TSUNAMI PRONE FRICTION FACTORS FROM WIND MEASUREMENTS

by

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SUMMARY

The long wave equations, used for tsunami run-up and flood wave calculations, have an unknown friction term. As an alternative to hydraulically determined friction factors, an adjustable three-level anemometer staff system is used for making wind profile measurements over typical Hawaii terrain. Results from measurements taken during trade wind conditions are given for three types of terrain: (1) golf course, (2) large flat knoll covered with 2 to 2 1/2 feet tall grass thin to medium dense, and (3) a large rock farm covered with several layers of stone 2 1/2 to 3 feet or more in diameter. Average values of Manning's "n" determined approximately from the von Karman friction length, $n \cong .06\, z_o^{1/6}$ vary from 0.028 over the golf course, 0.046 over the grass knoll, and 0.051 over the rock farm. The top level anemometer for both systems is at elevation 10.6 meters (35.8 feet) and the remaining anemometers are equally spaced on the log scale, with the bottom level anemometer at 1.3 meters (4.28 feet) above the support base. We are presently repeating the experiments using an adjustable five-level anemometer staff system.

It is pointed out that the results obtained from wind experiments have not yet been correlated with hydraulic experiments, and it is known that the friction factor decreases with increase in the Froude number, given by $F = \bar{V}/\sqrt{gR}$, where $\bar{V}$ is the mean velocity over the vertical distance of the hydraulic radius, R. The question seems to be, what is the equivalent hydraulic radius for the adiabatic atmosphere that would give the same friction factor for the same roughness for the von Karman velocity profile in hydraulic experiments? The wind experiments do show that there is a tendency for the friction factor to decrease with increase of mean wind speed. It would be of scientific interest to determine an equivalent hydraulic radius for wind profile experiments, making it possible to correlate the data with hydraulic experiments. This needs further investigation.

It is important in our wind experiments that we use only wind profiles that are adiabatic or nearly adiabatic in order that the von Karman velocity profile is in similitude with hydraulic water profiles for turbulent flow. It is also important that we do use only wind profiles having ten meter anemometer level wind speeds greater than about 6 to 7 meters per second, in order to assure us that the experiments are well

above the minimum friction velocity Reynolds number, $R_e = \frac{u_* k}{\nu} \geq 70$ or 80, where $K \hat{=} 30\, z_o$, and z_o = the von Karman friction length.

Finally, we have included a re-analysis of the canal experiments of Lane and Carlson (1953) and hope to open the way for further research and experimentation for possible correlation between wind experiments and hydraulic experiments.

1. INTRODUCTION

Two important purposes of the tsunami research are to increase the "State of the Art" - (1) tsunami forecasting for warning and evacuation purposes, and (2) tsunami hindcasting for prediction of future events for zoning and design criteria. In the past, most tsunami research has been directed more-or-less toward four general categories: (1) source area and mechanisms of tsunami generation; (2) propagation of tsunamis from source area to the coastline; (3) harbor surging and beach run-up; and (4) historical data collection and statistical interpretations.

Very little consideration has been given to the nature of the flooding problem as a consequence of tsunami transformation into a flood wave at the top of the beach or the coastline and its propagation over previously dry bed or coastal terrain. All tsunami statistics are based on data that were compiled for the then existing topographical conditions. In case of Hawaii, this covers up to 140 years of tsunami data at Hilo, for example. If the pre-existing topographical conditions are changed as a result of urban and industrial development and, if the same tsunami event occurred, then the consequences of flooding will be entirely different than those which occurred from past history. The U.S. Army Corps of Engineers recommends the use of rip-rap, seawalls, or other construction methods to reduce the hazards of flooding. On the other hand, land developers bulldoze and level the roughness terrain for urban and industrial development. This has a direct bearing on the two important purposes of tsunami research for the purpose of increasing the "State of the Art": (1) tsunami forecasting and warning for evacuation, and (2) tsunami hindcasting for prediction of future events and design criteria.

Since coastal regions are choice locations for urban and industrial development, there is a need to study the effect of bed roughness on potential tsunami flooding, because there is a potentially dangerous risk in loss of life and property if the terrain roughness is decreased, and the proper friction factors are not considered.

The long wave equations are generally used to determine tsunami run-up, flood wave, and inundation of low coastal areas. The two-dimensional computer program, developed by Houston and Butler (1979) of the U.S. Army Corps of Engineers Waterways Experiment Station, is applicable from deep water to beyond the coastline; and the one-dimensional analytical solution given by Bretschneider and Wybro (1976) is applicable only in the final reaches inland from the coastline. The main difference between the two solutions mentioned above is that the first one is

two-dimensional, neglects the convective acceleration terms and retains the local acceleration terms, whereas the second one is one-dimensional and assumes steady state by neglecting the local acceleration terms but retains the convective acceleration terms. Common to both solutions is the retention of the friction term. The friction term is related to bed-roughness, and is usually given by the Chezy coefficient "C" or Manning's "n". Presently, the friction coefficients used in the long wave equations are based on experiences with river, channel and canal flows, or are estimated from wind profile experiments or scaled from hydraulic model tests. The conditions are quite different for a tsunami flood wave over a previously dry bed or rough terrain. There are no measured friction factors determined under these conditions and it is not practical to measure friction factors over previously exposed terrain during a tsunami flood wave.

As an alternative to hydraulically determined friction factors, an adjustable three-level anemometer staff system was used for taking wind profile measurements over typical Hawaii terrain. Presently, a five-level anemometer staff is being used. The scheme of testing is shown in Figure 1. From the wind profile measurements under neutral atmospheric conditions, one can estimate Manning's "n" which is proportional to the sixth root of the von Karman friction length z_o.

