RESEARCH MEMORANDUM

NO. 29

PRELIMINARY MEASUREMENTS OF FLOW OVER MODEL, THREE-DIMENSION HILLS

by

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SUMMARY

A set of velocity distribution measurements were made over an approximate Gaussian shaped hill, a 1 to 4 slope, and 1 to 3 slope, cone shaped hill. The hills were approximately one tenth the height of the boundary layer thickness. Detailed velocity measurements were made for a free-stream velocity of 9.4 meters per second. A limited number of velocity profiles were also taken over the Gaussian hill for a free-stream velocity of 15.3 meters per second. The speed-up of velocity near the surface of the isolated three-dimensional hills is less than the speed-up observed for nearly all two-dimensional ridge configurations.

INTRODUCTION

Obvious sites for wind turbine installations will include both two- and three-dimensional topography. The isolated three-dimensional hill is commonly encountered in nature, and is a likely candidate for wind power sites. The present study considers the ideal symmetrical Gaussian and cone shaped hills. Information for these basic shapes is required to aid in the development of methods to predict the flow over local terrain. The present study is for hills that are small compared to the local boundary layer thickness (hill height to boundary layer thickness of approximately 0.1). Based on the previous studies of two-dimensional ridges of the same height, ref. 1, the effect of the hill would be expected to produce a speedup of the local wind velocities near the surface. Due to the three-dimensional nature of the hill the local speedup at any particular location will not be as great as that observed for the two-dimensional ridge. The present models will correspond to atmospheric hill heights of the order of 30 to 100 meters high.

EXPERIMENTAL SETUP

The measurements were taken in the Meteorological Wind Tunnel located in the Fluid Dynamics and Diffusion Laboratory at Colorado State University. The purpose of this experiment was to survey the flow characteristics over models of 3-dimensional hills emersed in deep turbulent layer. Experimental facilities and techniques are discussed in following sections.

Wind Tunnel Facility

As mentioned above the measurements were performed in the recirculating Meteorological Wind Tunnel, Fig. 1. The flow rate in the tunnel is controlled by a variable-pitch, variable-speed propeller and can be set between 0.3 and 37 m/s. The test section is approximately 1.8 m square, 28 m in length, and is proceeded by a 9:1 contraction. A zero pressure gradient along the length of the test section was maintained with the adjusting ceiling. The ambient temperature was kept at a constant with $\pm\frac{1}{2}$°C by the tunnel air conditioning system.

To prompt the formation and growth of a large turbulent boundary layer, at the entrance to the test section a 1.22 m long section of 1.27 cm gravel fastened to the floor was followed by a 3.80 cm high sawtooth fence spanning the width of the tunnel. A roughness made of aluminum with rounded ribs 0.16 cm in height randomly space on the surface, normal and parallel to the flow extended from the sawtooth fence to a distance of 11.4 meters downstream, ref. 2.

Model Description

Three, 3-dimensional, hills were used for the tests. Figure 2 illustrates the dimensions of these models. Numbers were used to distinguish these hills in this report as:

Hill No. 1 Gaussian Hill with crest height:radius = 1:6

Hill No. 2 Cone shaped hill with crest height:radius = 1:4

Hill No. 3 Cone shaped hill with crest height:radius = 1:3.

The models were made of Plexiglass. Each of the models was mounted with static pressure taps distributed over a centerline of the hill.

Instrumentation

Actuator and Carriage

The measurements for this experiment required vertical surveys (y-direction) of the flow at particular radial points (θ-r coordinates) around the crest of the hill. The existing carriage of the wind tunnel was employed. The carriage had been constructed on a rail and wheel system. The rails 101.6 cm from the floor run the full length of the test section. This allows the carriage to be positioned manually at any desired location. A control unit outside the tunnel monitors the vertical movement of the probes and probe support through the boundary layer. The actuator system, with a total traverse of 65 cm, provided a constant voltage change for a particular change in height.

STATIC PRESSURE MEASUREMENTS

A commercial cylindrical pitot-static tube was used along with the static pressure taps mounted on the surface of each hill to measure the local static pressure difference with respect to the free stream static pressure.

For the Gaussian hill and 1:4 cone-shaped hill, the surface static pressures on diameters 0°, 45° and 90° with the free stream flow direction were measured by rotating the model centerline static taps to the angular specific direction. The static pressure taps were drilled approximately normal to the surface. It was not possible in the case of the Gaussian hill to accurately aline the perpendicular direction, so some uncertainty may exist in the local surface pressure measurements.

VELOCITY MEASUREMENTS

Three different probes were used to measure the total pressure. They are a commercial pitot-static tube, a commercial Kiehl probe and a hot-film probe.

The pitot-static tube was mounted from the ceiling of the wind tunnel about 1 m upstream of the models. This probe was used not only as a reference static pressure for calculation of dynamic pressure but also to calibrate the hot-film probe.

The Kiehl probe and hot-film probe were mounted on the actuator probe support. Both were used for the measurement of mean velocity.

Velocity measurements were made for a specific free stream velocity. The dynamic pressure from the pitot-static tube was used to adjust and maintain the tunnel flow at a constant value. The Kiehl probe and hot-film probe were positioned at the desired point by adjusting the carriage manually. The mean velocity measurements at different heights were then calculated from the averaged pressure measured with the Kiehl probe and local static pressures, or from the voltage drop across the hot-film probe. The hot-film was operated with a commerical constant temperature anemometer. The time averaged signals were obtained using a digital minicomputer.

RESULTS

The present memorandum is intended mainly as a report of measurements. Tables I through IV list the results obtained for both the pressure distributions and mean velocity profiles. The velocity profiles were taken perpendicular to the smooth flat plate approach surface, and not perpendicular to the local hill surface. The normal vertical coordinate corresponds to the requirements of a wind power site, but it is different from the usual boundary layer coordinate system.

A limited flow visualization study was made for the surface flow around the Gaussian hill. Figure 3 shows a series of surface oil streak patterns observed for the Gaussian hill. The upstream portion of the hill was coated with a "light cooking" oil. White zink oxide was mixed with the oil to make the movement visible. The surface streaks indicate the local flow directions around the hill. The region of separation in the rear of the hill is also readily observed from the photographs. The area of separation is not as uniform as expected, which may in part be due to some gravity effect of the flow of the oil. The included angle of separation was found to be approximately 35°. Although the character of the separation appears somewhat different for the different velocities the included angle of separation remained roughly the same.

From the oil pictures the region of highest shear appears to be just off the peak on either side and slightly downstream. Directly downstream of this high shear region the oil flow pattern was observed to turn sharply outward. Two different flow regions are observed in the oil pictures. A fairly uniform sheet of oil is observed over the forward part of the hill. This uniform sheet exists around to about 100 degrees from the forward centerline. Around an angle of 100 degrees the patterns are very "streaky", which apparently are a combination of gravity effects on the oil and local intermittent fluctuations of flow separation. The apparent intermittent characteristic of separation is more pronounced at the lower velocities. The region which was assumed to be the location of a "true, mean, zero surface shear" separation shows very distinct convolutions of the oil pattern. The convolutions would suggest organized vortex motions were present. The photograph for a free stream velocity of 12.2 m/sec is somewhat distorted, since the shear forces where too small.

Figure 4 shows typical smoke streak patterns around the Gaussian hill. The smoke was produced by painting small spots and lines of $TiCl_4$ on the model surface. The $TiCl_4$ reacts with moisture in the air to produce a white smoke. The smoke study was done at a velocity of less than 1 meter per second. The smoke streaks show a distinct curl inward toward the separation region as they go over the hill. The motion near separation would appear to be in the opposite direction to the pattern of outward flow shown by the oil. The smoke indicates some vortex motion near separation, however the pattern is not well defined.

Figures 7 through 13 are plots of the mean velocity distributions listed in Tables III and IV. A speedup ratio of 0.57 was obtained at the crest of the Gaussian hill. It is possible that slightly higher speedup ratios may be obtained in the region just off the crest, however the present grid of measurements did not cover the crest region in sufficient detail to indicate a maximum away from the crest. In general the speedup ratio is of the order of 0.30 or less away from the crest. The cone hills obtain maximum speedup ratios of the order of 0.3 at the crest. Compared to the two-dimensional ridges, the isolated three-dimensional hills do not appear to be a great deal better than bluff, two-dimensional ridges.

CONCLUDING REMARKS

The present study suggests that the round crest hill will be a better wind power site than the sharp crested cones. The flow visualization suggests that the region around the crest on the shoulders may also produce local high wind velocities. The static pressure measurements on the Gaussian hill appear to indicate the higher velocities over a region of about H/7 to H/2 radius away from the crest at right angles to the flow direction. Thus, for the rounded three-dimensional hill it may not be necessary to mount the wind turbine directly at the crest. If, however, the prevailing wind flow direction varies over large angles, the crest of the hill is suggested as the best location. The separation region on the downstream face of the hill does not quite reach to the crest of the Gaussian hill, but the large fluctuations associated with the separation are evident near the crest. If a choice is available it would appear that two-dimensional ridges are much better as wind velocity amplifiers than the isolated three-dimensional hills.

REFERENCES

1. Meroney, R. N., Sandborn, V. A., Bouwmeester, R. J. B., and Rider, M. A.; Sites for Wind Power Installations, Second Annual Report, Colorado State Univ., CER77-78 RNM-VAS-RB March 6, 1977.

2. Rider, M. A., and Sandborn, V. A.; Boundary Layer Turbulence Over Two-Dimensional Hills, Colorado State Univ., Tech. Report CER77-78MAR-VAS 4, 1977.

Table I. Static pressure on the surface of Gaussian hill, ΔP = (Pstatic) free stream - (Pstatic) local (NT/cm^2).

