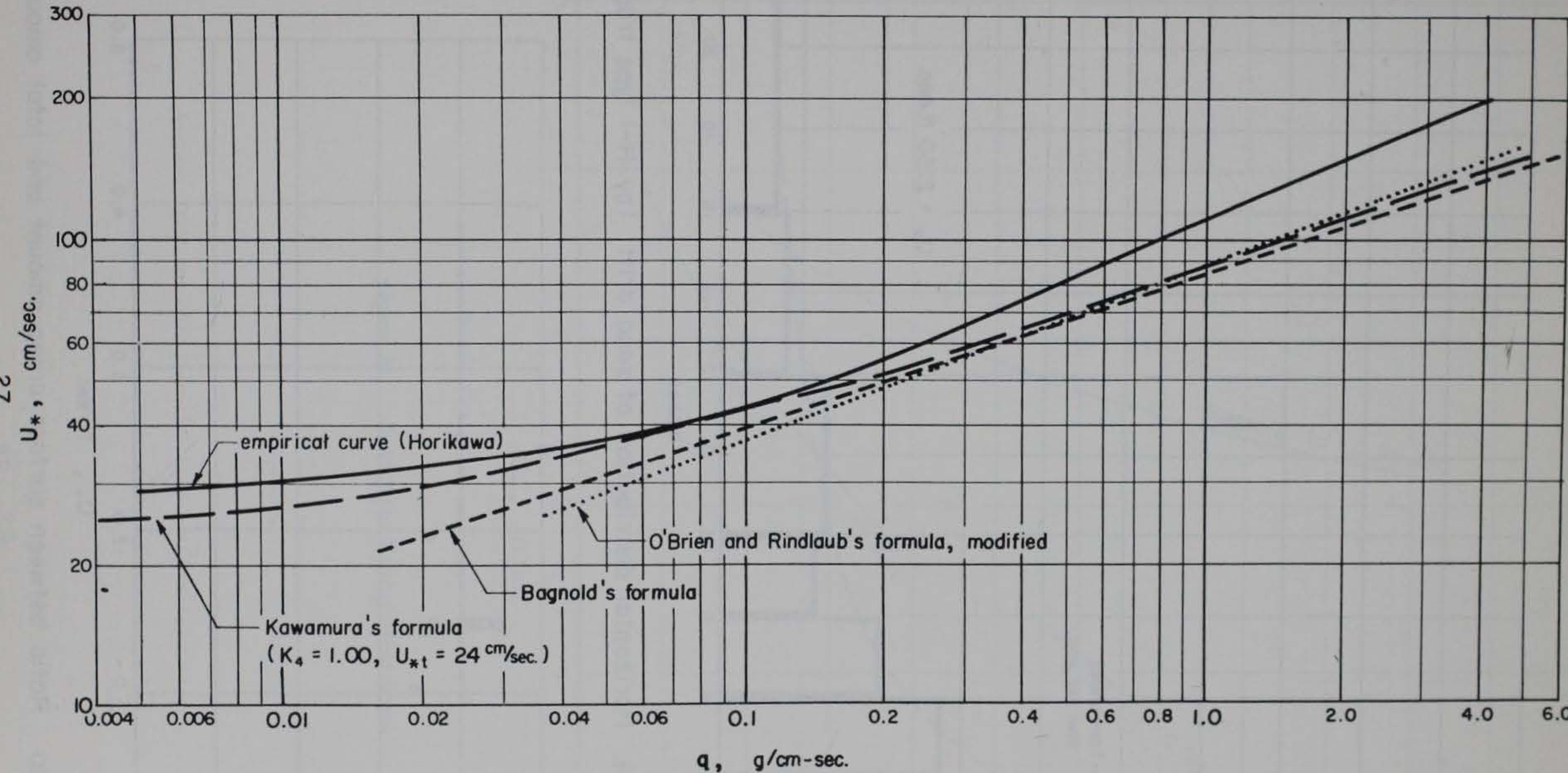


Figure 18. **Comparison of several formulas** (d_{max} = 0.20 mm)