Thus far, of a number of typical Hawaii terrain, three types have been studied: (1) a golf course, (2) a broad grassy knoll, with medium dense grass 2 to 2 1/2 feet tall, and (3) a rock farm, consisting of a large area of stock pile stones 2 to 3 feet average size and more-or-less level conditions as best as can be expected. The results of the data analysis are summarized in Table I, along with the compilation of Ann-Dof, Högstrom and Högstrom (1977). The z_o scale of Table I was originally given in meters. The left scale of z_o in meters has been changed to feet, and Manning's "n" $\cong 0.006\, z_o^{1/6}$ (in feet)$^{1/6}$ has been added on the right. This gives Manning's "n" to within ± 5 to 10 percent of the types of conditions expected in the present study.

2. BRIEF SUMMARY ON FRICTION FACTOR RELATIONSHIPS

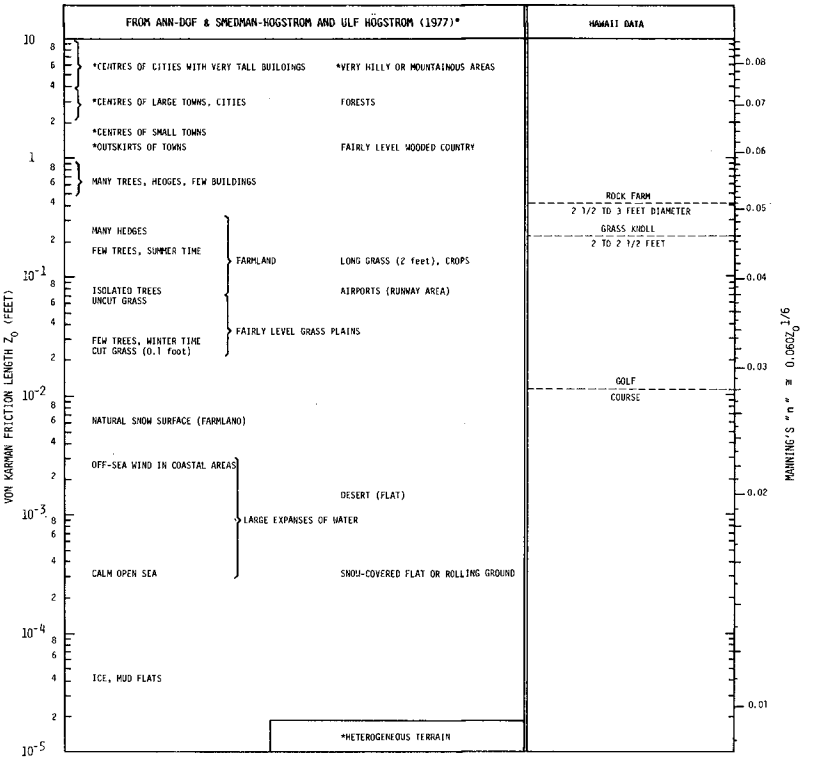
The various forms of the friction factors can be expressed as follows:

$$f_c = \frac{1}{4} f = \frac{2\tau_b}{\rho u^2} = \frac{2g}{C^2} = \frac{2gn^2}{(1.486)^2 R^{1/3}} = 2\left[\frac{k}{\log_e \frac{R}{ez_o}}\right]^{-2} \qquad (1)$$

where f_c and f are the Darcy-Weibach friction factors for open channel flow and full flow in closed conduits, respectively. τ_b is the bottom shear stress; ρ, the density of the fluid; u, the mean velocity of flow; g, the acceleration of gravity; C, the Chezy-Kutter coefficient; n,

TABLE I

TERRAIN DESCRIPTION OF AREA WITHIN SEVERAL KILOMETERS UPWIND OF SITE



*NOTE: ORIGINAL Z_0 WAS GIVEN IN METERS, NOW CHANGED TO Z_0 IN FEET (LEFT SCALE) AND MANNING'S "n"

Manning's "n"; R, the hydraulic radius; e, the base of the natural logarithm; z_o, the von Karman friction length; and k = 0.4 von Karman universal constant.

Rouse (1949) has shown that Manning's "n" is proportional to $z_o^{1/6}$ power over a wide range of conditions. Calculations over a wide range of z_o and hydraulic radius R shows that:

$$n/z_o^{1/6} \cong 0.060 \pm 5 \text{ to } 10\% \qquad (2)$$

Figure 1 shows the range of $n/z_o^{1/6}$ versus hydraulic radius R, for the ranges of z_o expected from the wind profile measurements.

The U.S. Air Force Air Research Development command (1961) summarized typical values of z_o. These values are given in Table II together with Manning's "n" based on eq. 2. Bretschneider and Wybro (1976) suggested values of Manning's "n" for various types of terrain and they are repeated in Table III. There is a tendency for reduction in friction factor with increase in velocity. This is similar to what one expects from hydraulic experiments where the friction factor decreases with increase of Froude number, as shown in Figures 2 and 3, based on the reanalysis of the canal data of Lane and Carlson (1953).

Table IV gives additional relations for Manning's "n" based on hydraulic experiments. Equations a, b, c, and d in Table IV can be made universally dimensionless by multiplying the left side by $\sqrt{g}/1.486$, and changing the K values from inches to feet. However, eq. e cannot be made dimensionless in a similar manner, except by introducing either another $R^{1/6}$ or $K^{1/6}$ in the denominator of the left side of eq. e. Using $R^{1/6}$ in the denominator of the left side of eq. e and rearranging terms and $\sqrt{g}/1.486$, one can determine eq. g. Using K instead of R, one can arrive at eq. h. Eliminating K from eq. e, one can arrive at eq. f. Evidently, eq. f is a function of R, eq. g is a function of K_m, eq. h is a function of R and K_m; but all three equations, f, g and h are functions of the flow as defined by the Froude number.

3. FREE AIR WIND EXPERIMENTS

There is nothing new in using wind experiments to study hydrodynamic problems due to water current forces. This has been done in the past by naval architects and marine engineers for offshore floating and rigid structures. What is unique in this study and approach is the use of prototype wind experiments for the determination of friction factors over typical Hawaii terrain to aid in the solution of the hydraulic problems associated with tsunami run-up, flood wave and inundation.