Measuring Angle θ =		0°	45°	90°
Tap No.	Radius (cm)	ΔP	ΔP	ΔP
1	20.95	+0.049	-0.18	-0.192
2	17.15	-0.049	---	---
3	13.00	---	-0.183	-0.200
4	9.35	-0.048	-0.183	-0.210
5	6.67	-0.051	-0.193	-0.220
6	4.12	-0.109	-0.200	-0.225
7	2.54	-0.208	-0.215	-0.227
8	0.00 (crest)	-0.218	-0.218	-0.230
9	- .80	-0.198	-0.215	-0.235
10	- 2.54	-0.183	-0.208	-0.230
11	- 4.45	-0.157	-0.220	-0.220
12	- 6.19	-0.090	-0.212	-0.217
13	- 8.26	-0.051	-0.200	-0.207
14	-10.80	0.0	-0.195	-0.200
15	-13.97	+0.121	-0.180	-0.192
16	-17.46	+0.048	-0.188	-0.145
17	-20.95	-0.051	-0.183	-0.185
U_{FS}		9.4 m/s	9.4 m/s	9.75 m/s

Table II. Static pressure on the surface of 1:4 cone hill, at U_{FS} = 9.4 m/sec, ΔP = (Pst) free stream - (Pst) local (NT/cm^2).

Measuring Angle θ =		0°	45°	90°
Tap No.	Radius (cm)	ΔP	ΔP	ΔP
1	14.35	---	-0.172	-0.185
2	12.07	-0.168	-0.175	-0.188
3	9.73	-0.170	-0.182	-0.192
4	7.29	-0.175	-0.185	-0.198
5	4.83	-0.185	-0.195	-0.205
6	3.81	-0.192	-0.198	-0.212
7	2.54	-0.195	-0.208	-0.215
8	1.27	-0.208	-0.215	-0.225
9	0.0 (crest)	-0.235	-0.240	-0.235
10	- 1.27	-0.225	-0.227	-0.225
11	- 2.54	-0.212	-0.215	-0.215
12	- 5.08	-0.187	-0.20	-0.205
13	- 7.62	-0.185	-0.195	-0.198
14	-10.16	-0.175	-0.168	-0.195
15	-12.70	---	-0.180	-0.188
16	-15.24	---	-0.175	-0.188

Table III. Tabulated upstream velocity profiles for each hill.

UPSTREAM VELOCITY PROFILES

TUNNEL TEMPERATURE--T IN DEG. C

BARAMETRIC PRESSURE--BAR IN NT/(CM.CM)

BOUNDARY LAYER THICKNESS--DELTA IN CM

REFERENCE VELOCITY--U(REF) IN M/S

NONDIMENSIONAL HEIGHT--Y* = Y/DELTA

NONDIMENSIONAL VELOCITY--U* = U(Y)/U(REF)

RADIAL DISTANCE FROM CREST--R IN CM

R	52.22	28.65	20.32
DELTA	65.02	42.70	45.36
U(REF)	9.78	9.33	9.24
T	21.11	21.83	21.33
BAR	8.38	8.39	8.39
DATE	29/10/1977	5/11/1977	7/11/1977

Hill No. 1		Hill No. 2		Hill No. 3	
Y*	U*	Y*	U*	Y*	U*
.007	.532	.006	.574	.006	.553
.013	.551	.037	.652	.022	.569
.017	.575	.063	.689	.045	.638
.087	.707	.115	.733	.069	.672
.113	.725	.166	.746	.102	.723
.143	.733	.235	.769	.134	.727
.185	.754	.301	.800	.182	.765
.229	.776	.370	.824	.230	.790
.272	.785	.456	.843	.278	.803
.353	.812	.523	.875	.342	.815
.422	.830	.593	.889	.406	.836
.494	.854	.660	.902	.470	.875
.567	.894	.746	.938	.550	.894
.639	.916	.830	.953	.630	.921
.712	.941	.916	.979	.712	.947
.783	.956	1.000	1.000	.807	.962
.855	.963			.903	.989
.927	.991			1.000	1.000

Table IV(a). Tabulated velocity profiles.

FOR HILL NO. 1

MEASURING ANGLE -0 DEG. FROM FLOW DIRECTION

R	0.00	50.80
DELTA	52.27	51.82
U(REF)	13.73	15.67
T	21.11	21.11
BAR	8.38	8.38
DATE	29/10/1977	29/10/1977

Y*	U*	Y*	U*
.005	.846	.005	.578
.014	.879	.014	.615
.028	.868	.021	.647
.042	.879	.031	.665
.057	.873	.043	.677
.076	.846	.057	.710
.099	.851	.074	.720
.121	.844	.094	.728
.151	.844	.122	.739
.182	.846	.173	.770
.222	.857	.212	.792
.268	.862	.259	.800
.316	.868	.336	.831
.369	.893	.410	.860
.443	.905	.482	.893
.510	.926	.547	.912
.581	.950	.620	.930
.677	.967	.692	.949
.790	.992	.792	.973
.891	.995	.898	.988
1.000	1.000	1.000	1.000

Table IV(b). Tabulated velocity profiles.

FOR MILL NO. 1 MEASURING ANGLE -0 DEG. FROM FLOW DIRECTION

R	31.90	20.80	9.25	4.60	0.00
DELTA	47.96	45.59	45.34	40.51	50.34
U(REF)	9.14	9.60	9.77	10.15	9.69
T	21.11	21.11	21.22	21.22	21.22
BAR	8.38	8.38	8.37	8.37	8.37
DATE	29/10/1977	29/10/1977	29/10/1977	29/10/1977	29/10/1977

Y*	U*	Y*	U*	Y*	U*	Y*	U*	Y*	U*
.007	.499	.011	.538	.012	.599	.012	.711	.010	.805
.013	.511	.013	.547	.019	.599	.021	.715	.021	.811
.017	.524	.017	.550	.027	.633	.030	.739	.035	.827
.035	.603	.020	.579	.035	.644	.040	.745	.043	.833
.061	.660	.025	.614	.041	.668	.048	.765	.056	.827
.087	.702	.033	.614	.056	.690	.050	.751	.064	.824
.114	.714	.041	.630	.073	.739	.067	.761	.071	.827
.143	.743	.057	.647	.084	.733	.075	.761	.078	.808
.183	.748	.073	.673	.093	.749	.094	.775	.085	.808
.230	.776	.088	.699	.100	.752	.111	.763	.100	.811
.272	.789	.120	.712	.112	.761	.129	.788	.115	.811
.353	.816	.153	.717	.132	.783	.146	.783	.129	.833
.422	.849	.184	.732	.148	.783	.166	.785	.161	.805
.494	.857	.232	.751	.165	.793	.192	.817	.202	.818
.568	.896	.329	.787	.180	.802	.219	.820	.245	.833
.639	.903	.376	.800	.211	.811	.245	.832	.303	.862
.711	.933	.423	.816	.244	.836	.272	.826	.364	.865
.783	.950	.473	.819	.276	.842	.300	.835	.422	.887
.855	.960	.519	.837	.309	.855	.334	.829	.495	.915
.927	.988	.568	.860	.340	.861	.371	.859	.569	.931
1.000	1.000	.616	.876	.373	.861	.409	.876	.640	.953
		.663	.895	.420	.880	.443	.865	.710	.965
		.713	.902	.469	.892	.498	.886	.781	.978
		.759	.926	.518	.911	.550	.919	.854	.984
		.807	.926	.566	.924	.604	.937	.929	.994
		.856	.941	.613	.939	.606	.955	1.000	1.000
		.903	.949	.662	.942	.713	.955		
		.951	.962	.710	.952	.769	.964		
		1.000	1.000	.757	.961	.820	.973		
				.806	.973	.874	.973		
				.854	.989	.929	.991		
				1.000	1.000	1.000	1.000		

Table IV(c). Tabulated velocity profiles.

FOR HILL NO. 1

MEASURING ANGLE 45 DEG. FROM FLOW DIRECTION

R	20.80	9.25	4.60
DELTA	47.37	47.47	47.32
U(REF)	9.33	9.60	9.60
T	21.56	21.56	21.56
BAR	8.35	8.35	8.35
DATE	1/11/1977	1/11/1977	1/11/1977

Y*	U*	Y*	U*	Y*	U*
.007	.591	.004	.547	.006	.460
.025	.647	.019	.629	.020	.671
.040	.654	.035	.673	.037	.688
.055	.693	.050	.673	.054	.717
.071	.708	.073	.708	.071	.724
.085	.729	.096	.736	.087	.743
.100	.742	.117	.743	.104	.732
.117	.753	.142	.751	.120	.739
.133	.757	.164	.756	.139	.747
.147	.774	.187	.768	.155	.768
.171	.774	.219	.777	.177	.764
.193	.787	.250	.790	.204	.777
.216	.791	.280	.794	.236	.794
.248	.810	.311	.822	.260	.809
.278	.820	.341	.828	.302	.813
.309	.817	.373	.846	.336	.819
.355	.828	.418	.850	.370	.830
.402	.846	.463	.857	.402	.837
.447	.857	.510	.873	.452	.860
.494	.871	.556	.876	.535	.876
.539	.882	.602	.895	.585	.889
.585	.908	.648	.902	.634	.911
.631	.922	.693	.911	.684	.914
.693	.935	.754	.962	.736	.941
.754	.961	.817	.971	.833	.990
.816	.971	.876	.981	.901	.990
.877	.987	.938	.990	.951	1.000
.938	.990	1.000	1.000	1.000	1.000
1.000	1.000				

Table IV(d). Tabulated velocity profiles.

FOR HILL NO. 1

MEASURING ANGLE 90 DEG. FROM FLOW DIRECTION

R	20.80	9.25	4.60
DELTA	45.44	40.98	43.84
U(REF)	9.60	9.60	9.60
T	21.36	21.36	21.89
BAR	8.36	8.36	8.34
DATE	31/10/1977	31/10/1977	1/11/1977

Y*	U*	Y*	U*	Y*	U*
.033	.441	.006	.532	.006	.619
.049	.609	.023	.632	.020	.671
.064	.635	.041	.673	.037	.688
.078	.671	.059	.695	.054	.717
.093	.695	.077	.717	.071	.724
.110	.717	.095	.712	.087	.743
.127	.739	.112	.747	.103	.732
.143	.743	.131	.732	.120	.739
.174	.756	.148	.743	.139	.746
.190	.760	.165	.768	.155	.768
.206	.781	.193	.768	.177	.764
.222	.772	.255	.797	.204	.777
.238	.797	.246	.797	.236	.794
.254	.790	.272	.800	.269	.809
.270	.800	.308	.816	.302	.813
.294	.809	.344	.828	.336	.819
.318	.816	.380	.837	.370	.830
.343	.819	.415	.857	.402	.837
.365	.828	.450	.860	.452	.860
.389	.837	.486	.867	.534	.876
.423	.833	.521	.876	.585	.889
.454	.846	.627	.902	.634	.911
.487	.867	.670	.895	.684	.914
.518	.876	.736	.930	.735	.941
.567	.886	.786	.945	.833	.990
.615	.898	.893	.981	.901	.990
.663	.918	.946	.990	.951	1.000
.710	.922	1.000	1.000	1.000	1.000
.760	.945				
.808	.962				
.856	.981				
.904	.990				
1.000	1.000				

Table IV(e). Tabulated velocity profiles.