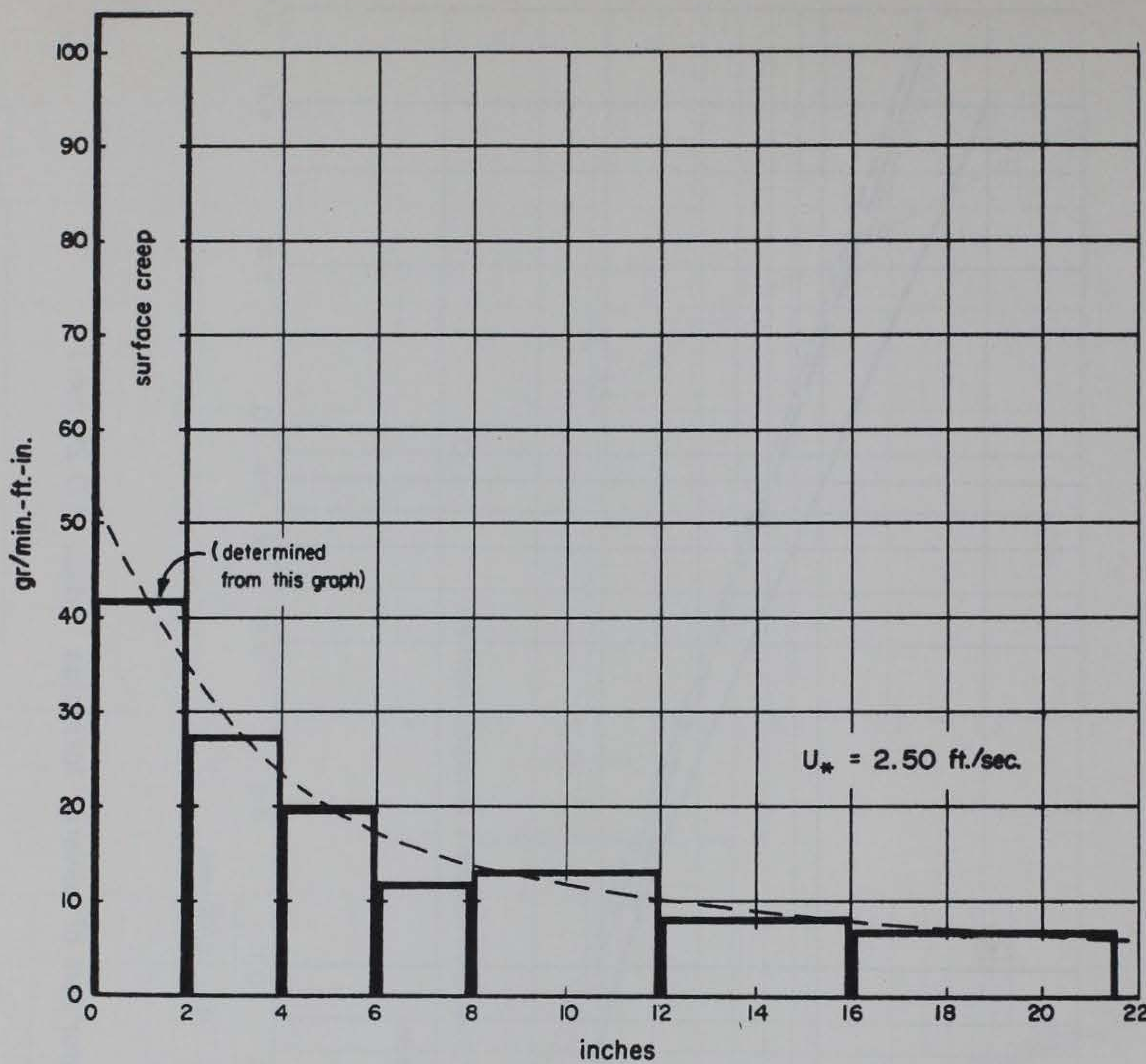


Figure 19. **Horizontal distribution of sand drift (by H-I type trap)**

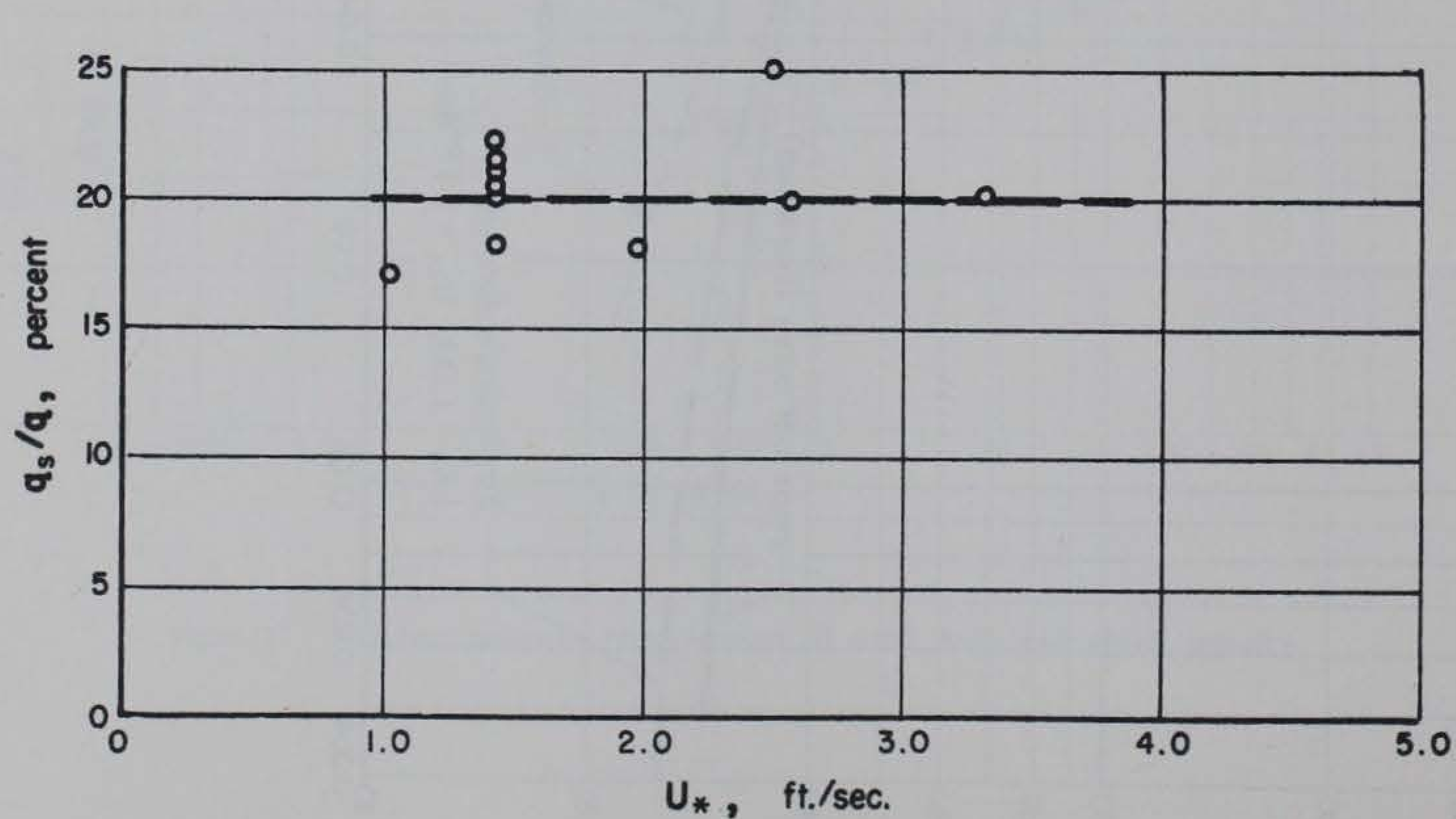


Figure 20. **Ratio between surface creep amount and total amount**

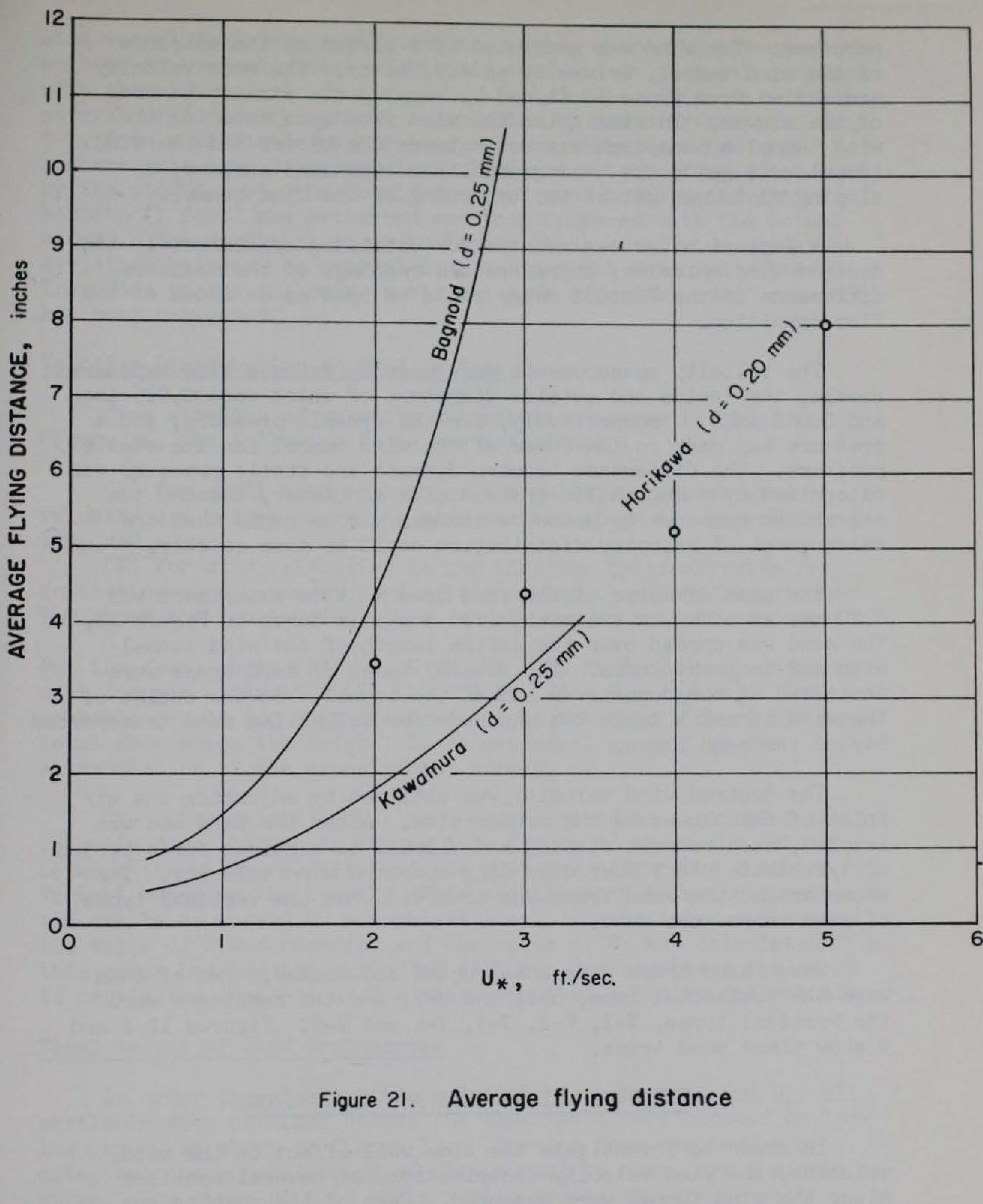


Figure 21. **Average flying distance**

purposes. The wind was generated by a blower at the entrance of the wind tunnel, driven by an A.C. motor. The mean velocity was varied from 20 to 50 ft/sec by varying the air intake area of the blower. To straighten the wind flow upon entering the wind tunnel a honeycomb was set between the blower and the wind tunnel. To guide the wind gradually on the sand surface, a sloping plate was set at the beginning of the wind tunnel.

A Venturi meter was mounted for obtaining approximately the desired wind velocity; therefore the readings of the pressure difference of the Venturi meter could be used as an index of the flow condition.

The velocity measurements were made by using a fine hypodermic needle, the inside and outside diameters of which were 0.025 inch and 0.042 inch, respectively, for the dynamic pressure, and a pressure tap made on the cover of the wind tunnel for the static pressure. The difference between dynamic and static pressure was determined by a magnehilic instead of a manometer, because the magnehilic response to pressure changes was so rapid that the measurement of velocity distribution could be made quickly.

The mean diameter of the sand used in this experiment was 0.20 mm. as shown by the mechanical analysis curve in Figure 11. The sand was spread over the entire length of the wind tunnel with a 2-inch thickness. The several types of sand traps were installed at the downstream end of the tunnel. At the outlet of the wind tunnel a large box was made for collecting sand transported beyond the sand traps.

The desired wind velocity was obtained by adjusting the air inlet of the blower to the proper size. After the sand bed was leveled, each run was started and allowed to continue for a period of 1/2 minute to 1 hour depending upon the wind velocity. The scour around the sand traps was observed when the vertical types of sand traps were used.

Seven sand traps were constructed and tested. Two of them were the horizontal type, H-1, and H-2, and the remainder were the vertical types, V-1, V-2, V-3, V-4 and V-5. Figures 12 A and B show these sand traps.

EXPERIMENTAL RESULTS AND DISCUSSION

In order to investigate the side wall effect on the wind velocity, the wind velocity distributions at several sections along the wind tunnel were measured. Part of the results are shown in Figure 13. The variation of wind velocity along the wind tunnel is fairly small, and the region where the effect of the wall on the velocity distribution is predominant is small compared with the width of the wind tunnel. In order to verify this finding, several preliminary tests were conducted by dividing the sand trap, H-1, into a middle compartment of 8- inch width, and two side compartments each 2 inches wide. From the weight of sand detained by the middle part, the total amount of sand through the entire section (1 foot) was estimated and then compared with the actual amount. The result as shown in Figure 14 does not give any great deviation between the estimated values and the measured values. Therefore in the following tests the side effect on sand transport has been neglected.

Velocity Distribution on Sand Surface

From a series of velocity distribution curves as given in Figure 15, the following facts are established:

(1) for small wind velocities the relation between wind velocity and height above the sand surface obeys the logarithmic law, and

(2) for wind velocities larger than the critical value for initiating sand movement, the relation also obeys the logarithmic law above the focal point, to which all curves seem to concentrate.

But the focal point ($Z' = 0.05$ ft, $U' = 13$ ft/sec) does not agree with Zingg's estimation ($Z' = 0.006$ ft, $U' = 5.9$ ft/sec). The probable reason for this disagreement is the selection of the base level from which the height, Z, is measured, as well as the extrapolation of the experimental curves.

The shear velocity, U_*, can be determined as a slope of the velocity distribution in Figure 15. Figure 16 shows the relation between the shear velocity and the pressure difference P at the Venturi meter in the tunnel. This relationship is quite consistent and can be expressed by a straight line. In the later tests only the value of P was recorded and the value of U_* was calculated from this graph because the period of each run was sometimes too short to permit the completion of a measurement of velocity distribution.

Total Amount of Sand Transported

In order to establish the relationship between q and U_*, all available data obtained during the experiment were plotted on log-log paper, as shown in Figure 17. There is some scattering of data, but the general trend of plotted points does form a single curve. The slope of this curve varies gradually, varying with the variation of U_*, but the slope at high values of U_* seems to be a comparison of 2.4 instead of 3 as found by Bagnold. Figure 18 was prepared for comparison of the above empirical curve with the formulas of previous investigators. The formulas presented on this graph are,

Bagnold's Formula: $q = 1.5\sqrt{\frac{0.20}{0.25}} \times 1.25 \times 10^{-6}\, U_*^3 = 1.676 \times 10^{-6}\, U_*^3$,

Modified O'Brien & Rindlaub's Formula: $q = 9.96 \times 10^{-7}(U_* + 10.8)^3$,

Kawamura's Formula: ($K = 1.0$, and $U = 24$ cm/sec, assumed)

$$q = 1.25 \times 10^{-6}(U_* - 24)(U_* + 24)^2.$$

The above three formulas agree fairly well except at the lower values of U_K. The empirical curve obtained from this study consistently gives lower values of transport rate than that of the other formulas; however, the Kawamura formula shows a good agreement with the empirical curve at lower values of U_*. Further experiments are urgently needed to investigate the above disagreement.

The amount of sand transport increases very rapidly with an increase of wind velocity; therefore a strong wind, which blows for only a short period, is more effective for the transportation of sand than a weak wind blowing for a long period.

Amount of Surface Creep

It is very hard to trap only the surface creep; therefore the following procedure for estimating the rate of surface creep was used for this study. For this purpose an H-1 type sand trap was used. This trap has seven compartments separated from each other by partition walls. The sand which dropped into each compartment was weighed and plotted on a graph to show the relation between the weight of sand per inch of length and the distance from the upstream edge of the sand trap (Figure 19). Through the columns in this graph (except the first compartment) the most reasonable curve was extended to determine the horizontal distribution of the amount of material in saltation. Then the amount of saltation which would be caught by the first compartment was established. Subtracting this amount from the total in the first compartment, the remainder was considered to be the surface creep. The ratios of the surface creep to the total amount of sand transported, q_c/q, were found to be about 20 percent and to be independent of the wind velocity (Figure 20).

It is quite possible that the ratio of q_c/q is a function of sand grain size. In order to establish the above functional relationship, further tests using several different grain sizes should be conducted.

Average Flying Distance

Bagnold and Kawamura gave the average flying distance for the sand size of 0.25 mm., as shown in Figure 21, but their results show a fairly large difference. In the present tests an attempt was made to determine the average flying distance by a different method than that used by the previous investigators. A sand size of 0.20 mm. was used in the tests. For this purpose the sand trap, H-2 type, was used, and the length of the sand trap was varied as 3, 6, 12, 22, and 34 inches.

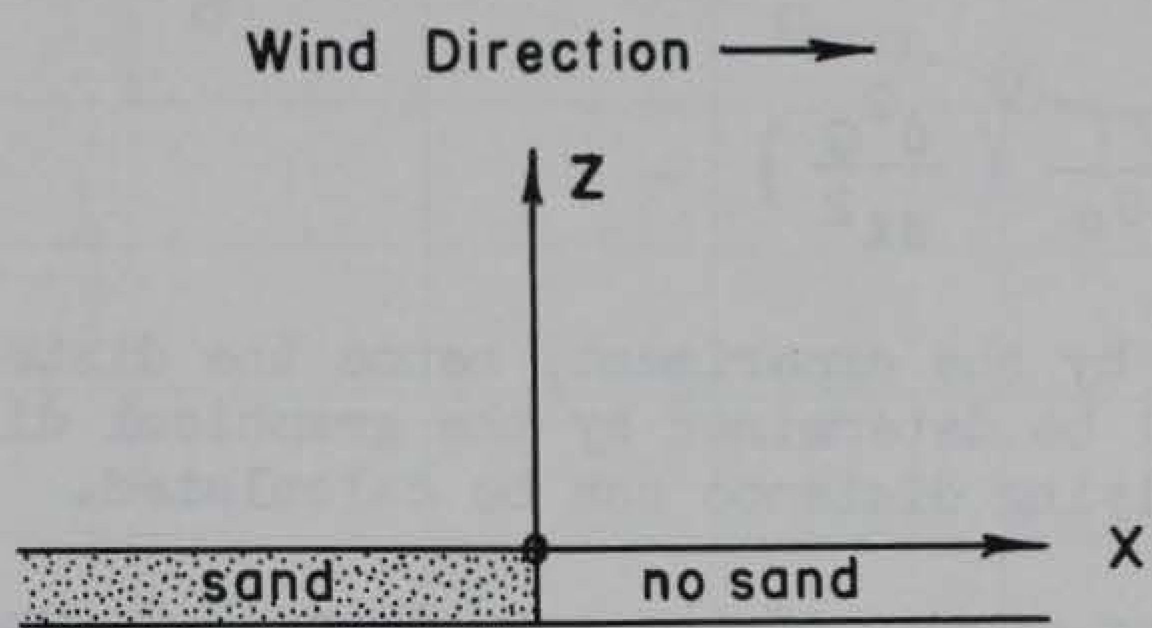


FIGURE 22

First, consider the condition as shown in Figure 22. The x-axis is taken in the direction of wind and the region of $x<0$ is covered with sand, from where the sand particles are flying and dropping into the sand trap set in $x>0$. The amount of sand falling in the unit area in $x>0$ per unit time, $F(x)$, is the summation of the sand particles jumping from the sand surface in the region $x<0$. Therefore if the frequency distribution function of flying length, $g(L)$ is known, $F(x)$ is expressed by the following integration,[15]

$$F(x) = G_0 \int_{-\infty}^{0} g(x-\xi)\, d\xi \, , \tag{43}$$

where G_0 is the amount of sand falling on the unit area of sand surface during the unit time. By considering the following condition,

$$\int_0^{\infty} g(\xi)\, d\xi = 1 \, , \tag{44}$$

the Equation (43) can be rewritten, such as

$$F(x) = G_0 \left[1 - \int_0^{x} g(t)\, dt \right] , \tag{45}$$

hence

$$g(x) = -\frac{1}{G_0} \left(\frac{dF}{dx} \right) . \tag{46}$$

Now the amount of sand caught by the sand trap, the length of which is L, is

$$G = \int_0^L F(x)\, dx \tag{47}$$

or

$$F(x) = \frac{dG}{dx} \quad . \tag{48}$$

Therefore the required function $g(x)$ is given by

$$g(x) = -\frac{1}{G_o}\left(\frac{d^2G}{dx^2}\right) \quad . \tag{49}$$

G can be obtained by the experiment, hence the distribution function $g(x)$ will be determined by the graphical differentiation, and the average flying distance can be calculated.