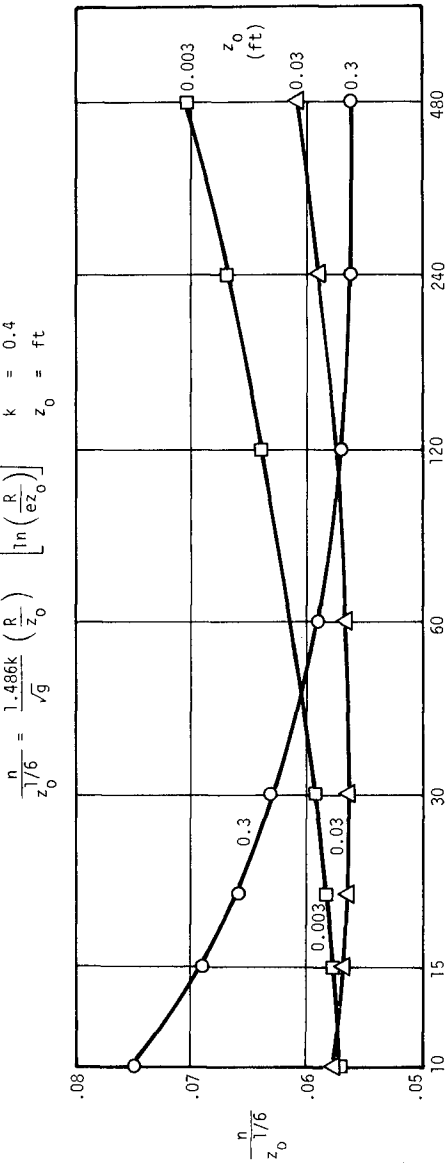


FIG. 1 Variation of $\frac{n}{z_o^{1/6}}$ for various values of z_o and R

TABLE II

SUMMARY VALUES OF z_o*

Values of z_o and Manning's "n"		
Type Surface	z_o(ft)	$n = .06\ z_o^{1/6}$
Very smooth (mud flats, ice)	0.00003	.011
Lawn grass up to 0.4 inches high	0.003	.023
Downland thin grass up to 4 inches high	0.02	.031
Thick grass up to 4 inches high	0.075	.039
Thin grass up to 20 inches high	0.16	.044
Thick grass up to 20 inches high	0.30	.049

*Obtained from U.S. Air Force Research Development Command (1961)

TABLE III

SUGGESTED VALUES OF MANNING'S "n" FOR VARIOUS COASTAL TERRAIN CONDITIONS

n	Conditions
0.015 - 0.025	Very smooth (mud flats, ice, well maintained concrete paved ways, beaches of fine sand)
0.025 - 0.030	Smooth (dried earth, coarse sand beaches, badly maintained concrete paved ways, very thin lawn grass up to 1 cm high)
0.030 - 0.035	Average for developed areas (lawn grass up to 5 cm high, gravel, presence of some buildings, houses, and other obstructions)
0.035 - 0.045	Open coast, relatively smooth and open area (grass up to 10 cm, sparse population of trees*, sparse bush, even bottom)
0.045 - 0.055	Moderately rough open coastal areas (thick grass, uneven bottom consisting of large rocks, coral, etc., presence of trees with low foliage, brush, lava rock, etc.)
0.055 - 0.070	Unusually rough coastal areas (dense brush, dense tree population with exposed roots, coarse lava rock formations)

*Trees with high foliage such that only trunks are exposed to flow

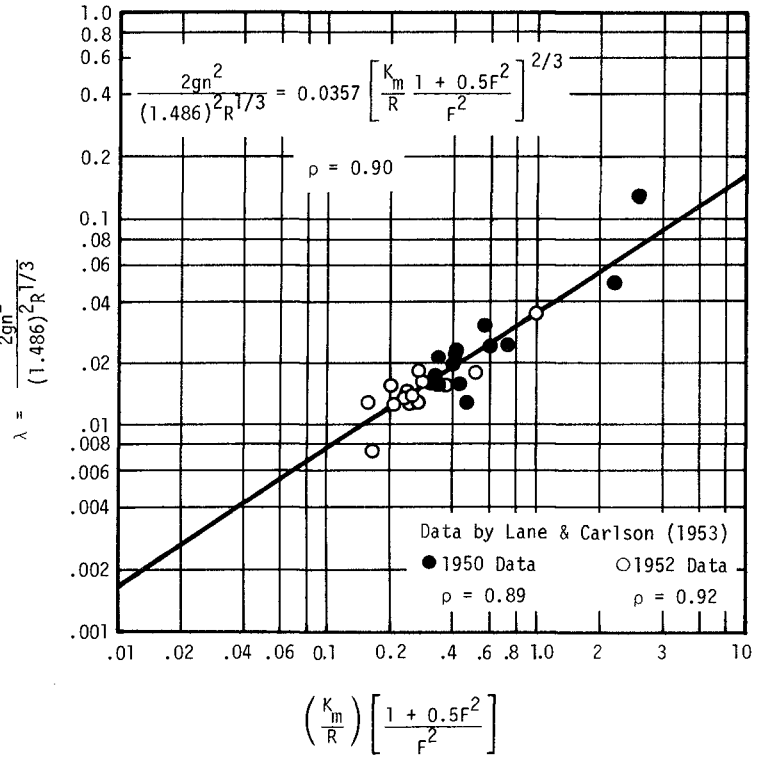


FIG. 2 Non-Dimensional Mannings "n", λ vs $\left(\frac{K_m}{R}\right)\left[\frac{1 + 0.5F^2}{F^2}\right]$

$F = \overline{V}/\sqrt{gR}$, λ = Kelegan Non-Dimensional Mannings "n"