FOR HILL NO. 2

MEASURING ANGLE -0 DEG. FROM FLOW DIRECTION

R	12.85	7.62	0.00
DELTA	57.91	48.67	44.68
U(REF)	9.17	9.20	9.24
T	21.83	21.83	21.83
BAR	8.39	8.39	8.39
DATE	5/11/1977	5/11/1977	5/11/1977

Y*	U*	Y*	U*	Y*	U*
.006	.595	.006	.599	.009	.648
.032	.643	.028	.659	.024	.683
.060	.704	.058	.710	.040	.697
.090	.728	.089	.738	.056	.715
.131	.770	.119	.759	.080	.727
.173	.782	.148	.779	.108	.753
.215	.804	.192	.792	.139	.777
.270	.817	.238	.797	.170	.785
.313	.837	.282	.825	.204	.799
.369	.864	.357	.858	.254	.822
.430	.880	.433	.877	.300	.828
.509	.904	.507	.904	.349	.836
.581	.920	.581	.927	.417	.866
.652	.940	.656	.950	.480	.894
.719	.961	.730	.962	.547	.911
.807	.977	.820	.985	.610	.924
.900	.989	.912	.997	.678	.944
1.000	1.000	1.000	1.000	.756	.962
				.838	.974
				.919	.990
				1.000	1.000

Table IV(f). Tabulated velocity profiles.

FOR HILL NO. 2

MEASURING ANGLE 45 DEG. FROM FLOW DIRECTION

R	12.85	7.62
DELTA	48.77	49.86
U(REF)	9.24	9.42
T	22.00	22.00
BAR	8.36	8.36
DATE	6/11/1977	6/11/1977

Y*	U*	Y*	U*
.005	.537	.005	.532
.022	.638	.023	.631
.036	.672	.052	.659
.060	.723	.081	.730
.094	.745	.126	.746
.134	.781	.169	.761
.179	.781	.214	.796
.239	.812	.271	.812
.298	.828	.315	.824
.361	.851	.373	.849
.432	.866	.432	.870
.507	.898	.504	.893
.598	.927	.578	.913
.673	.947	.665	.936
.761	.962	.738	.959
.851	.978	.825	.990
.929	.993	.915	.990
1.000	1.000	1.000	1.000

Table IV(g). Tabulated velocity profiles.

FOR HILL NO. 2

MEASURING ANGLE 90 DEG. FROM FLOW DIRECTION

R	22.86	12.85	7.62
DELTA	43.51	47.73	48.77
U(REF)	9.42	9.24	9.33
T	22.00	22.00	22.00
BAR	8.36	8.36	8.36
DATE	6/11/1977	6/11/1977	6/11/1977

Y*	U*	Y*	U*	Y*	U*
.006	.527	.005	.440	.005	.522
.030	.616	.025	.623	.022	.642
.056	.644	.040	.660	.036	.689
.081	.670	.062	.695	.060	.720
.116	.713	.086	.732	.095	.745
.149	.746	.123	.761	.134	.761
.180	.742	.161	.765	.179	.787
.213	.753	.268	.815	.239	.817
.247	.774	.314	.822	.299	.832
.298	.792	.390	.848	.361	.852
.349	.812	.466	.848	.432	.886
.397	.828	.542	.875	.507	.899
.464	.858	.618	.931	.598	.915
.535	.880	.710	.950	.673	.957
.599	.903	.802	.989	.762	.979
.668	.916	.893	.989	.850	.990
.748	.959	1.000	1.000	.930	.990
.817	.970			1.000	1.000

Table IV(h). Tabulated velocity profiles.

FOR HILL NO. 3

MEASURING ANGLE -0 DEG. FROM FLOW DIRECTION

R	10.16	4.32	0.00
DELTA	50.70	46.23	46.36
U(REF)	9.13	9.42	8.96
T	21.33	21.33	21.33
BAR	8.39	8.39	8.39
DATE	7/11/1977	7/11/1977	7/11/1977

Y*	U*	Y*	U*	Y*	U*
.005	.586	.006	.611	.005	.647
.021	.635	.024	.670	.018	.693
.045	.670	.048	.686	.041	.749
.071	.723	.080	.717	.074	.763
.105	.749	.134	.750	.104	.784
.138	.765	.182	.774	.136	.792
.189	.781	.229	.796	.168	.819
.241	.808	.292	.812	.199	.837
.291	.828	.354	.835	.245	.847
.359	.845	.417	.841	.292	.862
.426	.864	.480	.874	.339	.874
.493	.885	.544	.896	.403	.897
.578	.911	.607	.900	.466	.922
.662	.935	.685	.929	.529	.932
.746	.961	.763	.948	.606	.959
.830	.989	.843	.963	.685	.976
.916	1.000	.921	.971	.764	1.000
1.000	1.000	1.000	1.000		

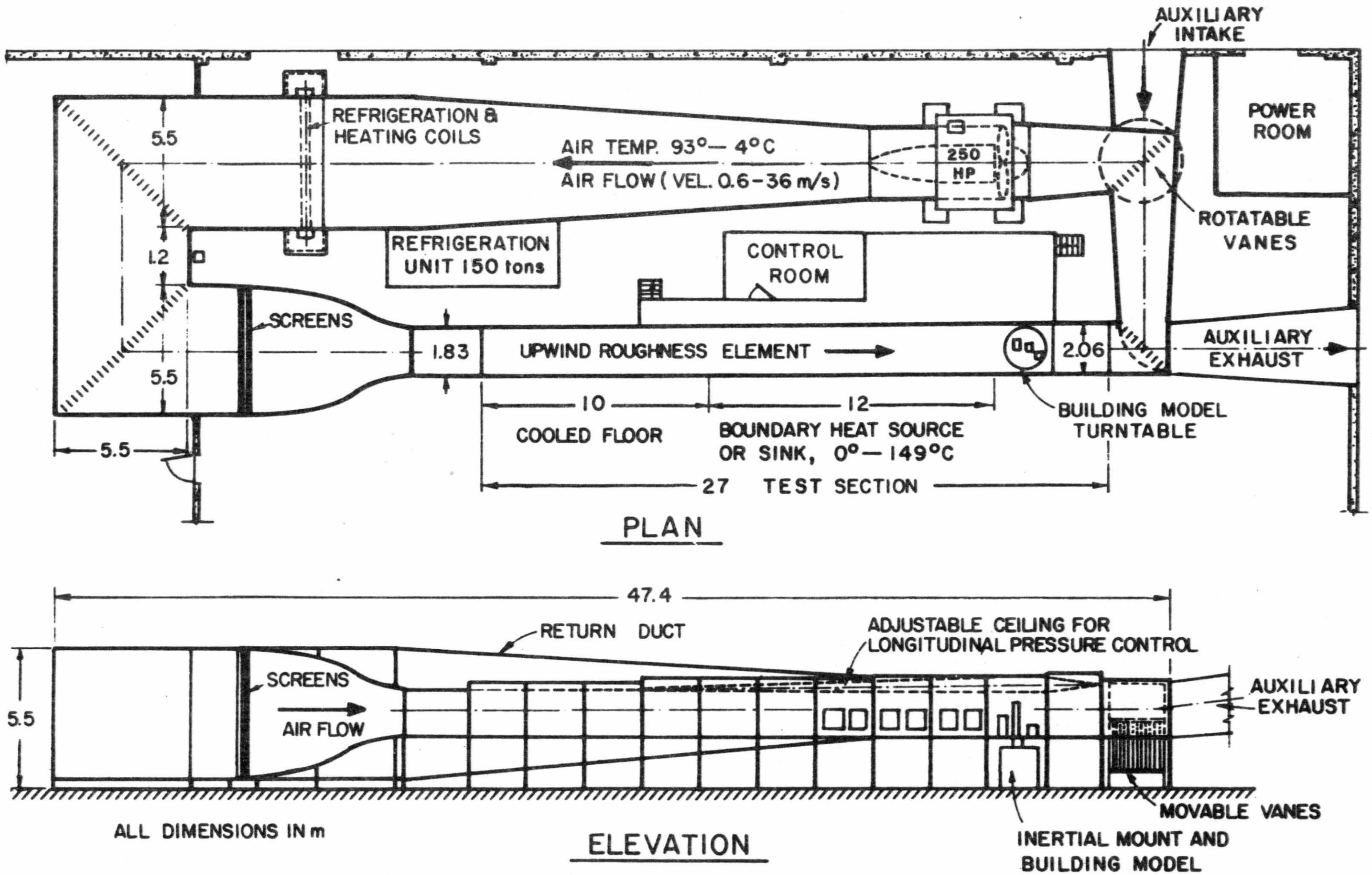
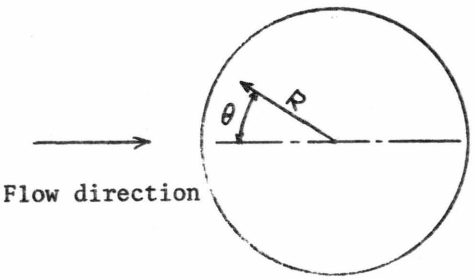
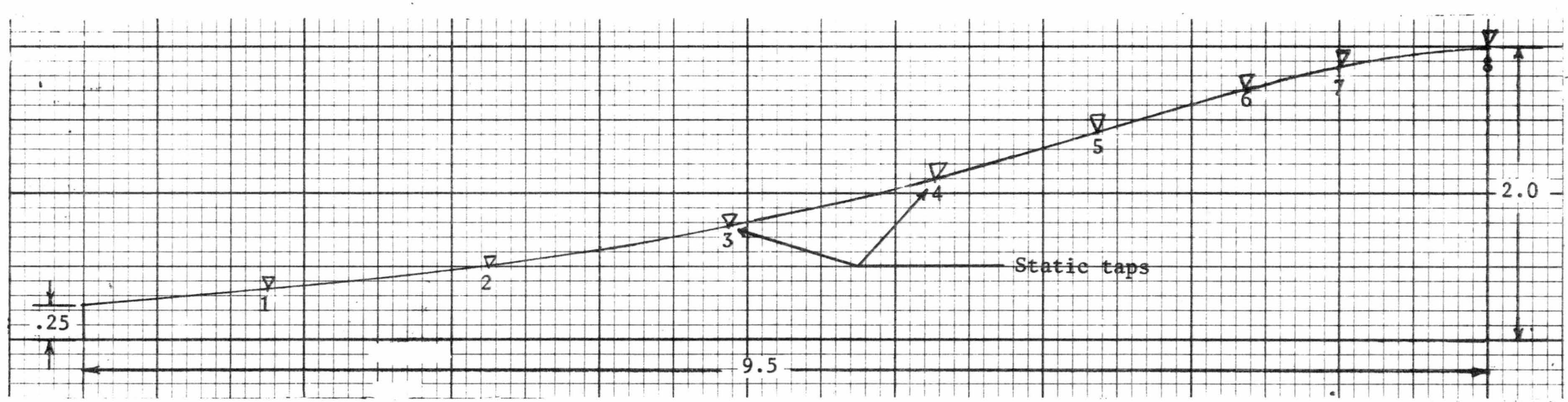