The efficiency curves of the sand trap, H-2 type, versus the shear velocity are shown in Figure 23, in which the length of the sand trap, L, is a parameter. Figure 24 shows the variation of efficiency with regards to the increase of L for each shear velocity. From these curves, the ratio of q_c/q appears to be about 20 percent, which was given in the previous section. In the above procedure any distinction between saltation and surface creep has not been made, but now only the saltation will be considered. Therefore the surface creep (20%) was subtracted and the new efficiency curves for saltation were established as shown in Figure 25.

As a result of graphical computation the average flying distance was obtained and plotted on the graph in Figure 21. If the contribution of surface creep on the average flying distance is included, the curve will be modified.

Characteristics of Sand Traps Tested

Sand traps can be mainly classified into two types--a horizontal type and a vertical type. The difference between these types may be described as follows:

(1) The horizontal type does not disturb the flow condition, but the vertical type does.

(2) The main difficulty of the horizontal type is the selection of its length for obtaining a certain efficiency. On the other hand, the difficulty of the vertical type is more complicated, that is, the question about what kind of structure would be most effective must be solved first of all.

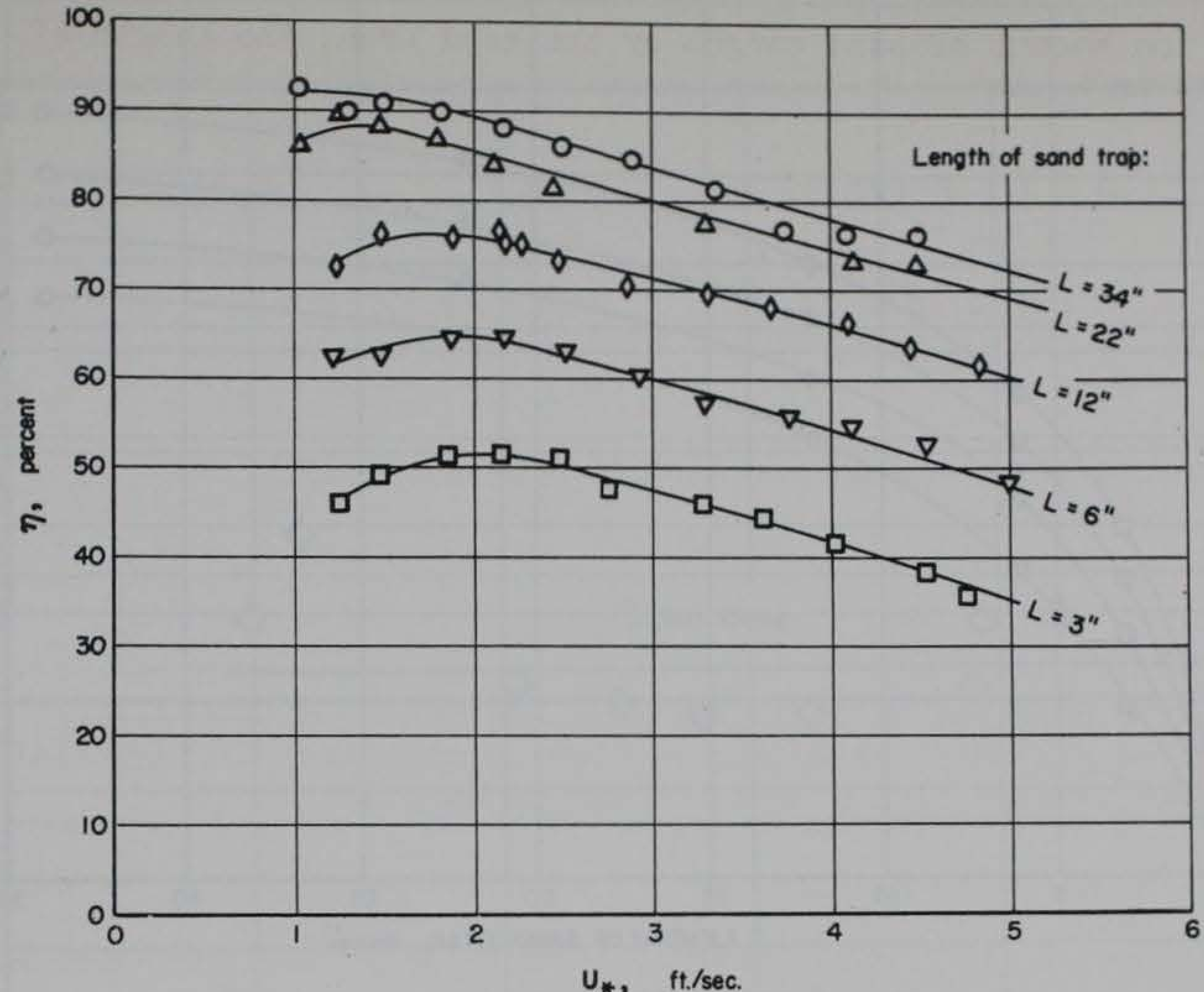


Figure 23. **Efficiency curves for H-2 type**

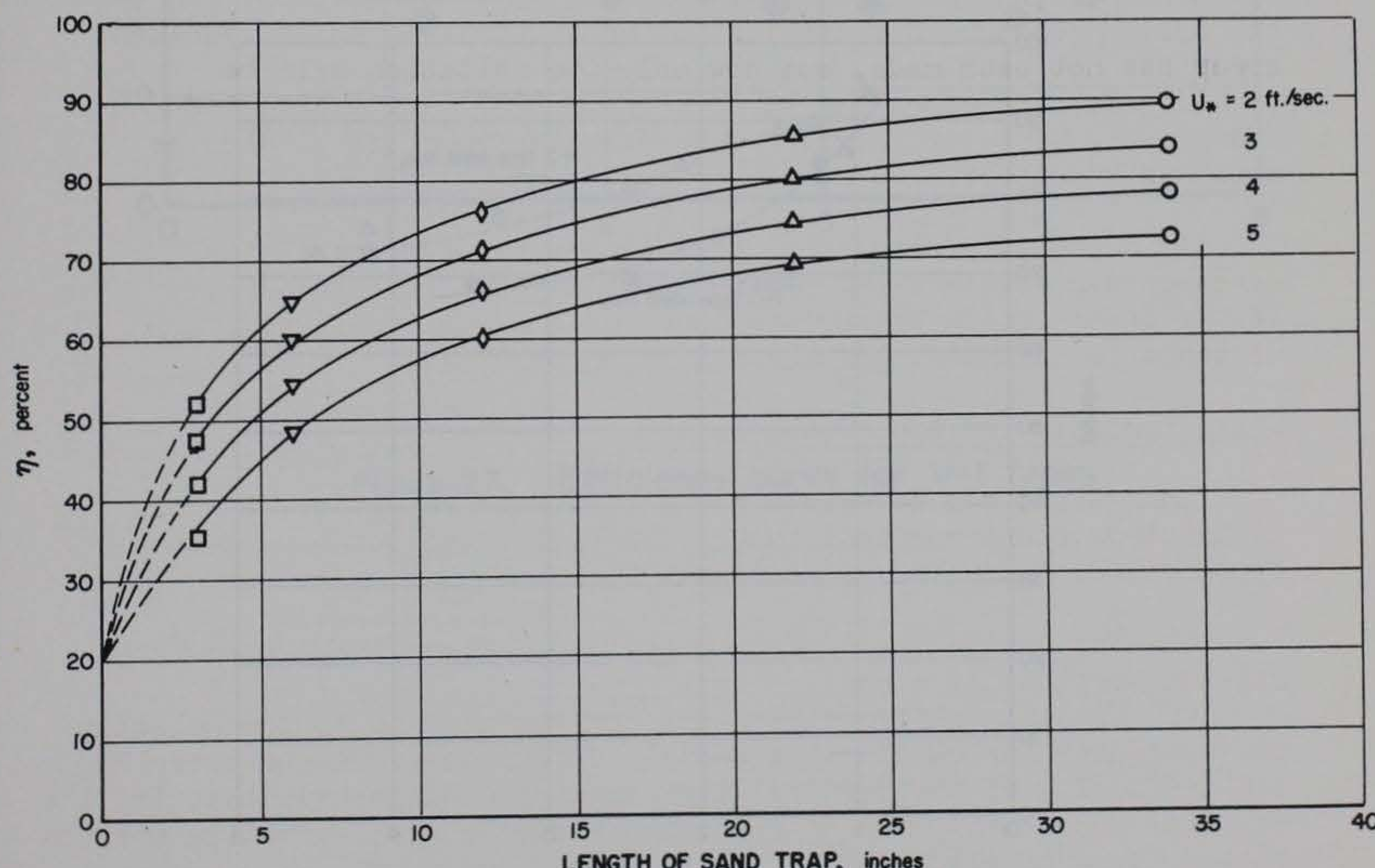


Figure 24. **Efficiency curves for H-2 type**

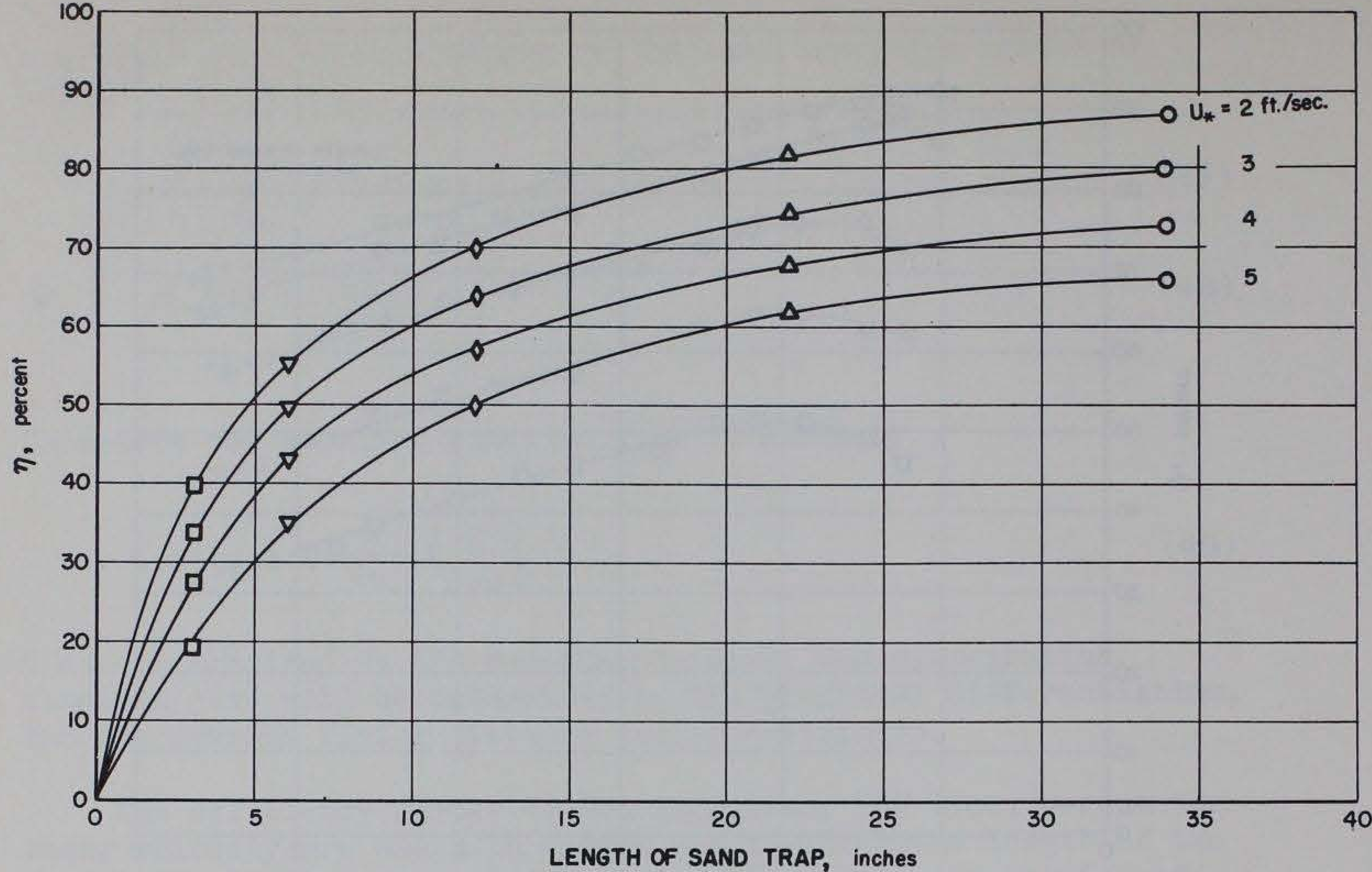


Figure 25. Efficiency curves for H-2 type (saltation only)