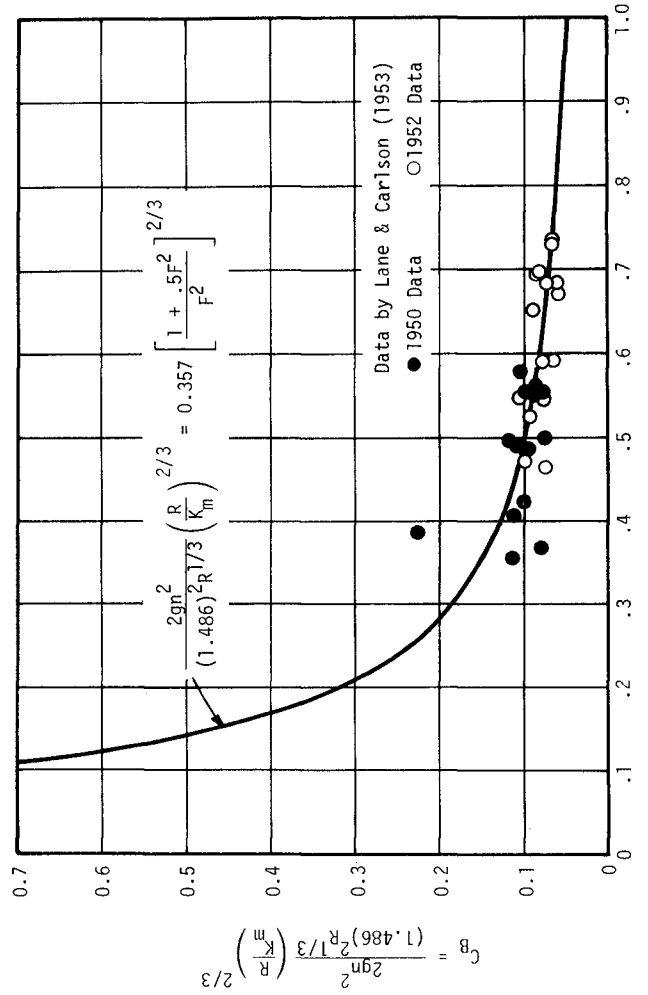


FIG. 3 Non-Dimensional Mannings "n", C_B vs Froude No. $F = \bar{V}/\sqrt{gR}$

$C_B = \frac{2gn^2}{(1.486)^2 R^{1/3}} \left(\frac{R}{K_m}\right)^{2/3}$

$F = \bar{V}/\sqrt{gR}$

TABLE IV SUMMARY OF ADDITIONAL RELATIONS FOR MANNINGS "n"

	EMPIRICAL EXPRESSIONS FOR MANNINGS "n"	
	Expression	Source
a)	$44.4\ n = K_{50}^{1/6}$	Strickler (1923)
b)	$46.9\ n = K_{50}^{1/6}$	Keulegan (1938)
c)	$39.0\ n = K_{25}^{1/6}$	Lane and Carlson (1953)
d)	$49.0\ n = K_{10}^{1/6}$	Irmay (1948)
e)	$26.0\ n = \left(\frac{K_{35}}{R}\right)^{1/6}$	Lane and Carlson (1953)
	NON-DIMENSIONAL EXPRESSIONS FOR MANNINGS "n"	
f)	$\lambda = \frac{2gn^2}{(1.486)^2 R^{1/3}}$	Keulegan (1967)
g)	$C_M^2 = \frac{gn^2}{(1.486)^2 K_m^{1/3}}$	Squarer, Mostafa & McDermid (1971)
h)	$C_B = \frac{2gn^2}{(1.486)^2 R^{1/3}} \left(\frac{R}{K_m}\right)^{2/3}$ or $C_B = \frac{2gn^2}{(1.486)^2 K_m^{1/3}} \left(\frac{R}{K_m}\right)^{1/3}$	Bretschneider (1978) (See Figs. 4 and 5)
i)	$C_B = \lambda \left(\frac{R}{K_m}\right)^{2/3} = 2C_M^2 \left(\frac{R}{K_m}\right)^{1/3}$	(Relations between Eqs. c, d & e)

K_{50}, K_{25}, K_{10} bed material size in inches of which 50, 25 and 10 % are larger by weight, respectively k_m = medium size (50%) in feet.

Sutton's (1953) Micrometeorology is one of many books on meteorology dealing with lower level atmospheric turbulence and motion. Sutton (1953), as well as all meteorologists, uses the same basic fluid mechanics equations of flow over smooth and rough surfaces that hydraulic engineers use, but the meteorologists also include atmospheric stability criteria. The free air can be treated as incompressible flow. Anticipated winds will not be greater than 30 or 40 knots. The primary interest is to obtain wind profile measurements during neutral atmospheric conditions. There are plenty of tradewinds in Hawaii. Midday measurements should be avoided when thermal gradients near the ground would affect the interpretation of the data.

Under absolute neutral atmospheric conditions, only two level anemometer readings are necessary for obtaining z_o friction length in the logarithmic velocity profile equation. The third level can be considered as a check point. The three points should fall along a straight line on semi-log graph paper. If the deviations are too great, the data should be rejected for the proposed method of analysis. A very sophisticated method of analysis of five-level anemometer wind data over the tops of pine trees in Canada was made by Lo (1977). An eight-level anemometer was used by O'Brien (1965) to study the diabatic wind profile for winter and summer conditions over a hay field near Dallas, Texas. One of the purposes of many previous wind profile experiments was to aid in wind predictions under various atmospheric stability conditions. Since we are only interested in those data for adiabatic conditions, we can be selective, and the data can be analyzed more easily using the von Karman logarithmic profile.

4. INSTRUMENTATION

Figure 4 shows a schematic of the three-level adjustable anemometer staff, which includes sensors for wind speed, wind direction and temperature at each of the three levels. The top of the staff is at 10 meters making the top sensor (No. 1) at 10.9 meters = 35.8 feet. Anemometers No. 2 and No. 3 can be adjusted to various elevations. Anemometer No. 2 was located half way on the log scale between No. 1 and No. 3.