Figure 1. METEOROLOGICAL WIND TUNNEL (Completed in 1963)



Coordinates



*All dimensions are in inches.

Figure 2. Dimension of 3-dimensional hills and location of static taps on their surfaces (Real scale).

(a) Gaussian Hill (approximate).

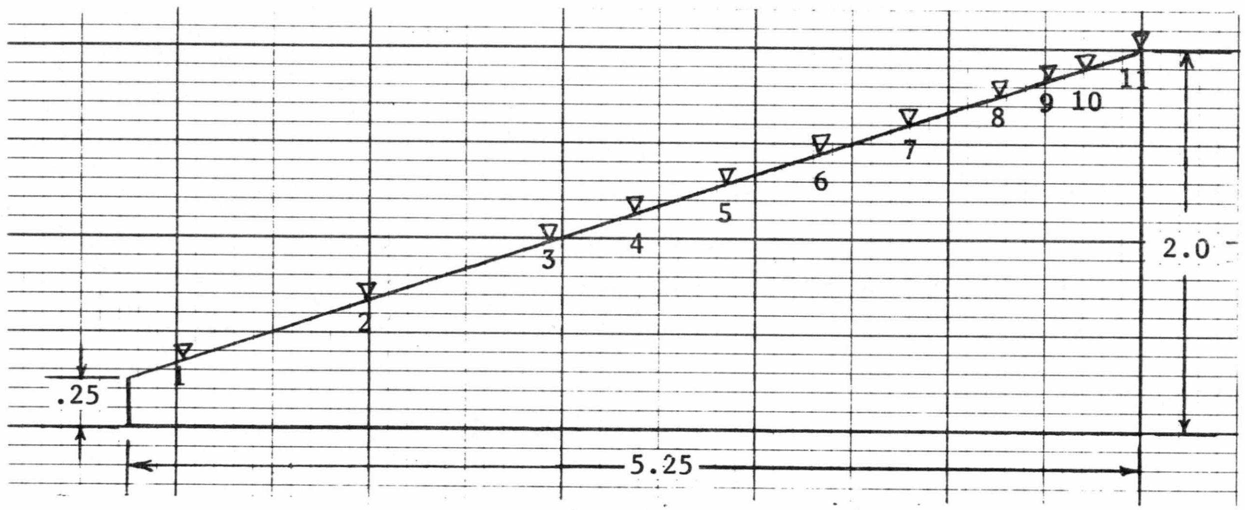


Figure 2. (b) Cone shaped hill with 1:4 slope.

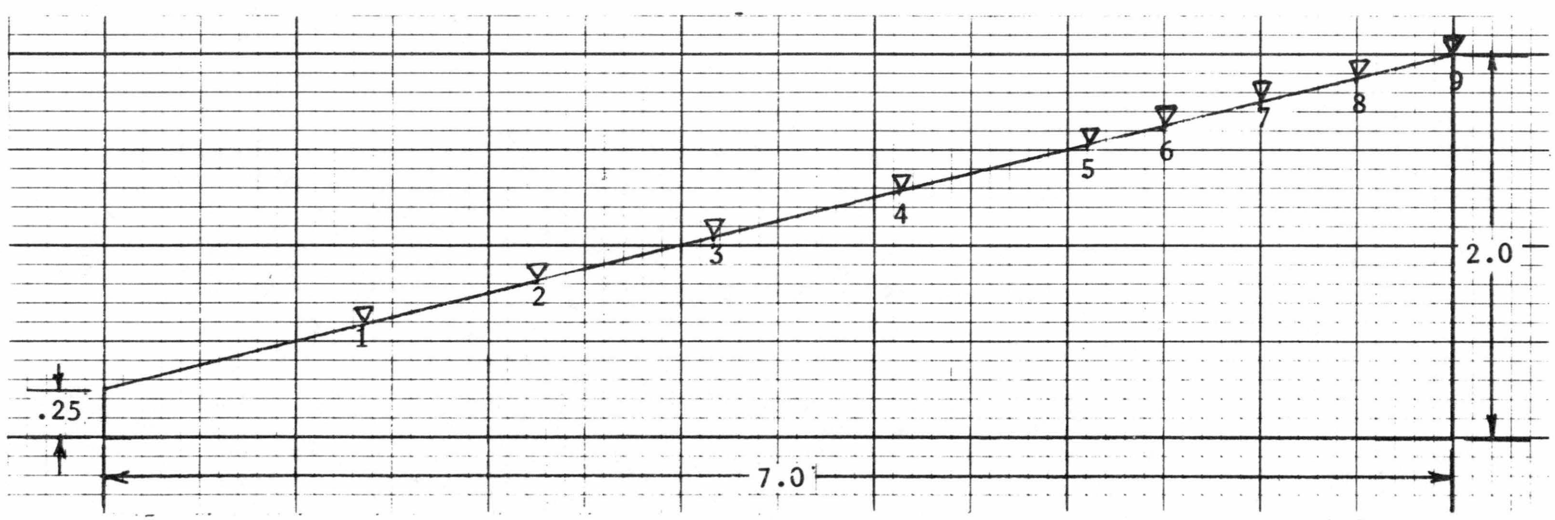
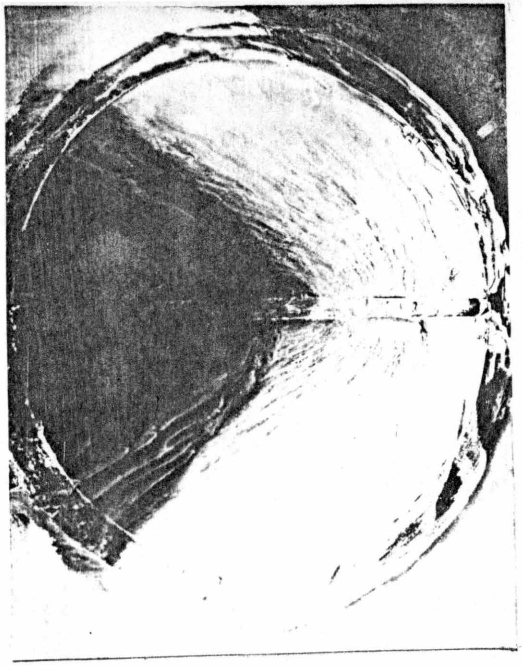


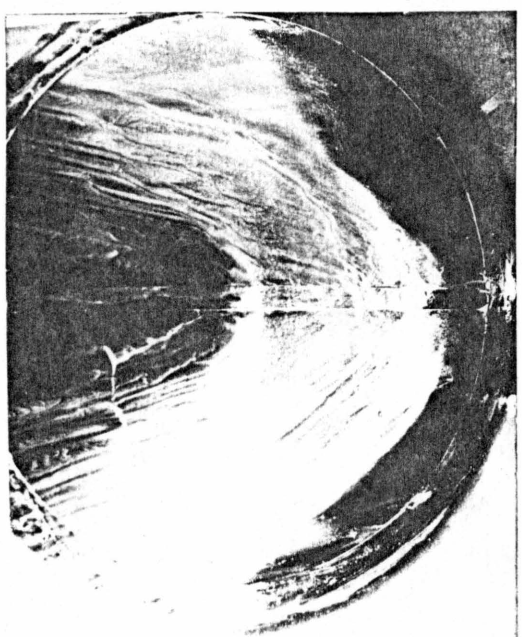
Figure 2. (c) Cone shaped hill with 1:3 slope.