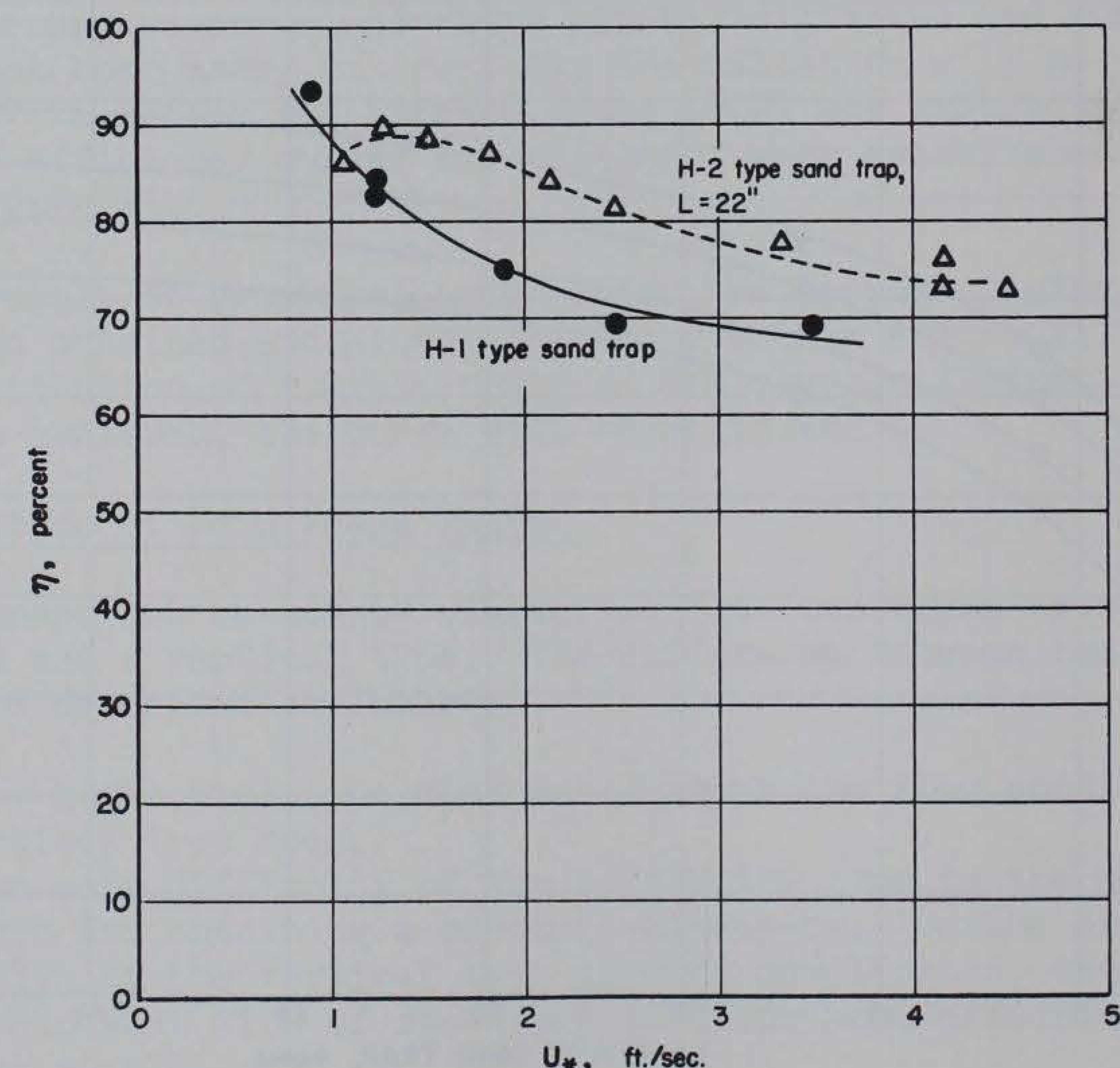


Figure 26. Efficiency curves for traps H-1, H-2

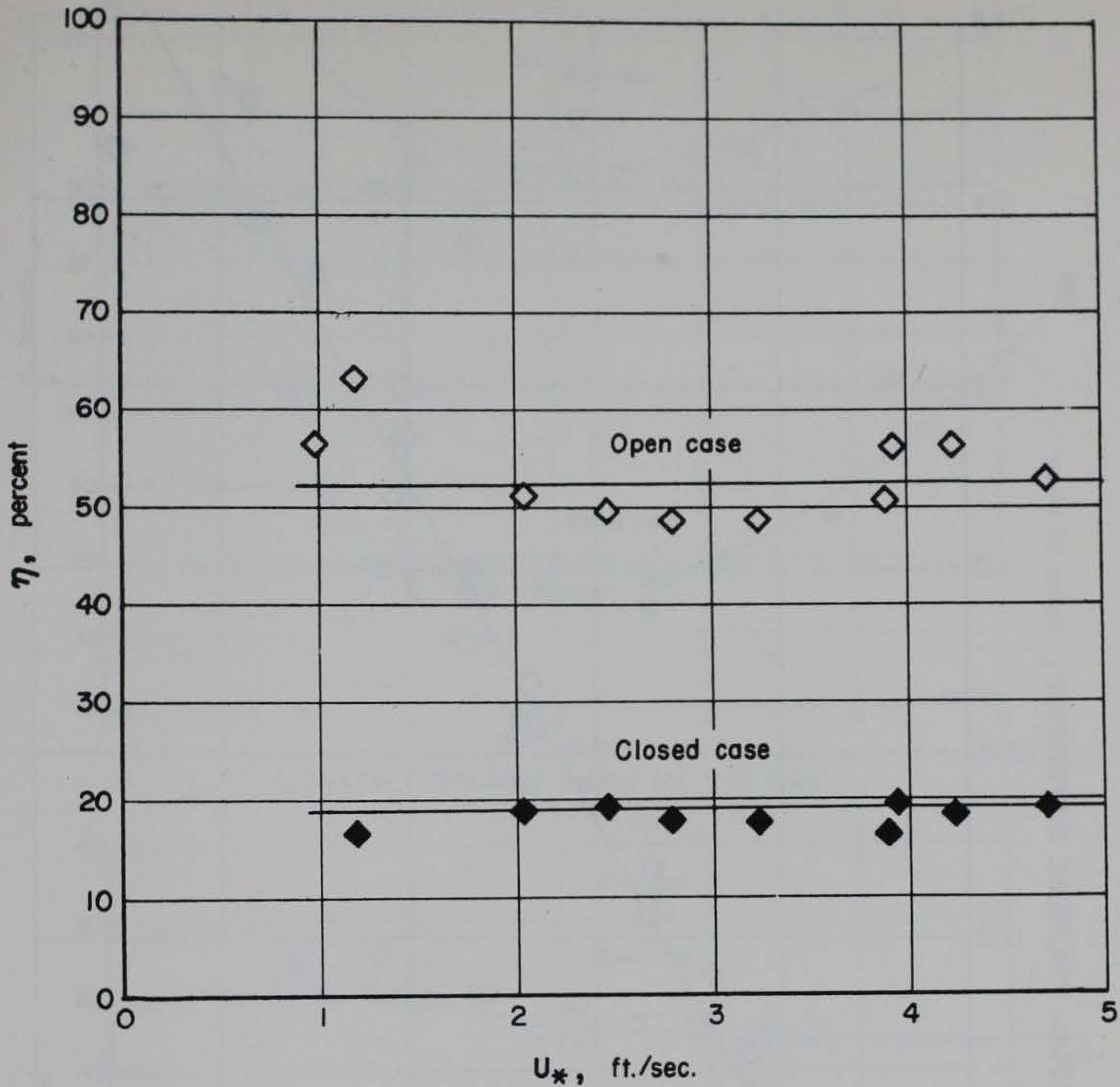


Figure 27. **Efficiency curve for V-I type**

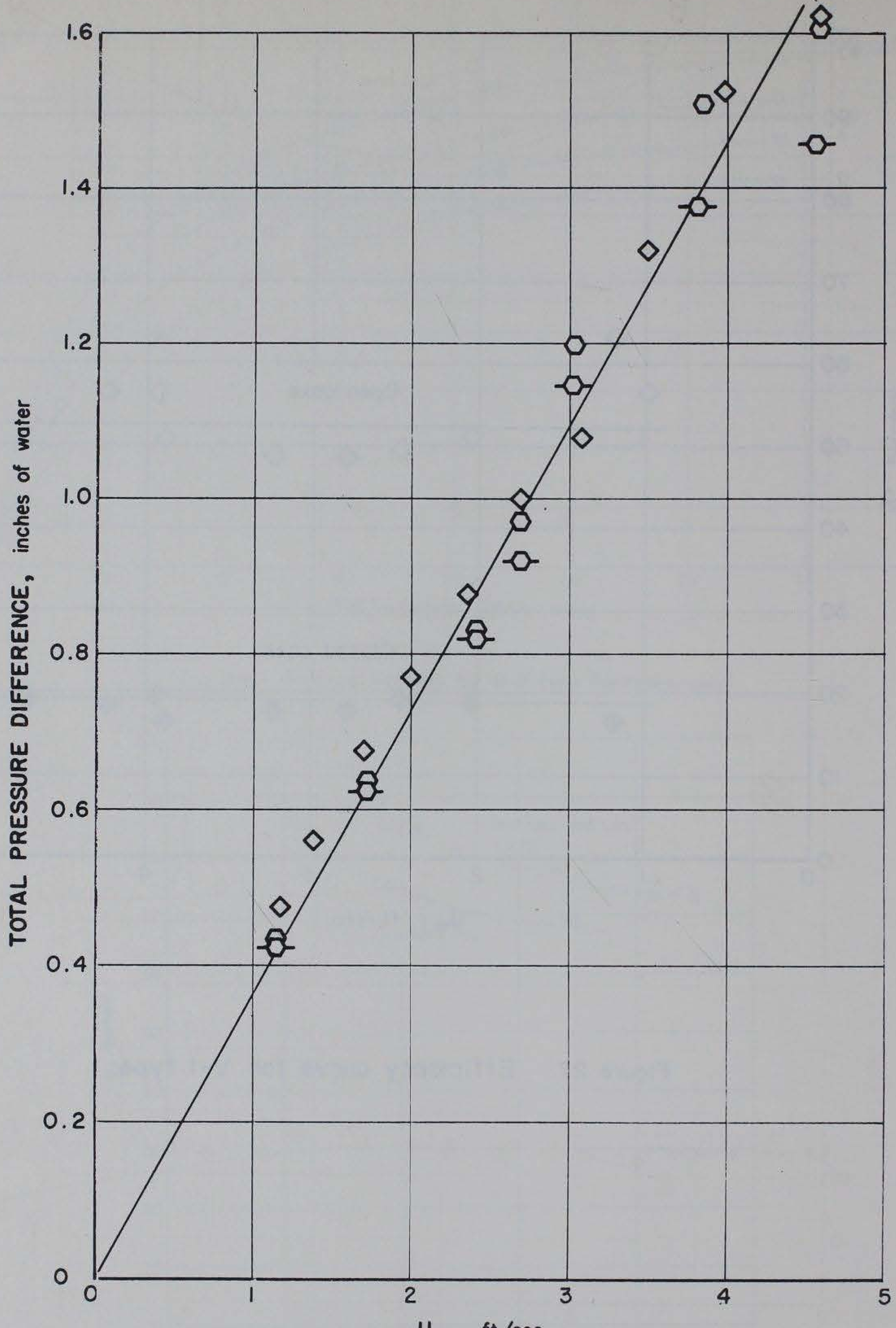


Figure 28. Difference in total pressure between the sand exit inside the sand trap and outside the wind tunnel (open cases)