The instrumentation package consists of Weather Measure Corporation's: (3 ea.) W103-DC-3SS, low threshold anemometer, D.C. generator with stainless steel cups; (3 ea.) W104, lightweight wind direction vane 0-360--540 degrees; (3 ea.) W1034-CAW pre-wired cross arm to mount wind sensors; (1 ea.) SC-710 card file, pre-wired for 10 parameters; (3 ea.) MD103-DC, wind speed translator module 0-540 deg.; (1 ea.) MD910, power supply; (1 ea.) MO-OPM-S, digital panel meter, switch selectable channels; (1 ea.) WM-INT, systems integration and documentation. Air temperature sensors are located at each anemometer position, and can be shifted as necessary.

The analog data are recorded in a digital format by a 16 channel Datel Cassette Recorder. Following field data acquisition, the data cassette is then read by a Datel Cassette Reader into a Hewlett-Packard

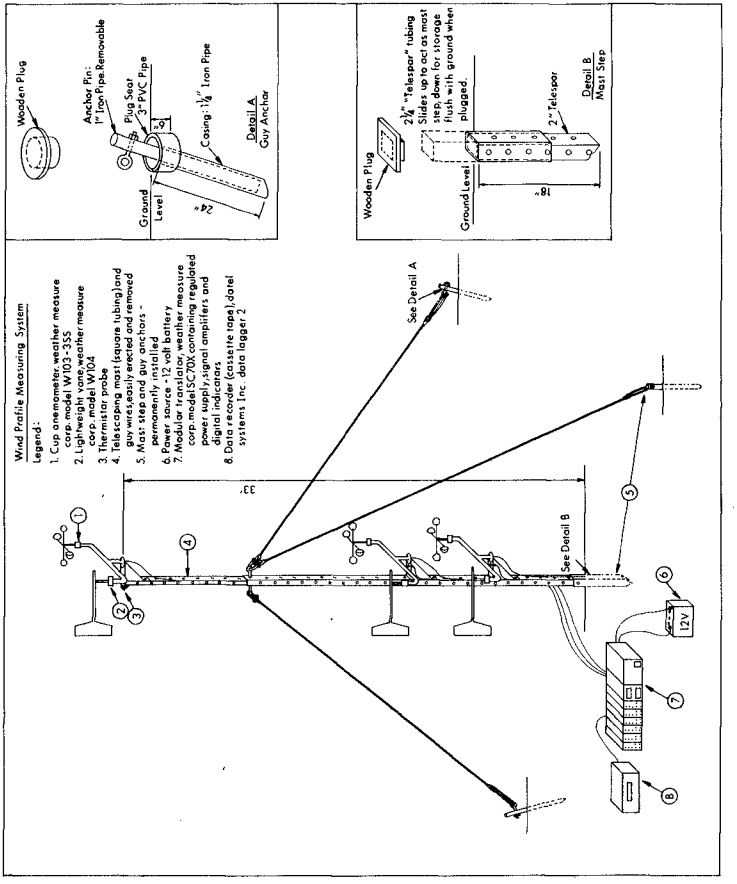


Fig. 4 SCHEMATIC ARRANGEMENT OF ADJUSTABLE THREE LEVEL ANEMOMETER STAFF

HP-9845 Mini-Computer System. The HP-9845 system then performs all data calculation and analysis, and either prints or directly generates computer drawn graphs for visual display of the data.

5. A SIMPLE METHOD OF WIND PROFILE DATA ANALYSIS

The three-level anemometer experiments. There is no proof that eq. 2 is probably a better relationship than eq. 1 between Manning's "n" and von Karman's z_o. However, it is found that eq. 2 is very useful for the three-level anemometer data analysis, as can be demonstrated.

The von Karman logarithmic velocity profile is:

$$\frac{u}{u_*} = \frac{1}{k} \ell n \frac{z + z_o}{z_o} \tag{3}$$

where u is the wind speed at elevation z above the mean reference surface, z_o is the friction length and $u_* = \sqrt{\tau/\rho}$ the friction velocity. Equation 3 does not include the zero displacement concept such as used by O'Brien (1965) or Lo (1977).

Assuming $z_o << z$ for the lowest anemometer elevation, then by rearranging the terms in eq. 3, multiplying through by 1/6 and using eq. 2, one obtains

$$n = .06 z^{1/6} \, e^{-\frac{1}{6}\left(\frac{ku}{u_*}\right)} \, (\text{feet})^{1/6} \pm 10\% \tag{4}$$

Equation 4 is a straight line on semi-log graph paper when $z^{1/6}$ is on the log scale and u is on the linear scale. Anemometer Nos. 1, 2 and 3 are elevations 35.8, 11.48 and 4.26 feet, respectively, which results in the anemometer levels in terms of $0.06z^{1/6}$ equal to 0.109, 0.009 and 0.076 $(\text{feet})^{1/6}$, respectively. At u = 0, $n = 0.06 z_o^{1/6}$.

The above method was introduced as a matter of convenience in order to give engineers an idea of Manning's "n" determined from wind experiments. There is nothing unique about the method, except that the data can be shown on a one cycle semi-log scale instead of on four to six cycle semi-log log.

Figures 5 and 6 show typical examples of Hawaii terrain and corresponding values of Manning's "n". Values of Manning's "n" by this method are only estimates.