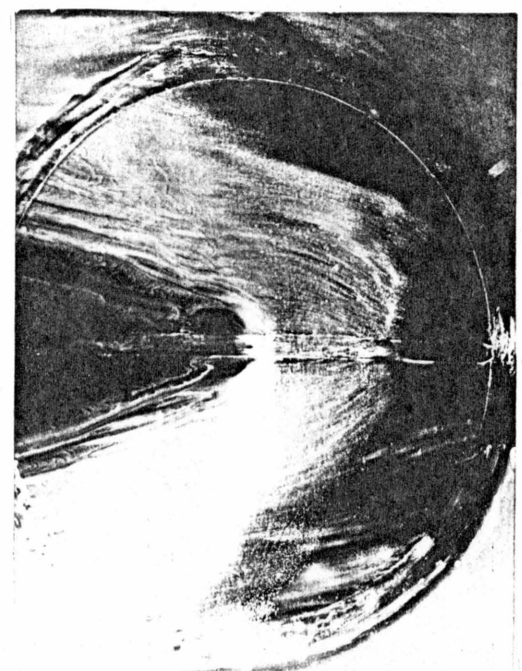
a) 12.1 m/sec

b) 15.2 m/sec

← Flow direction

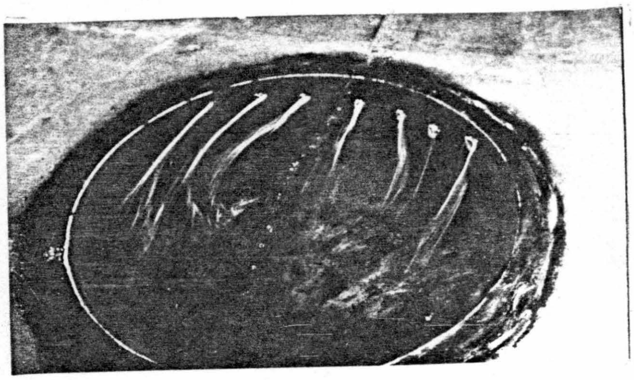


c) 18.3 m/sec

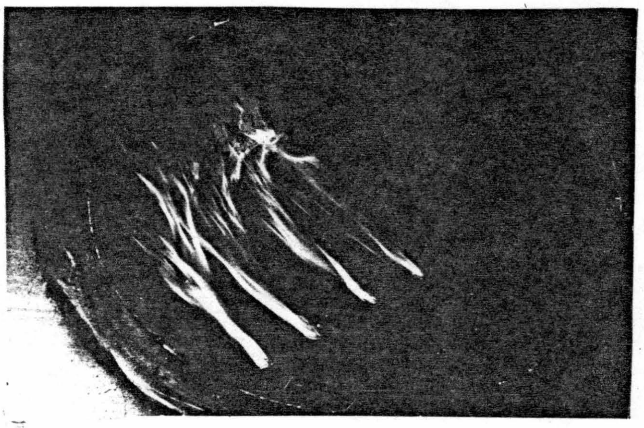


d) 21.2 m/sec

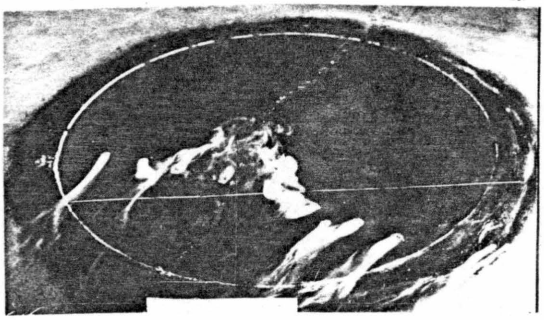
Figure 3. Surface oil streak patterns over the Gaussian hill. (top view)



a) Upstream smoke streaks.



b) Side view.



c) Downstream separation effect.

Figure 4. Smoke streak patterns over the Gaussian hill.

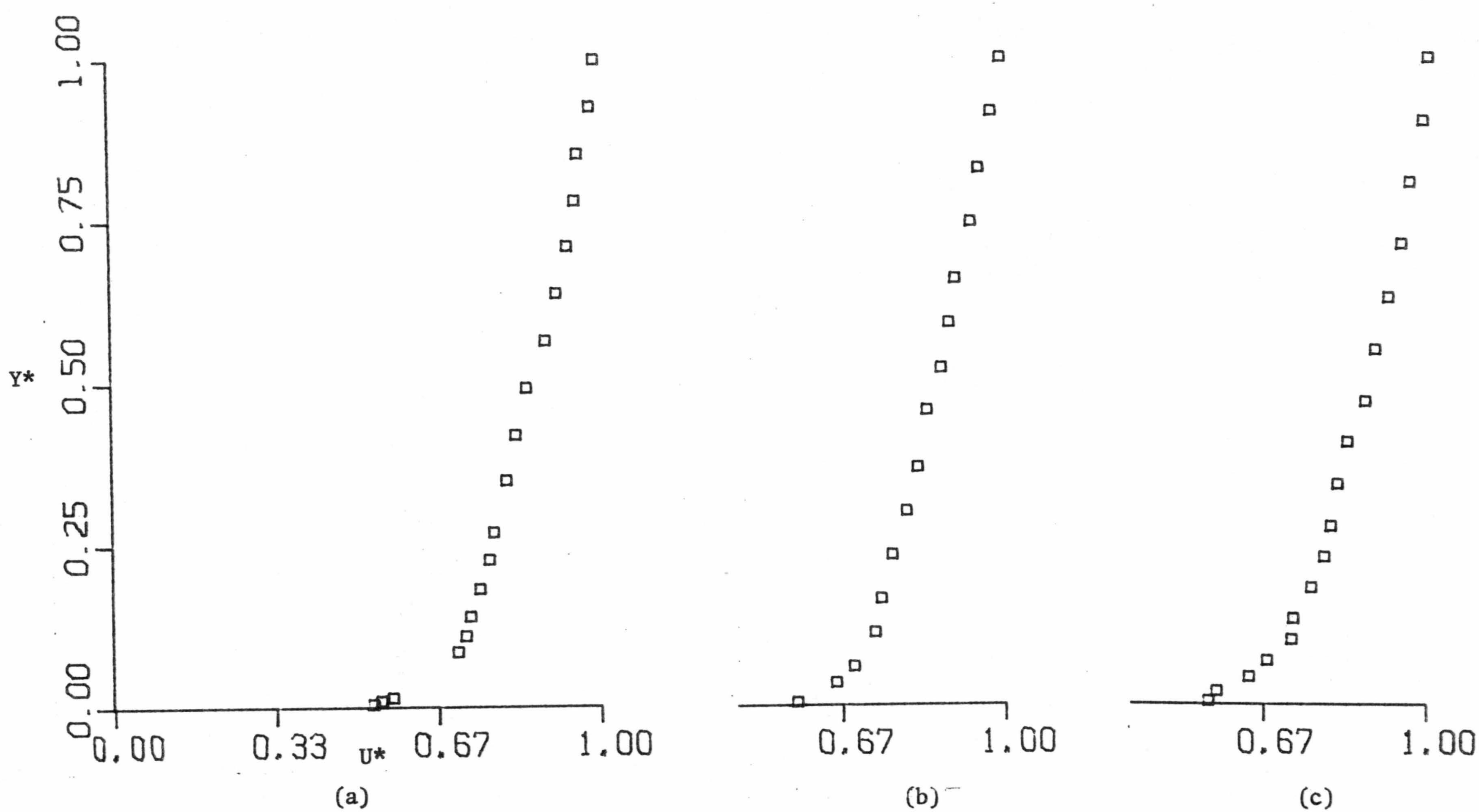


Figure 5. Upstream velocity profiles. (a) 50.8 cm upstream crest of Hill No. 1 -- Gaussian hill U(REF) = 9.78 m/s. (b) 28.7 cm upstream crest of Hill No. 2 -- 1:4 hill U(REF) = 9.33 m/s. (c) 20.3 cm upstream crest of Hill No. 3 -- 1:3 hill U(REF) = 9.24 m/s.

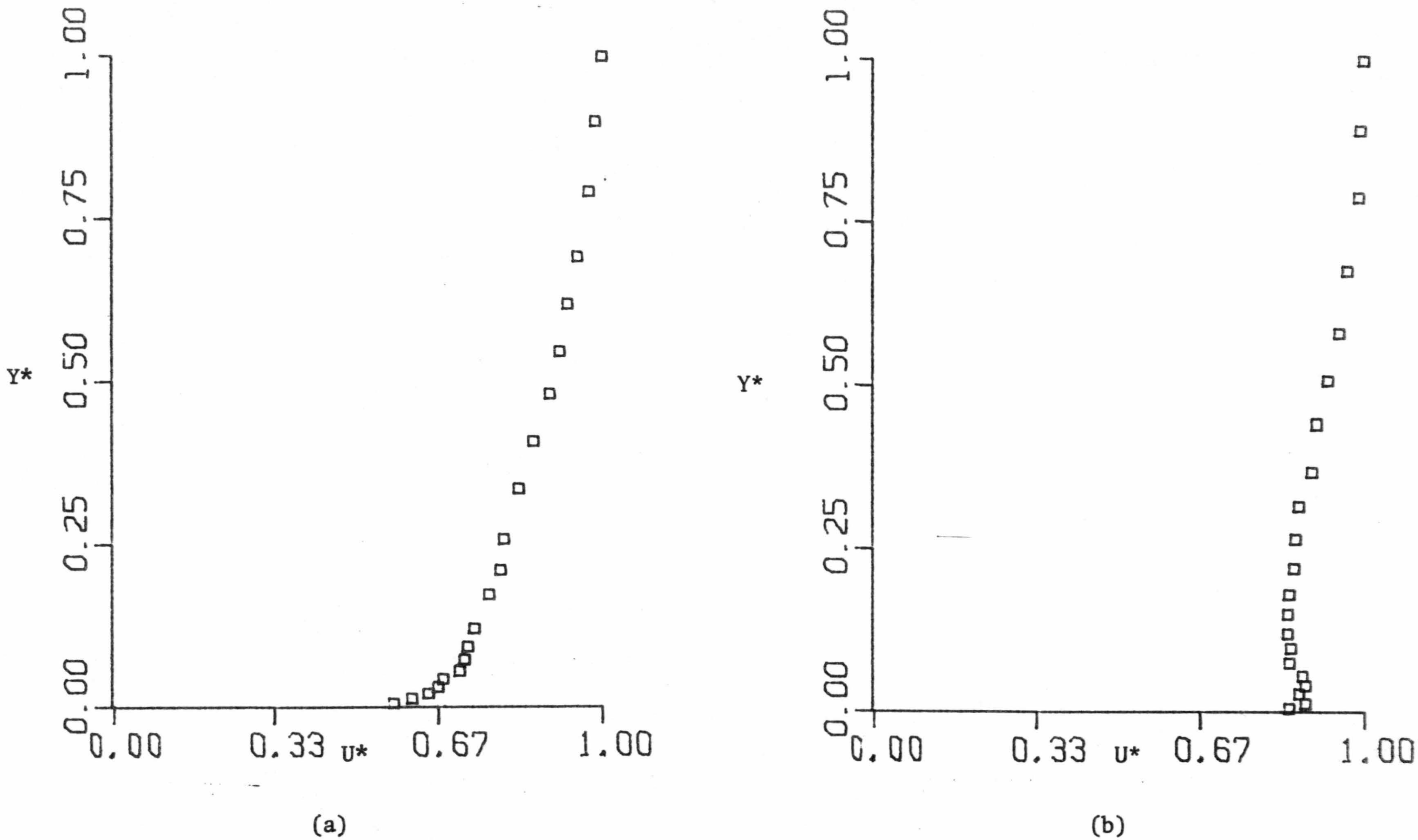


Figure 6. Velocity profiles for Hill No. 1 at U_{FS} = 15.25 m/s and measuring angle 0° from flow direction. (a) 50.8 cm upstream crest of hill, (b) crest of hill.