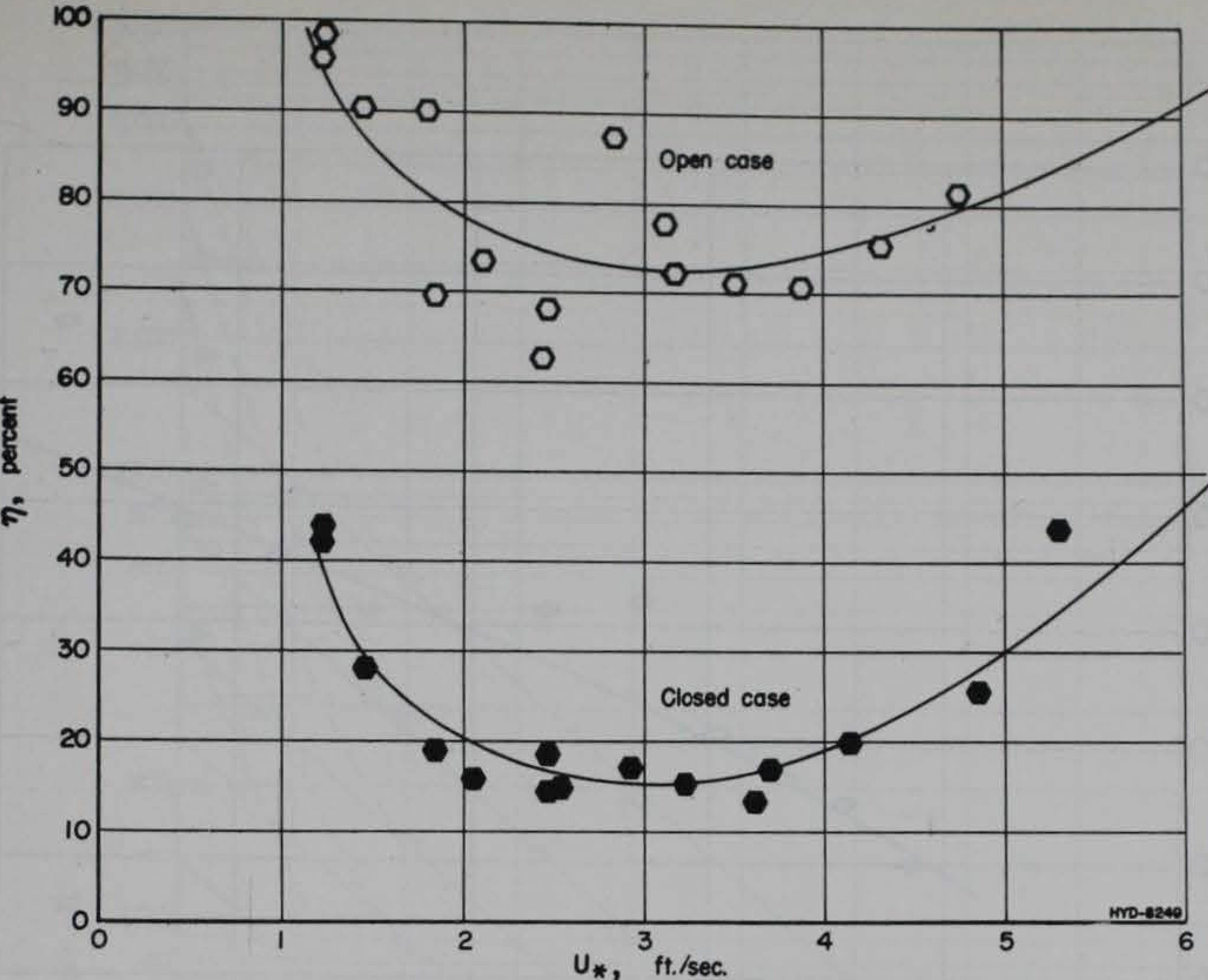


Figure 29. Efficiency curves for V-2 type

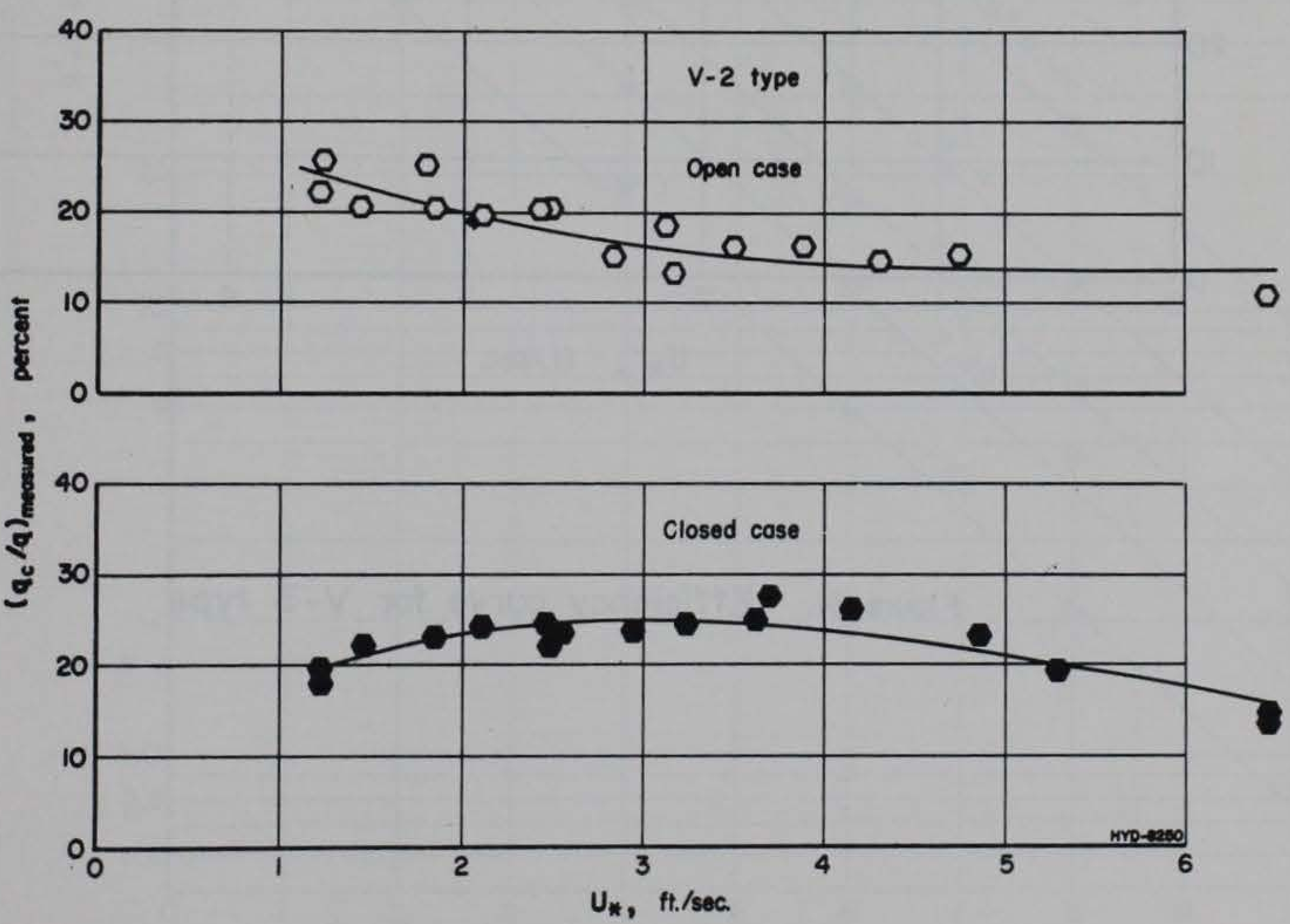


Figure 30. Ratio between q_c and q

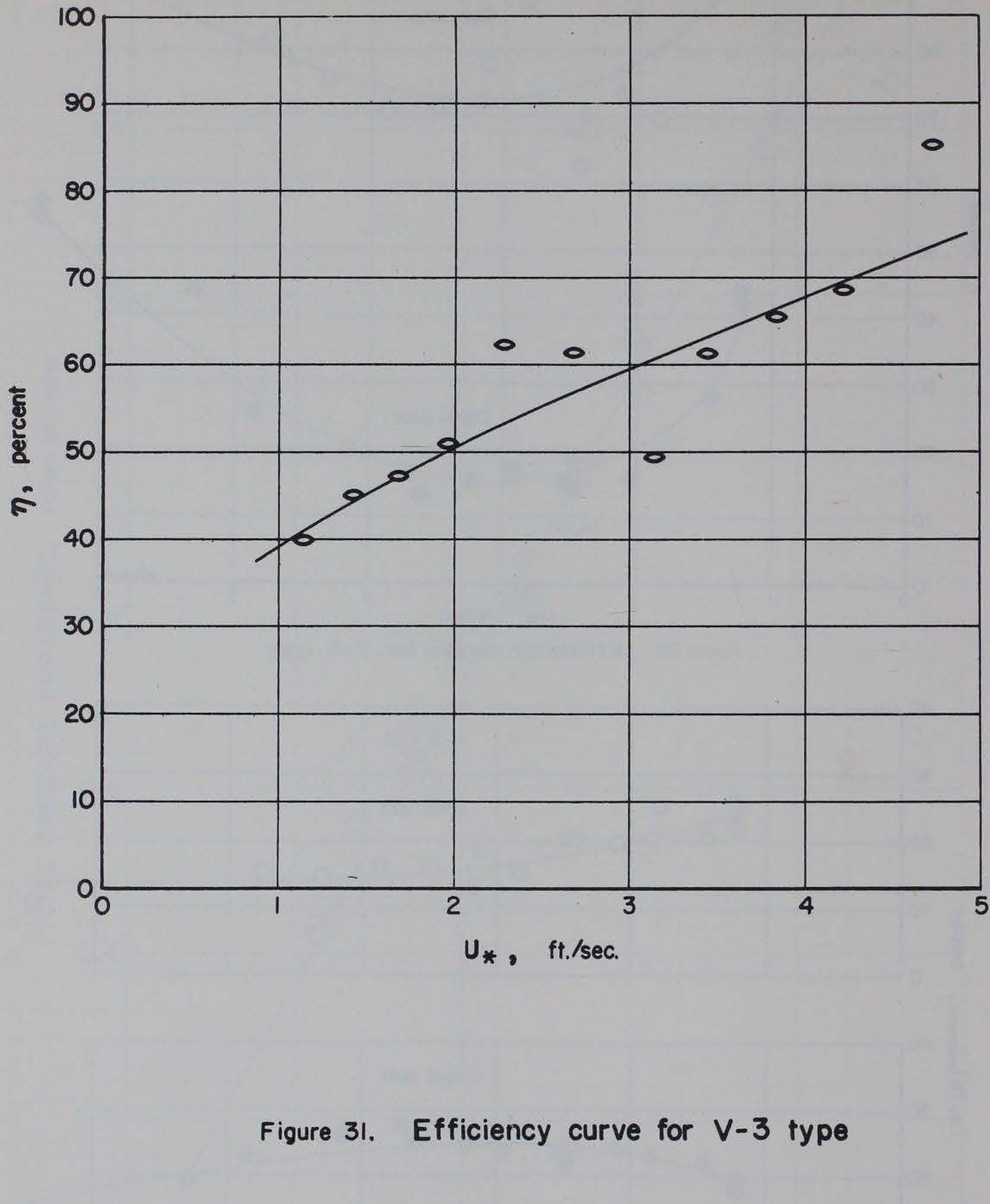


Figure 31. **Efficiency curve for V-3 type**

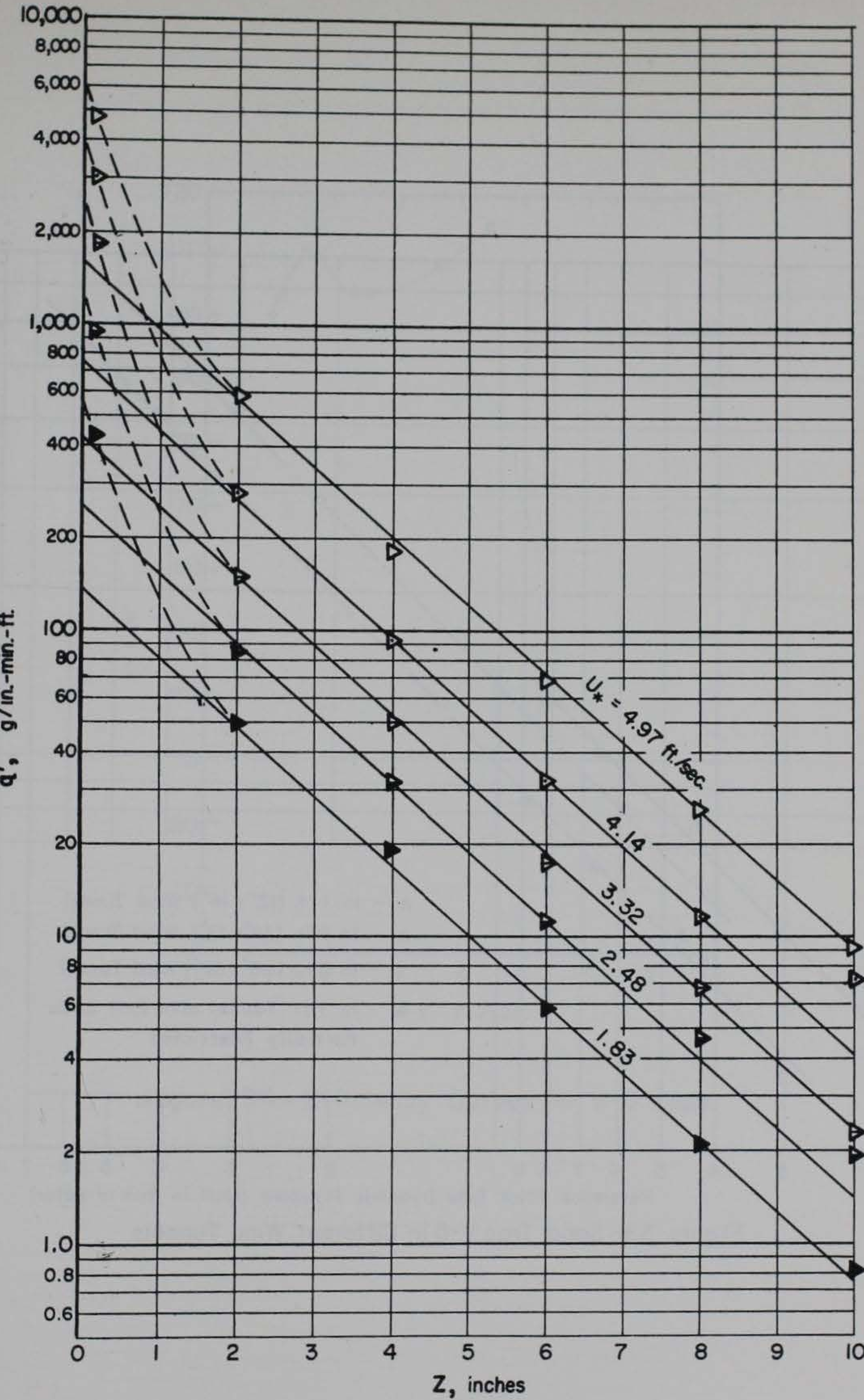


Figure 32. Vertical distribution of sand drift by V-4 type

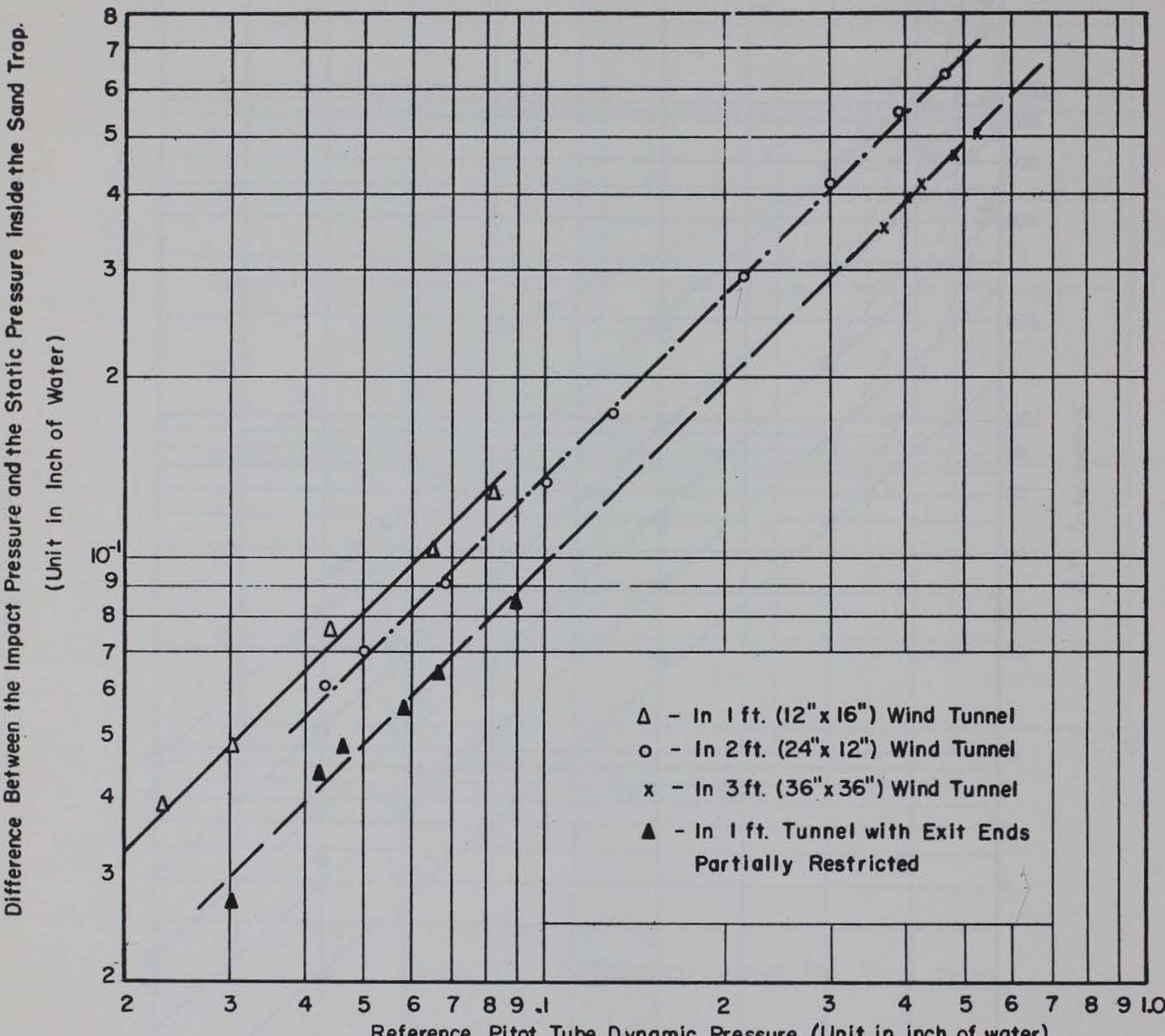


Figure 33 - Sand Trap V-6 in Different Wind Tunnels

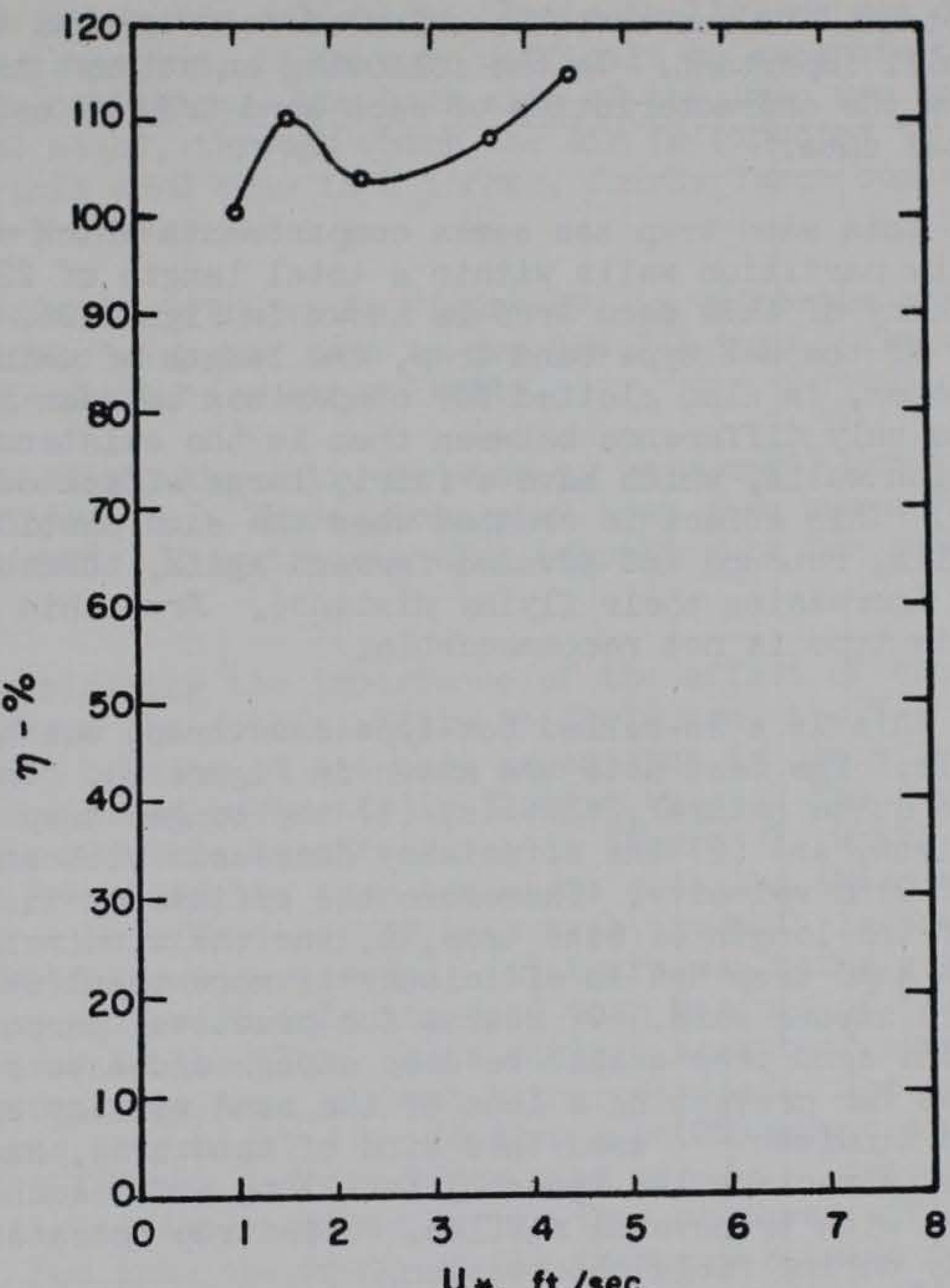


Figure 34 - Efficiency Curves for V-5 Type

In water, (1) how to eliminate the effect of back pressure on the movement of materials in the vicinity of the sand trap, and (2) how to prevent scouring around the sand trap, are the main difficult problems to be solved. In air it is assumed that the particles have such large momentum that there is no effect of back pressure. If this is true, the first item mentioned above is unimportant. Of course the problem of scour around the sand trap is still important. In the following an attempt is made to describe the characteristics of each sand trap by using the experimental data.

<u>H-1 Type</u>: This sand trap has seven compartments which are separated by partition walls within a total length of 22 inches. The efficiency of this sand trap is shown in Figure 26. The efficiency of the H-2 type sand trap, the length of which is also 22 inches, is also plotted for comparison between the two types. The only difference between them is the existence of the partition walls, which have a fairly large effect on the efficiency. This effect is created when the sand particles hit the walls, rebound and advance forward again, thereby apparently increasing their flying distance. From this point of view this type is not recommendable.