The five-level anemometer experiments. The five-level anemometer staff is shown in Figure 7. The log-linear regression analysis of the

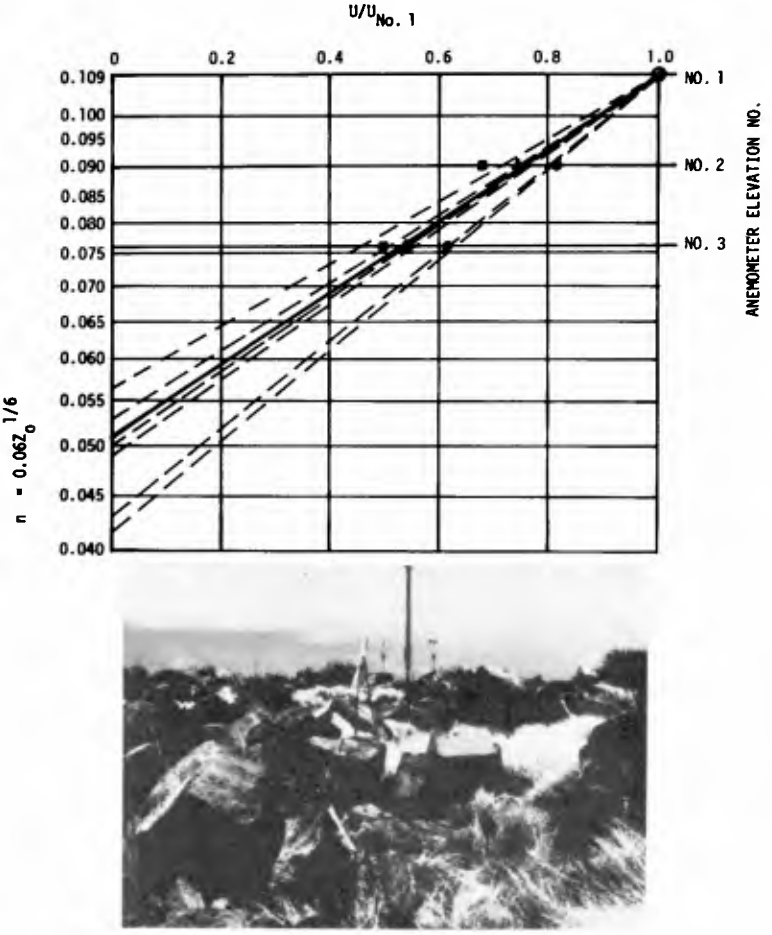


Fig. 5 MANNING'S "n" DETERMINATIONS FOR ROCK FARM STONE 2 1/2 TO 3 FT. AVE. DIAMETER

ONE-MINUTE WIND AVERAGES

EIGHT-MINUTE WIND AVERAGES

$\bar{U}$ (NO. 1) = 23 FT/SEC (8-MIN. AVE.)

DATE 7/24/79 TIME 12:41

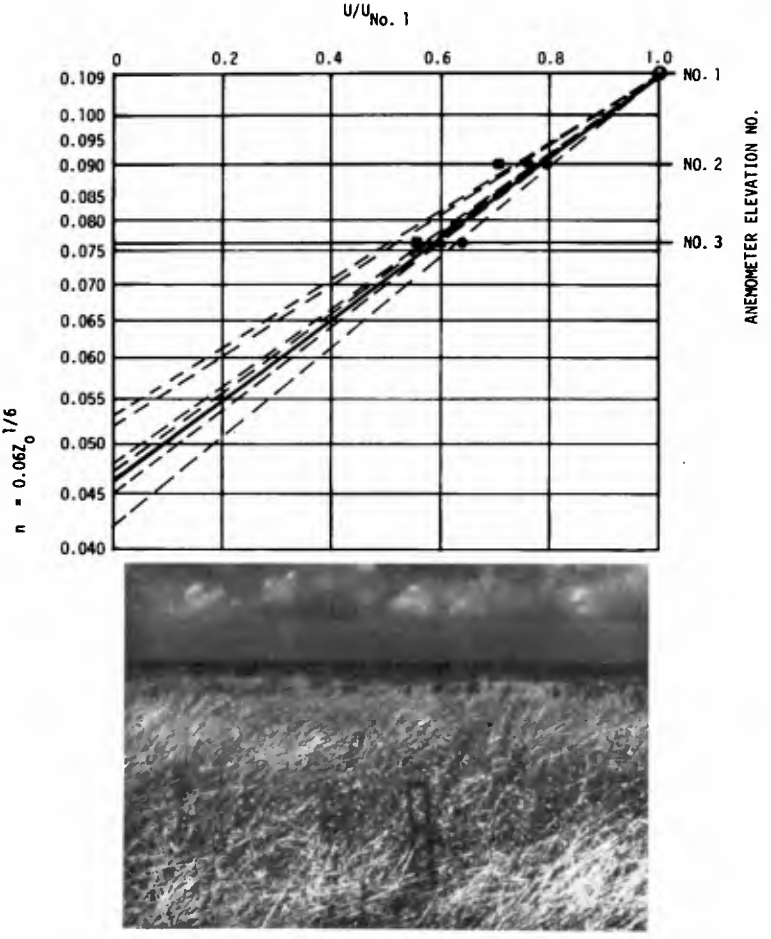


Fig. 6 MANNING'S "n" DETERMINATIONS FOR GRASS KNOLL THIN TO MEDIUM 2 TO 2 1/2 FT. TALL

■———■ ONE-MINUTE WIND AVERAGES

▲———▲ EIGHT-MINUTE WIND AVERAGES

$\bar{U}$ (NO. 1) = 32 FT/SEC (8-MIN. AVE.)

DATE 7/23/79 TIME 13:39

FIG. 7 Photograph of the Five-Level Anemometer Staff

data is used including the zero-plane displacement concept, in which case the data fall more closely along a straight line than that given in the paper. The results of these analyses, however, will be reported at a later date, after the project has been completed.

6. POSSIBLE METHODS OF CORRELATING WIND EXPERIMENTS WITH HYDRAULIC EXPERIMENTS

One of the missing links between the wind experiments and the hydraulic experiments is the determination of the equivalent hydraulic radius R or the slope of the energy grade line for the wind experiments. The hydraulic radius and/or energy slope can be measured for the hydraulic experiments.