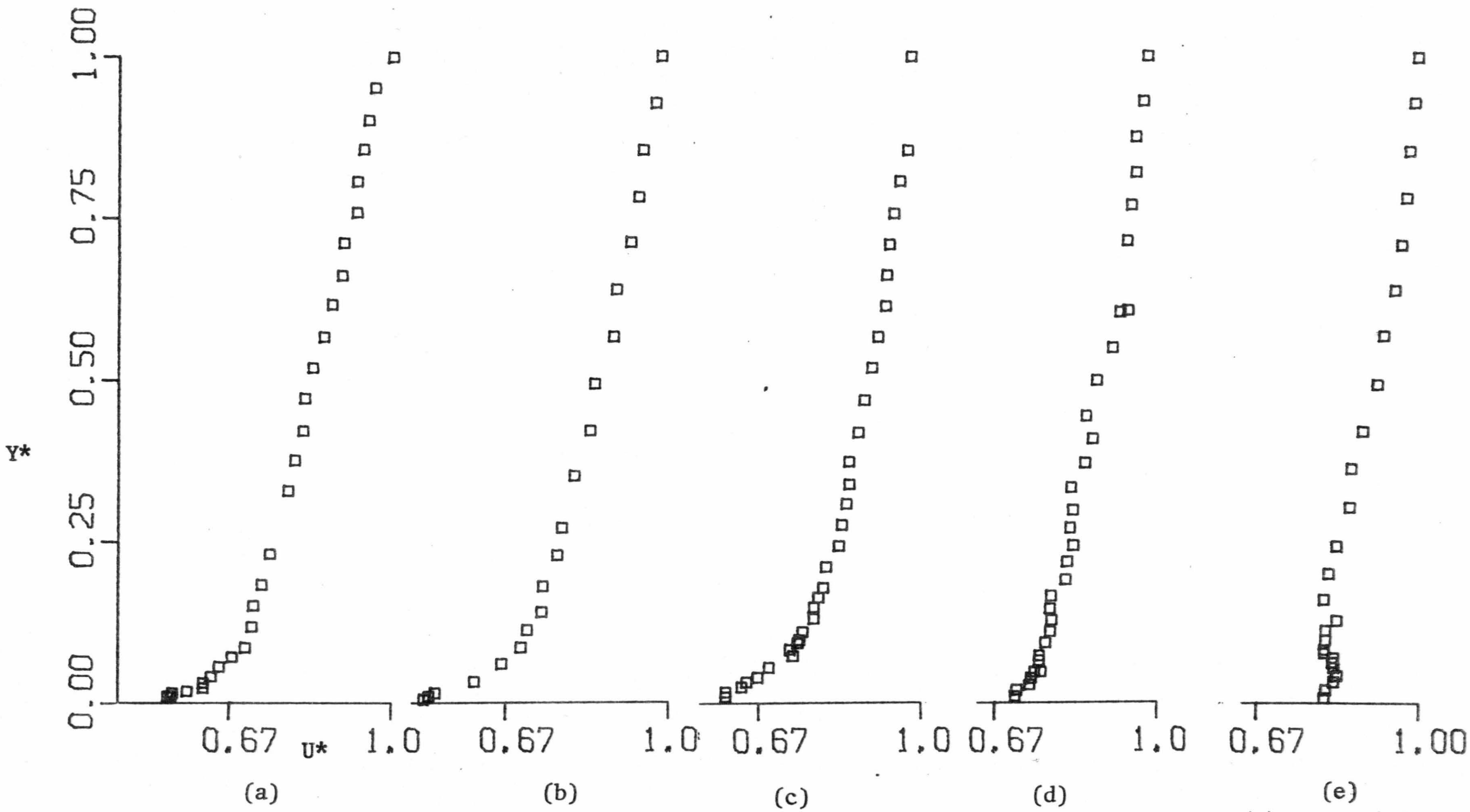


Figure 7. Velocity profiles for Hill No. 1 at θ = 0°, (a) R = 31.90 cm, U(REF) = 9.14 m/s, (b) R = 20.80 cm, U(REF) = 9.60 m/s, (c) R = 9.25 cm, U(REF) = 9.77 m/s, (d) R = 4.60 cm, U(REF) = 10.15 m/s, (e) crest of the hill, U(REF) = 9.69 m/s.

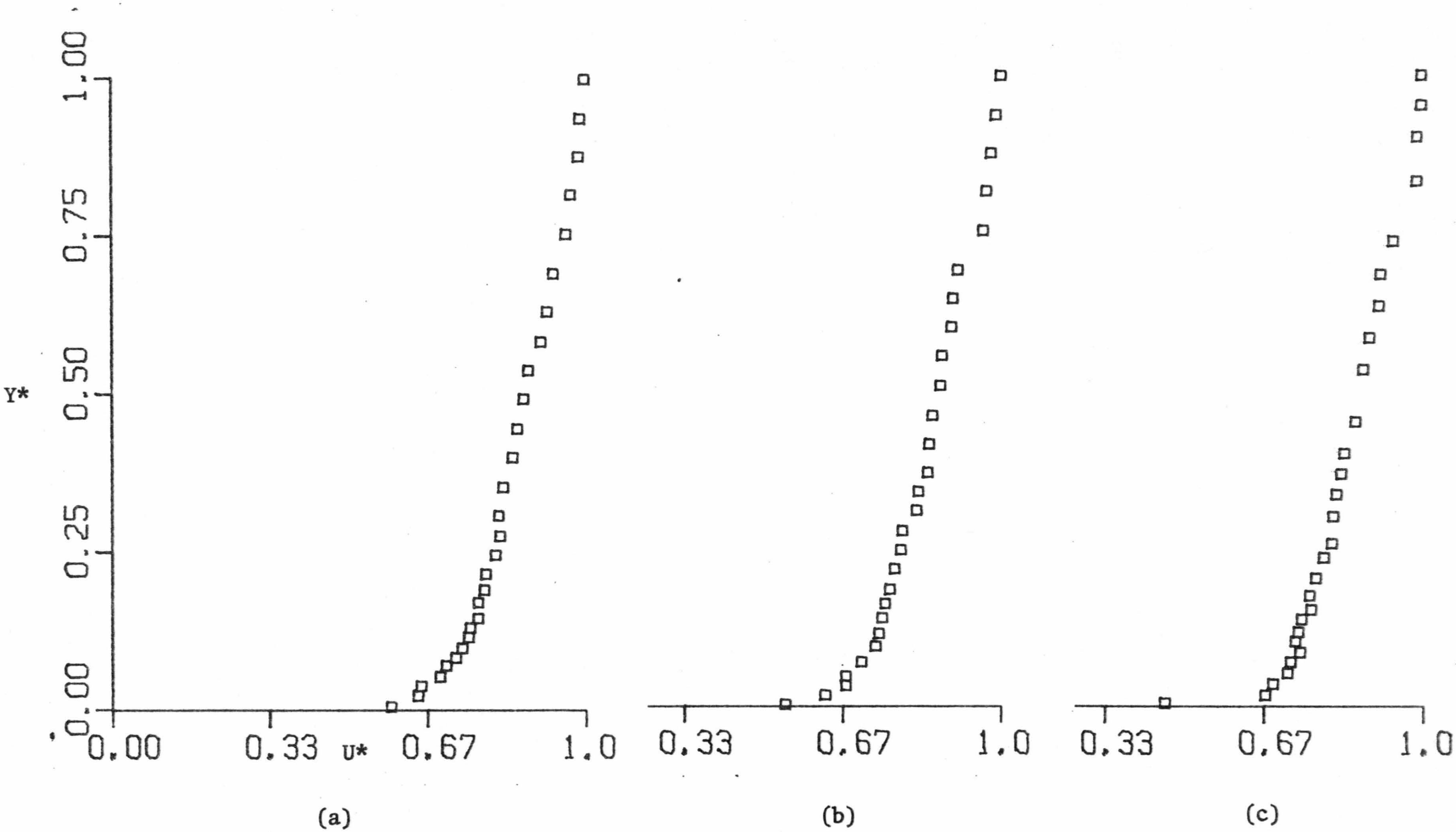
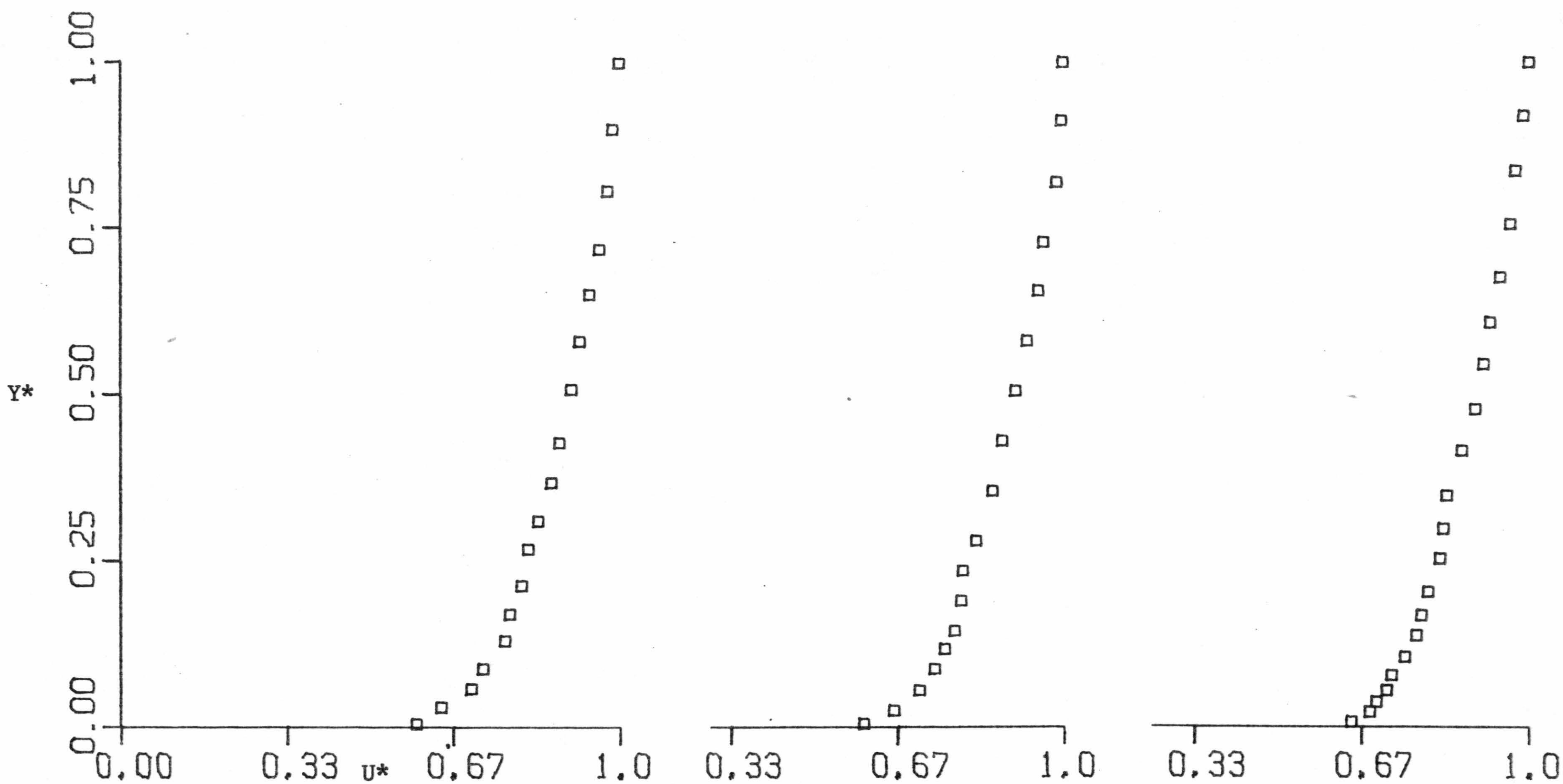