<u>H-2 Type</u>: This is a so-called box-type sand trap, which is quite simple. The test data are shown in Figure 24. The results are quite natural, that is, (1) the longer trap is more efficient, and (2) the efficiency decreases with an increase of wind velocity. Therefore the efficiency is a function of the length of sand trap, L, and the wind velocity. The 30-inch sand trap has an efficiency of more than 70%, even for a fairly strong wind. Of course for practical purposes in the field the sand trap should be deep enough and have some cross strips for preventing a loss of the sand already caught. O'Brien and Rindlaub[20] used this kind of sand trap, and it consisted of a rectangular trough 3 feet long and 6 inches wide, fitted with transverse riffles. This trap operated successfully during field observation.

<u>V-1 Type</u>: This type of sand trap was originally used by Bagnold for catching the saltation material. Later on Chepil[4a] modified the shape of Bagnold's trap for catching the total sand transport. The model tested in this study is almost identical to Chepil's sand trap. Its operating characteristics are shown in Figure 27. The unit was operated under two conditions; (1) with the container tightly fitted to the sand trap, (closed case), and (2) the container separated from the sand trap so that air passed through the unit, (open case). The difference in total pressure between the top of the sand exit inside the sand trap and outside of the wind tunnel for the open case was measured and is shown in Figure 28. The characteristics under the above two conditions are quite different; therefore the effect of back pressure cannot be

neglected. The efficiency in both cases is almost independent of the shear velocity; this fact is of a great advantage for comparing the erodibility of soil and sand. But for the purpose of measuring sand transport the efficiency is too low.

V-2 Type: This sand trap has two compartments, one for surface creep, and the other for saltation. But actually, as was discussed in the previous section, it is very difficult to separate the surface creep from the saltation. The back side of the trap was covered with fine mesh (200 mesh), through which the air is expected to flow away. The width of this sand trap is 4 inches, fairly large compared with that of the V-1 type.

The efficiency is shown in Figure 29, in which the closed case and the open case mean the same as for the V-1 type. The efficiency is clearly dependent on shear velocity.

For references, the ratio between q_s (measured) and q (measured) is shown in Figure 30. These plots show that q_s/q has a value of approximately 20%. This type is also inapplicable for general field use.

V-3 Type: Considering the importance of the effect of back pressure from the trap and the applicability to field use, the V-3 type of trap was tested because of the past experience in its effectiveness in catching suspended sediments in flowing water. The result of the calibration of this trap is given in Figure 31, which shows that the efficiency of the trap increases with the shear velocity. The relatively low efficiency of this trap probably is due to either or both of the following reasons: (a) there was not a representative amount of sand that went into the sand trap because of the disturbance of the trap to the flow, (b) a certain amount of sand could have gone through the trap without being retained. The second possibility was investigated by feeding a known amount of sand into the mouth of this trap under various wind speeds. These tests showed that the amount retained by the trap compared with the total amount fed into the mouth of the trap was between 6-60%, depending upon the wind speed. It is possible that performance of trap V-3 could be improved by modifying its shape.

V-4 Trap: All of the vertical type traps described above are the so-called "total quantity" type. The V-4 trap is the distribution type, that is, the amount of sand is estimated by the integration of the vertical distribution of sand as determined by the trap. The vertical distribution of measured sand drift is shown in Figure 32, from which it will be recognized that the profiles are quite similar to that obtained by Kawamura (Figure 7), and that all of the points, except the one determined by the compartment at the lowest elevation, can be represented by a straight line on semi-log paper, the slopes of which are almost constant. On the other hand, the amount caught by the compartment for surface creep is relatively small, therefore, the writer assumed that the compartment at the lowest elevation also caught some part of surface creep and that the distribution could be represented by a straight line. Therefore the equation of the vertical distribution is,

$$q'(Z) = Ae^{-BZ} \tag{50}$$

and the total amount of saltation is

$$q_s = \int_0^{\infty} Ae^{-BZ}\, dZ = \frac{A}{B} \quad . \tag{51}$$

By assuming the ratio of q_s/q is 0.80, owing to the experimental value of $q_c/q = 0.20$, the total amount of sand q is estimated by

$$q = \frac{q_s}{0.80} = \frac{A}{0.80\ B} \tag{52}$$

The result of computations by this relationship is shown in Table 4, from which it can be recognized that the above assumption seems to be fairly satisfactory.

Table 4

Comparison of the total amount of sand movement by the estimation from trap Type V-4 against the true amount.

U_* ft/sec	A g/in-min-ft	B inch	q_s g/min-ft	q estimated g/sec-cm	q from graph g/sec-cm
1.83	135	0.515	262	0.18	0.19
2.48	255	0.515	495	0.34	0.40
3.32	450	0.515	874	0.60	0.82
4.14	740	0.515	1437	0.98	1.37
4.97	1620	0.515	3146	2.15	2.10

In order to be sure of these assumptions and to make this sand trap more reliable, further investigations are desirable. Other factors which should be considered in the construction of a sand trap, are, (1) observation period was restricted by the capacity of the compartment located in the lower elevations, and (2) the lowest compartment also seems to catch some part of surface creep.

V-5 Type: This trap was designed according to the following principles: (a) to provide a large area inside the trap to decrease the velocity of the wind in that region, (b) to provide some device inside the trap to absorb the momentum of the sand particles, and (c) to reshape the trap so as to give a relatively small disturbance to the flow pattern. Since the over-all width of this trap is almost five inches, a difference in velocity distribution should be expected between the condition with the trap placed in a one-foot wind tunnel and the trap placed on an actual sand dune. This was proved by installing a Pitot tube inside the trap and testing the trap in three different sizes of wind tunnels. In each tunnel a second Pitot tube was placed about one foot in front of the trap to give a reference speed for comparative purposes. As shown in Figure 33, when the trap was placed in the one-foot tunnel there was a higher wind speed inside the mouth of the trap with respect to the reference speed, than in any of the other tunnels.

Unfortunately, due to the construction of the wind tunnels, there was no opportunity to place sand on the bottom of the larger tunnels to test the trap characteristics with sand. However, the trap could be tested in the following way. The trap was placed in the one-foot wind tunnel and the exit openings of the trap were partially restricted so as to give the same wind speed inside the mouth of the trap as if it were placed inside the three-foot wind tunnel for the same reference wind speed. A 2-inch layer of sand was then placed on the bottom of the one-foot tunnel, and this modified sand trap was tested under different wind speeds. For each wind speed two runs, "A" and "B", were made. In run "A", sand trap V-5 was placed inside the one-foot tunnel and tested. The duration of the run was restricted by the nature of scouring condition around the trap. The amount of sand detained by the trap was weighed. The total indicated transport in the 1-foot wide tunnel was then calculated by multiplying the trapped amount (trap opening was 3/8 inch) by 32. Next, run "B" was performed under the same wind speed and with the same length of run as in run "A" but without trap V-5 in the tunnel. In run "B" the total amount of sand transported over the entire 12-inch width of the tunnel was measured. It was advisable to conduct run "B" immediately after run "A" to minimize the humidity and temperature changes of the air. The efficiency of the sand trap was defined as the amount of the sand measured by the trap, as obtained in run "A", divided by the total amount of sand transported as measured in run "B". As shown in Figure 34, the efficiency was between 100-110%. An efficiency higher than 100% probably is due to the fact that the mouth of the trap was placed at the center line of the wind tunnel where the transport is higher than on either side. The projected area of the trap is 12 x 5 inches which is about 31% of the cross sectional area of the 12 x 16-inch wind tunnel, but it is only 4.6% of the cross sectional area of the 36 x 36-inch wind tunnel. Thus, it is believed that placing the trap in the 3-foot tunnel gave approximately the same velocity distribution that will be obtained with the trap installed in the field.

Scour Around Sand Traps

This subject has not been discussed in the above description of the characteristics of sand traps. In the process of the experiment, scour around the sand traps, especially the V-2 and V-3 types, was quite severe; therefore the observation period was limited by this condition. As the width of the wind tunnel is restricted, the scour condition was probably more than that which would occur in field tests.

SUMMARY OF TEST RESULTS

The experiments demonstrated that none of the available sand traps used by previous investigators gave entirely satisfactory results. The efficiency of the horizontal type trap is dependent on the shear velocity. Because the flying length of the sand particles is dependent on the shear velocity, the efficiency of the horizontal type of trap can be made relatively high only by making the trap relatively long. The performances of the vertical type traps were influenced by the disturbance of the trap on the flow pattern. The vertical type traps can be improved to give satisfactory results. With trap V-1 a suction force by mechanical pumping can be provided under the trap. With trap V-3 the shape of trap may be modified to improve its efficiency. The latter condition was chosen because of the simplicity of such a method, with the development of trap V-5 being the final result.

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REFERENCES

1. Bagnold, R. A., The physics of blown sand and desert dunes, Methuen & Co. Ltd., London, 1954.

2. Bagnold, R. A., The movement of a cohesionless granular bed by fluid flow over it, British Journal of Applied Physics, Vol. 2, No. 2, Feb. 1951.

3. Chepil, W. S., Dynamics of wind erosion, II, Initiation of soil movement, Soil Science, Vol. 60, No. 5, Nov. 1945.

4. Chepil, W. S., Dynamics of wind erosion, III, The transport capacity of the wind, Soil Science, Vol. 60, No. 6, 1945.

4a. Chepil, W. S., Width of field strips to control wind erosion, Agricultural Experiment Station, Kansas State College of Agriculture and Applied Science, Tech. Bull. 92, Dec. 1947.

5. Cooper, W. S., Coastal sand dunes of Oregon and Washington, The Geological Society of America, Memoir 72, June 1958.

6. Deacon, E. L., Vertical diffusion in the lowest layers of the atmosphere, Royal Meteorological Society, Quarterly Journal, Vol. 75, No. 323, Jan. 1949.

7. Einstein, H. A., Determination of rates of bed-load movement, Proc. of the Federal Inter-Agency Sedimentation Conference, 1947.

8. Einstein, H. A., and N. Chien, Second approximation to the solution of the suspended load theory, University of California, Inst. of Engr. Reasearch, M. R. D. Sediment Series No. 3, Jan. 1954.

9. Ellison, T. H., Atmospheric turbulence, Surveys in Mechanics, Cambridge University Press, 1956.

10. Exner, F. M., Sitzungsber, Mathem-naturw. Kl., Wien Ab., II a 137, 1928.

11. Ford, E. F., The transport of sand by wind, Trans. A.G.U., Vol. 28, No. 2, April 1957.

12. Hamada, T., K. Okubo, and N. Hase, Technical report of Ishinomaki and Toha Harbors, Trans. Tech. Research Inst., 1951 (in Japanese).

13. Ishihara, T., and Y. Iwagaki, Studies on the countermeasures to prevent Aliro Harbor from filling up with sand drift, Bull. of the Committee for the Countermeasure of Sand Drift, Tottori Prefecture, 1950 (in Japanese).

14. Ishihara, T., and Y. Iwagaki, On the effect of sand storm in controlling the mouth of the Kiku River, Bull. of the Disaster Prevention Research Inst., Kyoto Univ., No. 2, 1952.

15. Kawamura, R., Study on sand movement by wind, Rept. of the Inst. of Science and Technology, Univ. of Tokyo, Vol. 5, No. 3/4, Oct. 1951 (in Japanese).

16. Kawata, S., On the break-wind, Jour. of the Japan Soc. of Civil Engr., Vol. 33, No. 2, 1948 (in Japanese).

17. Kawata, S., Experiment on the sand drift by wind, Bull. of Investigation on the Forest for Disaster Prevention, Forestry Agency, 1950 (in Japanese).

18. Mason, C. C., and R. L. Folk, Differentiation of beach, dune, and aeolian flat environment by size analysis, Mustang Island, Texas, Journal of Sedimentary Petrology, Vol. 28, No. 2, June 1958.

19. Novak, P., Bed load meters - development of a new type and determination of their effeciency with the aid of scale models, Proc. of the Seventh General Meeting, Internat'l Assoc. for Hydraulic Research, 1957.

20. O'Brien, M. P., and B. D. Rindlaub, The transportation of sand by wind, Civil Engineering, May 1936.

21. Rider, N. E., Eddy diffusion of momentum, water vapour and heat near the ground, Phil. Trans., A, 246, 1954.

22. Twenhofel, W. H., Minerological and physical composition of the sands of the Oregon Coast from Coos Bay to the mouth of the Columbia River, Oregon Dept. Geol. and Min. Industries, Bull. 30, 1946.

23. U. S. Atomic Energy Commission, Meteorology and atomic energy, AECU, 3066, July 1955.

24. Vanoni, V. A., Some effects of suspended sediment on flow characteristics, Proc. of the Fifth Hydraulics Conference, 1952.