The friction velocity method. Beginning with the von Karman velocity profile equation,

$$u_z = \frac{u_*}{k} \ln \frac{z}{z_o} \qquad z_o \ll z \ , \tag{5}$$

one can obtain a mean velocity $\bar{u}_z$ as follows:

$$\bar{u}_R = \frac{1}{R} \int_0^R u_z \, dz = \frac{u_*}{k} \ln \frac{R}{e z_o} \tag{6}$$

and

$$u_R = \frac{u_*}{k} \ln \frac{R}{z_o} \tag{7}$$

where u_R is the velocity at elevation $z = R$ and $\bar{u}_R$ is the integrated mean velocity between $z = 0$ and $z = R$. $u_* = \sqrt{\tau/\rho}$ the friction velocities, $k = 0.4$ and z_o = friction length as given before.

It can then be shown for the von Karman velocity profile that

$$u_* = k(u_R - \bar{u}_R) = \sqrt{gRS} \tag{8}$$

where S is the slope of the energy grade line.

The friction velocity Reynolds number and Froude number (if such is a possibility) are given as follows:

$$R_e^* = \frac{u_* K_m}{\nu} = \frac{k(u_R - \bar{u}_R) K_m}{\nu} \tag{9}$$

where ν = kinematic viscosity and K_m = mean stone size.

$$F_R^* = \frac{u_*}{\sqrt{gR}} = \frac{k(u_R - \bar{u}_R)}{\sqrt{gR}} \tag{10}$$

The minimum hydraulic radius method. It is quite well established in the literature, for example, Squarer, et al (1971), among many others, and also as shown in Figure 3 based on a re-analysis of the canal data of Lane and Carlson (1953), that the non-dimensional friction factor relationships are a function of the Froude number. The friction factor relationships decrease with increase in the Froude number.

The Froude number is given by

$$F_R = \frac{\bar{u}_R}{\sqrt{gR}} \tag{11}$$

where $\bar{u}_R$ is the mean velocity and is the same as $\bar{v}$ used in Manning's equation and also in Figure 3.

Using $\bar{u}_R$ from equation 6, one obtains

$$F_R = \frac{\frac{u_*}{k} \ell n \frac{R}{ez_o}}{\sqrt{gR}} \tag{12}$$

Differentiating equation 12 and setting the expression equal to zero, one obtains an expression for minimum hydraulic radius as follows:

$$R_{min} = e^3 z_o \tag{13}$$

It then follows that

$$u_{R_{min}} = \frac{u_*}{k} \ell n \, e^3 \frac{z_o}{z_o} = 3 \frac{u_*}{k} \tag{14}$$

and

$$\bar{u}_{R_{min}} = \frac{u_*}{k} \ell n \frac{e^3 z_o}{ez_o} = 2 \frac{u_*}{k} \tag{15}$$

whence

$$F_{R_{min}} = \frac{\bar{u}_{R_{min}}}{\sqrt{gR_{min}}} = \frac{2 \frac{u_*}{k}}{\sqrt{ge^3 z_o}} \tag{16}$$

where $u_* = k(U_{R_{min}} - \bar{u}_{R_{min}}) = k(u_R - \bar{u}_R) = k(u_z - \bar{u}_z)$.

u_R, $\bar{u}_R$ and z_o can be obtained from velocity profile measurements, whether in water or air without any knowledge of the actual hydraulic radius, provided the von Karman velocity profile conditions exist over the elevations of measurements.

It can also be shown that

$$z_o = R\, e^{-\left(\frac{ku_R}{u_*}\right)} = R\, e^{-\left(\frac{u_R}{u_R - \bar{u}_R}\right)} \tag{17}$$

Therefore, it might be possible to correlate wind and water experimental results. At least, this is worthy of further investigation.

For example, one might re-define the Keulegan non-dimensional form of Manning's "n" $\lambda = \lambda^*$ as follows:

$$\lambda^* = \frac{2gn^2}{(1.486)^2 R_{min}^{1/3}} \tag{18}$$

A re-analysis of the data by Lane and Carlson (1953) is given in Table V. R_{min} is determined from eq. 13, where z_o is determined from eq. 1, using values of R and n from the data of Lane and Carlson (1953). It is noticed in the re-analysis of the data that test nos. 8 and 10 can be considered questionable. For example, there is one case (test no. 10 (1950)) where R_{min} is actually greater than the true hydraulic radius, R, and also K_m is very large compared with R_{min}. It is for these reasons that in all previous analysis, Lane and Carlson (1953), Squarer, Mostafa and McDermid (1971), and also in this present paper that the data for test nos. 8 and 10 fall considerably out of the range of the other test data. The analysis of the data in Table V for λ^* and $\sqrt{\hat{\lambda^*}}$ are given separately for the 1950 and 1952 tests and also for the combined 1950 and 1952 tests. Omitting tests 8 and 10 results in considerable reduction in the variance from the mean values of $\bar{\lambda}^*$ and $\sqrt{\hat{\lambda^*}}$, particularly for the 1950 test data, which were for normal flow. The 1952 data were for peak discharge, which increased the actual hydraulic radius and decreased the minimum hydraulic radius, $R_{min} = e^3 z_o$.