Figure 8. Velocity profiles for Hill No. 1 at θ = 45°, V = 9.4 m/s.
(a) R = 20.80 cm, U(REF) = 9.33 m/s.
(b) R = 9.25 cm, U(REF) = 9.60 m/s.
(c) R = 4.60 cm, U(REF) = 9.60 m/s.



(a) (b) (c)

Figure 9. Velocity profiles for Hill No. 1 at $\theta = 90°$.
(a) R = 20.80 cm, U(REF) = 9.60 m/s.
(b) R = 9.25 cm, U(REF) = 9.60 m/s.
(c) R = 4.60 cm, U(REF) = 9.60 m/s.

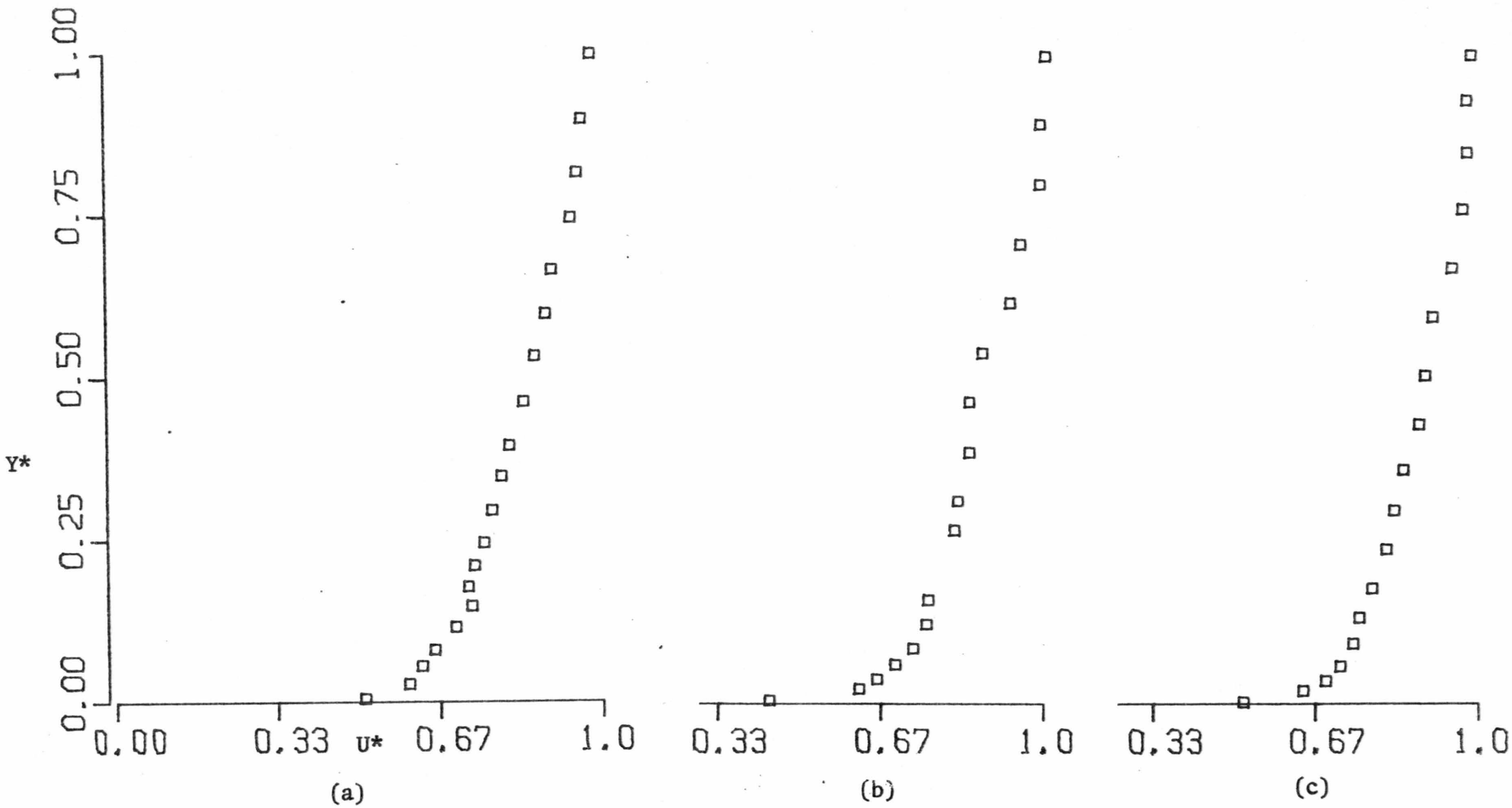
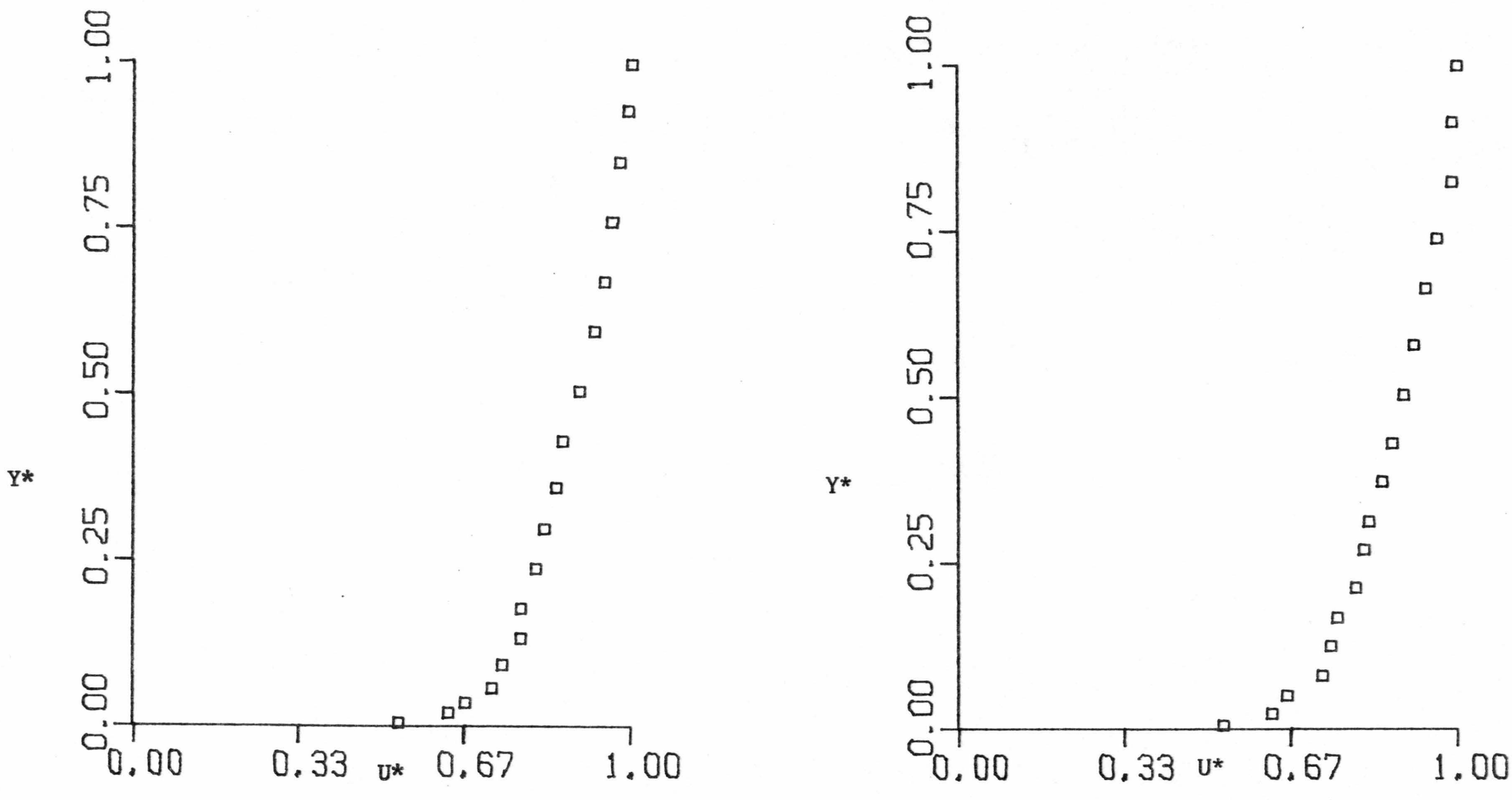