25. Vinckers, J. B., E. W. Bijker and J. B. Schijf, Bed-load transportmeter for fine sand "Sphinx", Proc. of the Minnesota Internat'l Hydraulics Convention, Internat'l Assoc. for Hydraulic Research, 1953.

26. Woodruff, N. P., and L. Lyles, Effect of crops and tillage methods on the shearing force of the atmospheric wind, 1956 (unpublished).

27. Zingg, A. W., Wind tunnel studies of the movement of sedimentary material, Proc. of the Fifth Hydraulics Conference, 1952.

APPENDIX

I. SAND TRAP H - 1 TYPE

P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total sand transported, q,gr/cm-sec.	Efficiency, η, %
0.162	0.88	26.8	5.8×10^{-4}	93.4
0.227	1.22	37.2	7.23×10^{-2}	83.9
0.227	1.22	37.2	7.18×10^{-2}	82.8
0.230	1.24	37.8	5.99×10^{-2}	83.2
0.230	1.24	37.8	7.39×10^{-2}	82.6
0.230	1.24	37.8	5.72×10^{-2}	82.9
0.230	1.24	37.8	5.19×10^{-2}	82.6
0.354	1.89	57.6	2.20×10^{-1}	75.1
0.466	2.48	75.6	4.13×10^{-1}	69.2
0.650	3.48	106.7	7.83×10^{-1}	69.1

II. SAND TRAP H-2 TYPE

L, inches	P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total sand transported, gr/cm-sec.	η, %
3	0.231	1.25	38.1	7.06×10^{-2}	46.0
	0.274	1.47	44.8	1.20×10^{-1}	49.1
	0.343	1.84	56.1	1.99×10^{-1}	51.5
	0.398	2.14	65.2	2.69×10^{-1}	51.5
	0.461	2.46	75.0	3.54×10^{-1}	50.9
	0.533	2.75	83.8	4.89×10^{-1}	47.8
	0.613	3.27	98.4	6.46×10^{-1}	46.0
	0.681	3.63	110.6	8.69×10^{-1}	44.1
	0.749	4.01	122.2	1.11	41.6
	0.849	4.52	137.8	1.54	38.4
	0.892	4.74	144.5	1.92	35.7
6	0.228	1.22	37.2	5.94×10^{-2}	62.3
	0.272	1.47	44.8	9.66×10^{-2}	62.1
	0.350	1.87	57.0	1.73×10^{-1}	64.6
	0.404	2.16	65.8	2.32×10^{-1}	64.2
	0.468	2.50	76.2	3.15×10^{-1}	62.9
	0.550	2.94	89.6	4.57×10^{-1}	60.1
	0.616	3.29	100.3	6.00×10^{-1}	57.4
	0.706	3.77	114.9	8.10×10^{-1}	55.7
	0.771	4.12	125.6	1.03	54.6
	0.852	4.54	138.4	1.32	52.4
	0.937	4.99	152.1	1.79	49.2
12	0.228	1.23	37.5	2.11×10^{-2}	72.6
	0.274	1.47	44.8	1.26×10^{-2}	76.2
	0.347	1.87	57.0	2.37×10^{-1}	75.8
	0.398	2.14	65.2	3.06×10^{-1}	76.8
	0.424	2.27	69.2	5.44×10^{-1}	75.2
	0.406	2.17	66.1	3.35×10^{-1}	75.3
	0.461	2.47	75.3	4.53×10^{-1}	73.2
	0.538	2.87	87.5	6.20×10^{-1}	70.6
	0.616	3.29	100.3	8.38×10^{-1}	69.3
	0.685	3.66	111.6	1.07	68.4
	0.771	4.12	125.6	1.41	66.2
	0.832	4.45	135.6	1.76	63.7
	0.906	4.83	147.2	2.28	61.2
22	0.233	1.25	38.1	8.36×10^{-2}	90.0
	0.272	1.47	44.8	1.37×10^{-1}	88.0
	0.333	1.78	54.3	2.13×10^{-1}	87.1
	0.188	1.02	31.1	3.98×10^{-3}	86.1
	0.333	1.78	54.3	2.25×10^{-1}	79.9
	0.464	3.48	106.1	4.44×10^{-1}	79.4
	0.392	2.10	64.0	2.90×10^{-1}	84.5

II. SAND TRAP H-2 TYPE (contd)

L, inches	P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total sand transported, gr/cm-sec.	η, %
22	0.457	2.45	74.7	4.22×10^{-1}	81.1
	0.535	2.85	86.9	5.99×10^{-1}	74.1
	0.688	3.57	108.8	1.51	57.4
	0.756	4.05	123.4	1.92	70.0
	0.776	4.14	126.2	1.18	76.4
	0.776	4.14	126.2	1.25	73.5
	0.840	4.48	136.6	1.63	68.1
	0.934	4.96	151.2	2.24	61.7
	0.617	3.29	100.3	7.84×10^{-1}	77.4
	0.844	4.50	137.2	1.28	73.0
34	0.193	1.05	32.0	$3,76 \times 10^{-2}$	92.7
	0.235	1.27	38.7	9.09×10^{-2}	90.2
	0.279	1.50	45.7	1.39×10^{-1}	91.0
	0.339	1.83	55.8	2.08×10^{-1}	89.7
	0.404	2.16	65.8	2.88×10^{-1}	88.1
	0.466	2.50	76.2	3.80×10^{-1}	86.4
	0.543	2.90	88.4	5.07×10^{-1}	84.9
	0.630	3.37	102.7	7.13×10^{-1}	81.1
	0.702	3.75	114.3	9.24×10^{-1}	76.5
	0.776	4.14	126.2	1.22	69.0
	0.776	4.14	126.2	1.18	75.9
	0.776	4.14	126.2	1.12	76.2
	0.844	4.50	137.2	1.52	75.8
	0.928	4.95	150.9	1.99	68.6

III. SAND TRAP V-1 TYPE

P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total sand transported, gr/cm-sec.	Closed case, gr/cm-sec.	Closed case, η, %	Opened case, gr/cm-sec.	Opened case, η, %
0.219	1.17	37.4	5.88×10^{-2}	9.36×10^{-3}	15.9	3.73×10^{-2}	63.4
0.390	2.07	66.2	2.60×10^{-1}	4.82×10^{-2}	18.6	1.31×10^{-1}	50.6
0.461	2.47	79.0	4.04×10^{-1}	7.71×10^{-2}	19.1	2.00×10^{-1}	49.5
0.523	2.79	89.3	4.96×10^{-1}	8.75×10^{-2}	17.6	2.39×10^{-1}	48.3
0.608	3.24	103.7	6.21×10^{-1}	1.10×10^{-1}	17.6	3.01×10^{-1}	48.4
0.730	3.88	124.2	8.80×10^{-1}	1.43×10^{-1}	16.3	4.49×10^{-1}	51.0
0.732	3.92	125.4	1.18	2.28×10^{-1}	19.4	6.56×10^{-1}	55.9
0.791	4.22	135.0	1.44	2.74×10^{-1}	19.0	8.13×10^{-1}	56.6
0.884	4.71	150.7	2.17	4.13×10^{-1}	19.0	1.14	52.7

IV. SAND TRAP V-2 TYPE

(a) Opened Cases

P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total amount from curve, gr/cm-sec.	Estimated Amount, gr/cm-sec.	η, %	Surface creep (measured), %
0.226	1.22	37.2	4.85×10^{-2}	4.77×10^{-2}	98.4	25.7
0.268	1.44	43.9	9.70×10^{-2}	8.75×10^{-2}	90.2	20.6
0.332	1.78	54.3	1.82×10^{-1}	1.64×10^{-1}	90.2	25.2
0.393	2.10	64.0	2.73×10^{-1}	2.00×10^{-1}	73.1	19.6
0.455	2.44	74.4	3.92×10^{-1}	2.45×10^{-1}	62.4	20.3
0.530	2.83	86.3	4.78×10^{-1}	4.18×10^{-1}	87.5	15.2
0.587	3.13	95.4	6.95×10^{-1}	5.41×10^{-1}	77.9	18.4
0.593	3.16	96.3	7.10×10^{-1}	5.11×10^{-1}	72.0	13.5
0.656	3.50	106.7	9.10×10^{-1}	6.48×10^{-1}	71.2	16.1
0.729	3.88	118.3	1.18	8.31×10^{-1}	70.8	16.1
0.811	4.32	131.7	1.50	1.12	75.2	14.7
0.892	4.75	144.8	1.88	1.53	81.5	15.1
0.464	2.48	75.6	4.08×10^{-1}	2.78×10^{-1}	68.1	20.5
1.219	6.47	197.2	3.90	3.77	96.7	10.7
0.228	1.22	37.2	4.92×10^{-2}	4.72×10^{-2}	95.9	22.1
0.347	1.85	56.4	2.03×10	1.41×10^{-1}	69.5	20.6

(b) Closed Cases

P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total amount from curve, gr/cm-sec.	Estimated Amount, gr/cm-sec.	η, %	Surface creep (measured), %
0.230	1.23	37.4	4.95×10^{-2}	2.16×10^{-2}	43.6	19.7
0.230	1.23	37.4	4.95×10^{-2}	2.09×10^{-2}	42.2	18.1
0.271	1.45	44.2	1.00×10^{-1}	2.81×10^{-2}	28.1	22.1

IV. SAND TRAP V-2 TYPE (contd)

(b) Closed Cases

P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total amount from curve, gr/cm-sec.	Estimated amount, gr/cm-sec.	η, %	Surface creep (measured), %
0.344	1.83	55.8	1.95×10^{-1}	3.73×10^{-2}	19.1	23.2
0.391	2.10	64.0	2.74×10^{-1}	4.31×10^{-2}	15.7	24.5
0.463	2.47	75.3	3.94×10^{-1}	5.76×10^{-2}	14.6	24.5
0.474	2.53	77.1	4.22×10^{-1}	6.42×10^{-2}	15.2	23.7
0.547	2.93	89.3	5.94×10^{-1}	1.03×10^{-1}	17.3	23.8
0.603	3.23	98.5	7.58×10^{-1}	1.15×10^{-1}	15.2	24.7
0.678	3.62	110.3	9.95×10^{-1}	1.35×10^{-1}	13.5	25.4
0.745	3.70	112.8	1.05	1.80×10^{-1}	17.1	27.8
0.831	4.15	126.5	1.37	2.73×10^{-1}	20.0	26.3
0.911	4.86	148.1	1.99	5.10×10^{-1}	25.7	23.6
0.464	2.48	75.6	4.08×10^{-1}	7.64×10^{-2}	18.7	22.3
1.219	6.47	197.2	3.90	2.22	56.8	14.3
1.219	6.47	197.2	3.90	2.13	54.6	14.0
1.045	5.30	161.5	3.90	1.09	43.9	18.3

V. SAND TRAP V-3 TYPE

P, inches of water	U_*, ft/sec.	U_*, cm/sec.	Total amount from curve, gr/cm-sec.	Total amount estimated, gr/cm-sec.	η, %
0.212	1.14	34.8	3.25×10^{-2}	1.29×10^{-2}	39.8
0.264	1.42	43.3	9.20×10^{-2}	4.11×10^{-2}	44.7
0.316	1.69	51.5	1.58×10^{-1}	7.55×10^{-2}	47.8
0.367	1.97	60.1	2.78×10^{-1}	1.42×10^{-1}	51.1
0.424	2.27	69.2	3.30×10^{-1}	2.06×10^{-1}	62.5
0.502	2.68	81.7	4.80×10^{-1}	2.95×10^{-1}	61.4
0.588	3.15	96.0	7.18×10^{-1}	3.55×10^{-1}	49.4
0.647	3.45	105.2	8.90×10^{-1}	5.44×10^{-1}	61.1
0.719	3.84	117.0	1.15	7.51×10^{-1}	65.3
0.792	4.23	128.9	1.42	9.71×10^{-1}	68.4
0.885	4.72	143.9	1.82	1.55	85.1

VI. SAND TRAP V-4 TYPE

P, inches of: water	0.342	0.465	0.622	0.774	0.934
surface creep, : g/ft-min.	23.3	37.1	60.0	90.2	152.3
Z = 0.156 in:	434.9	948.8	1834.9	3033.2	4775.0
Z = 2 in.:	49.1	84.4	146.8	280.3	590.9
Z = 4 in.:	19.1	31.5	49.1	90.9	179.1
Z = 6 in.:	5.8	11.1	17.3	32.2	68.3
Z = 8 in.:	2.1	4.6	6.7	11.6	26.0
Z = 10 in.:	0.8	1.9	2.2	7.2	9.1