It then follows for the data of Lane and Carlson (1953), excluding test nos. 8 and 10 that

TABLE V

A RE-ANALYSIS OF DATA OF LANE & CARLSON (1953)
USING MINIMUM HYDRAULIC RADIUS

TEST SECTION	K_m (ft)	R (ft)	R_{min} (ft)	λ^* --	R (ft)	R_{min} (ft)	λ --
1	0.269	2.93	0.485	.040	3.53	0.403	.038
2	.253	1.92	0.552	.046	2.27	0.196	.037
4	.249	2.15	0.385	.031	2.48	0.140	.035
5	.177	1.74	0.274	.040	2.17	0.163	.036
6	.138	1.29	0.166	.039	1.40	0.067	.035
7	.135	1.01	0.200	.042	1.31	0.066	.035
8	.128	0.44	0.257	.059	0.80	0.088	.038
10	.210	0.48	0.737	.112	0.48	0.178	.049
11	.158	1.29	0.249	.042	1.56	0.126	.036
12	.112	1.25	0.099	.036	1.41	0.084	.035
14	.066	1.26	0.100	.036	1.52	0.068	.035
15	.164	1.65	0.128	.036	2.61	0.170	.036
16	.161	1.39	0.102	.036	No Data	---	---
17	.125	1.39	0.145	.038	2.22	0.112	.035
18	0.069	1.13	0.051	.035	2.08	0.021	.034

(1950, 15 Tests) $\overline{\lambda^*}$ = .0445 VAR = 44.3%

(1952, 14 Tests) $\overline{\lambda^*}$ = .0367 VAR = 10.2%

(1950 and 1952, All 29 Tests) $\overline{\lambda^*}$ = .0408 VAR = 36.2%

FOR ALL TESTS EXCEPT NOS. 8 and 10

(1950, 13 Tests) $\overline{\lambda^*}$ = .0382 VAR = 10.1%

(1952, 12 Tests) $\overline{\lambda^*}$ = .0356 VAR = 3.0%

(1950 and 1952, 25 Tests) $\overline{\lambda^*}$ = .0370 VAR = 8.47%

(1950, 15 Tests) $\sqrt{\widehat{\lambda^*}}$ = .2078 VAR = 18.4%

(1952, 14 Tests) $\sqrt{\widehat{\lambda^*}}$ = .1914 VAR = 4.8%

(1950 and 1952, 29 Tests) $\sqrt{\widehat{\lambda^*}}$ = .1999 VAR = 14.5%

FOR ALL TESTS EXCEPT NOS. 8 and 10

(1950, 13 Tests) $\sqrt{\widehat{\lambda^*}}$ = .1953 VAR = 5.0%

(1952, 12 Tests) $\sqrt{\widehat{\lambda^*}}$ = .1886 VAR = 1.5%

(1950 and 1952, 25 Tests) $\sqrt{\widehat{\lambda^*}}$ = .1921 VAR = 4.2%

$$n = .060\ z_o^{1/6}, \quad \text{var} = 5.0\% \quad (13 \text{ tests}) \text{ 1950 data}$$

$$n = .058\ z_o^{1/6}, \quad \text{var} = 1.5\% \quad (12 \text{ tests}) \text{ 1952 data}$$

and

$$n = .059\ z_o^{1/6}, \quad \text{var} = 4.2\% \quad (25 \text{ tests}) \text{ 1950 and 1952 data .}$$

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8. REFERENCES

ANN-DOF and SMEDMAN-HÖGSTROM and ULF HÖGSTROM (1977) "A practical method of determining wind frequency distributions for the lowest 200 meters from routine meteorological data." Report no. 47, Meteorological institutionen, Uppsala, p. 7.

BRETSCHNEIDER, C.L. and WYBRO, P. (1976) "Tsunami inundation predictions." Proc. 15th Coastal Engr. Conf. (ASCE), Vol. I, Ch. 60, pp. 1006-1024, Research in partial support under NOAA/Sea Grant Contract No. 04-06-158-44026.

HOUSTON, J.R. and BUTLER, H. (1979) "A numerical model for tsunami inundation." U.S. Army Waterways Experiment Station, Tech. Rept. H-79-2.

IRMAY, S. (1949) "On steady flow formulas in pipes and channels." Paper No. III-3, Third Meeting, IAHR, Grenoble, France.

KEULEGAN, G.H. (1967) "Tidal flow in entrances: Water level fluctuations of basins in communication with the sea." U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Committee on Tidal Hydraulics, Tech. Bulletin No. 4.

KEULEGAN, G.H. (1938) "Laws of turbulent flow in open channels." United States Department of Commerce, National Bureau of Standards, Res. Paper RP1151.

LANE, E.W. and CARLSON, E.S. (1953) "Some factors affecting the stability of canals constructed in course granular materials." In Proceedings, Minnesota International Hydraulic Convention IAHR/ASCE, pp. 37-88.

LO, A.K. (1977) "An analytical-empirical method for determining the roughness length and zero-plane displacement." Boundary-Layer Meteorology 12, pp. 141-151, Reidel Publishing Co., Dordrecht, Holland.

MONIN, A.S. and OBUKHOV, A.M. (1954) "Basic regularity in turbulent mixing in the surface layer of the atmosphere." Akad. Nauk/SSSR Geobiz. Inst. Trudy, No. 24, pp. 163-186.

O'BRIEN, J.J. (1965) "An investigation of the diabatic wind profile of the atmospheric boundary layer." Journal of Geophysics Research, Vol. 70, No. 10, pp. 2277-2290.

RAMSER, C.E. (1929) "Flow of water in drainage channels." U.S. Department of Agriculture, Tech. Bulletin No. 129, p. 102.

ROUSE, H. (1949) "Engineering Hydraulics." In Proceedings of the 4th Hydraulic Conference, Iowa Institute of Hydraulic Research, p. 1039, John Wiley and Sons, Inc.

SQUARER, D.M., MOSTAFA, G. and MC DERMID, R.M. (1971) "Sediment transportation mechanics F. hydraulic relations for alluvial streams." In ASCE Proceedings, Journal of the Hydraulics Division 97 (HY 10): pp. 1775-1780.

STRICKLER, K. "Beitrage zur Frage der Geschwinddigkeitsformal und der Rauhigkeitszahlen fur Strom Kanale und geschlossene Leitungen." Mitt. No. 16, des Eidg. Amtes fur Wasserwirtshaft, Bern, 1923.

SUTTON, O.G. (1953) Micrometeorology, 333 pages, McGraw-Hill Book Co., Inc.

U.S. AIR FORCE AIR RESEARCH DEVELOPMENT COMMAND (1961) Handbook of Geophysics, Revised Edition. The MacMillan Co., New York, chapter 9.