Figure 10. Velocity profiles for Hill No. 2, at $\theta = 0°$.
(a) R = 12.85 cm, U(REF) = 9.17 m/s.
(b) R = 7.62 cm, U(REF) = 9.20 m/s.
(c) crest of hill, U(REF) = 9.24 m/s.



(a) (b)

Figure 11. Velocity profiles for Hill No. 2 at θ = 45°.
(a) R = 12.85 cm, U(REF) = 9.24 m/s.
(b) R = 7.62 cm, U(REF) = 9.42 m/s.

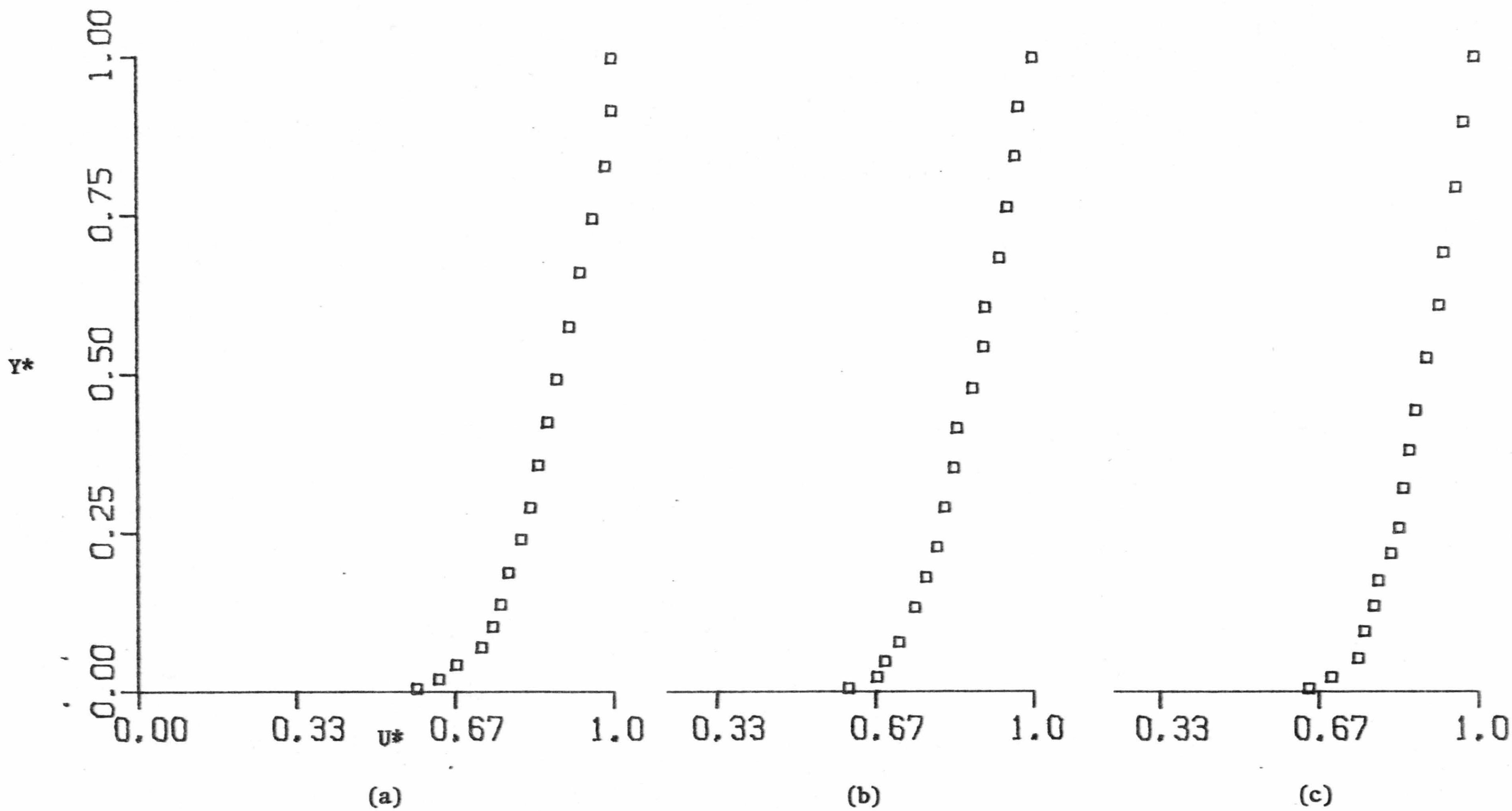


Figure 12. Velocity profiles for Hill No. 2 at $\theta = 90°$.
(a) R = 22.86 cm, U(REF) = 9.42 m/s.
(b) R = 12.85 cm, U(REF) = 9.24 m/s.
(c) R = 7.62 cm, U(REF) = 9.33 m/s.

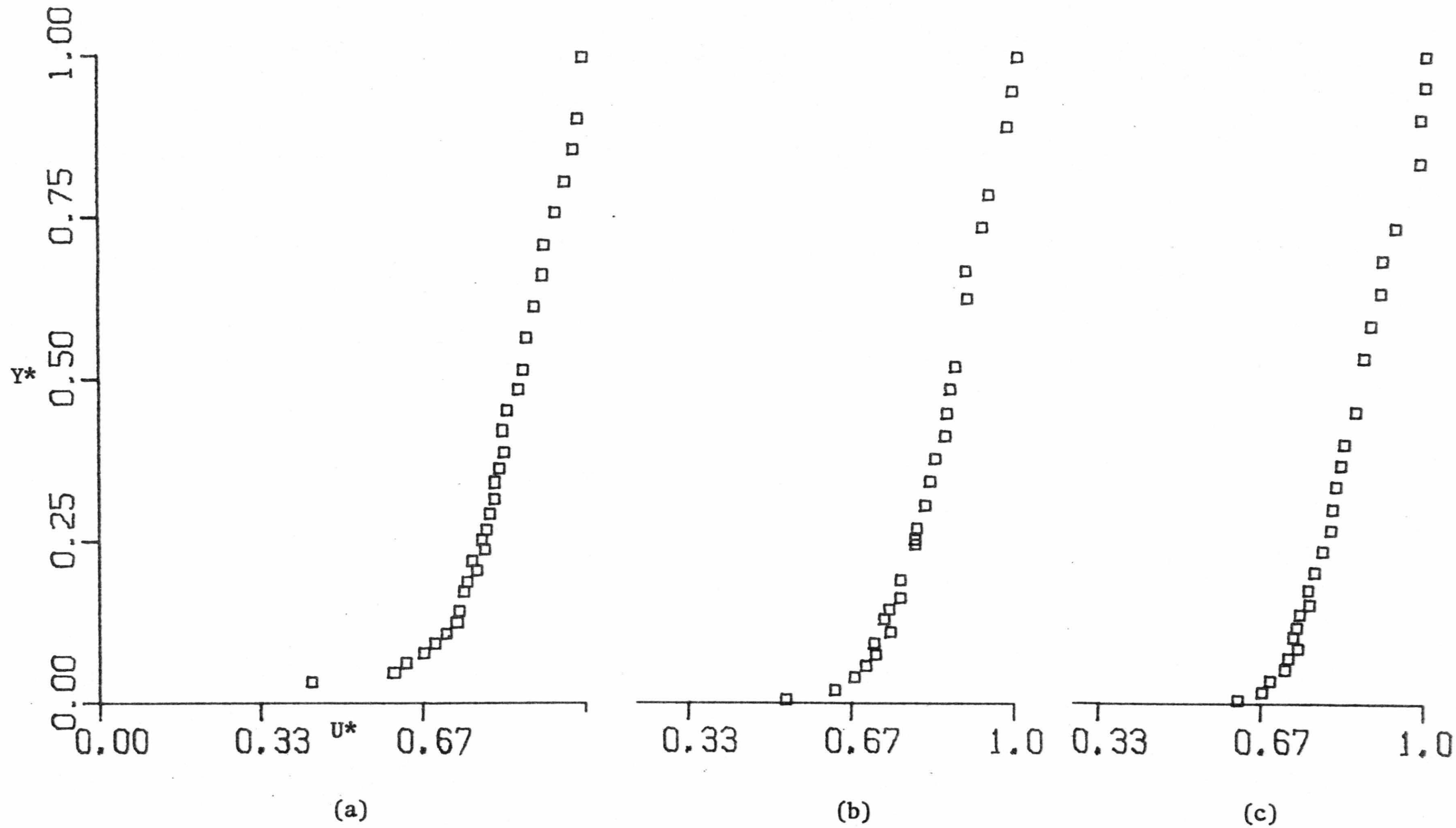


Figure 13. Velocity profiles for Hill No. 3 at $\theta = 0°$.
(a) R = 10.16 cm, U(REF) = 9.13 m/s.
(b) R = 4.32 cm, U(REF) = 9.42 m/s.
(c) Crest of hill, U(REF) = 8.96 m/s.