

ESTIMATION AND ANALYSIS
OF
HORIZONTAL BOTTOM VELOCITIES DUE TO WAVES

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ABSTRACT

Maximum bottom velocities caused by waves were calculated using digital computers. Four wave theories, Airy, Stokes third order, Cnoidal and Solitary, were applied in the computation.

Results of the study were tabulated and presented graphically to highlight the importance of various parameters affecting the maximum bottom velocity.

PREFACE

The study described in this report was conducted as part of continuing research within the Ocean Engineering Program at Texas A&M University.

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ESTIMATION AND ANALYSIS OF HORIZONTAL
BOTTOM VELOCITIES DUE TO WAVES

I. INTRODUCTION

A storm or a hurricane generated in the sea produces waves which move towards the shoreline. Water particles under such waves move in orbits. When the wave is in deep water the orbital velocity of the particles along the seabed is negligibly small and as such creates no problems. However, when the wave approaches the shallow water it undergoes considerable change. The height of the wave (H) increases, the length (L) decreases and thus the wave becomes more and more steep. A dimensionless parameter commonly used is the wave steepness. The orbital velocity of the particle also undergoes change. The wave finally breaks in the surf zone. The bottom velocity generated by waves is a function of the wave height, the wave period (T) and the water depth (h). Considerable bottom velocities have been observed particularly when a hurricane passes a certain area of the sea. These bottom velocities cause sediment movement of immense magnitude. At times the bottom velocities were found to be so high as to cause considerable damage to marine structures and offshore pipelines. Considerable research was therefore done in this field to improve the understanding of wave phenomena. Many scientists and engineers have developed theories to describe the various parameters of waves in the best possible manner. Notable among these are Airy, Stokes, Keulegan, Le Méhaute; Dean, and others. Attempts were also made to compare the theories with the actual waves generated in nature. In the present report one important aspect of the waves, i.e., the horizontal bottom velocity is examined in view of its importance

in the sediment movement along the seabed and also its possible effect on the structures and pipelines placed on the seabed.

II. PRESENT STUDY

Four wave theories, i.e., Airy, Stokes III, Cnoidal and Solitary Wave have been examined in the present studies. The important parameters considered are the wave height, wave period and water depth. The following ranges of values are selected for these parameters in order to cover a wide range of possibilities.

- i. Wave Heights 2 feet to 24 feet (significant)
 3.56 feet to 42.72 feet (H_{max})
- ii. Wave Periods 2.9 seconds to 15 seconds
- iii. Water Depths 8 feet to 150 feet

Computations for the bottom velocities were made on the digital computer. Bottom horizontal velocities (maximum) under wave crest and wave trough were computed for different wave theories indicated above. The validities of the various wave theories were taken into account while preparing the computer programs. The data obtained from the computer were tabulated (Tables 1 to 18) and plotted to show the effects of the various parameters on the bottom velocities (Figures 1 to 14).

III. DATA ANALYSIS

The results obtained were found to be quite interesting and emphasized the importance of various parameters being considered.

Figures 1 to 9 present plots of maximum bottom horizontal velocities under wave crest as a function of the water depth for different significant and corresponding maximum wave heights for two different periods.

The results indicated the following:

1. Some variation in the maximum horizontal bottom velocities was noticed for different wave theories as expected. The variation was marginal for low wave heights but increased considerably for higher wave heights.

2. The bottom velocities increase with increase in wave height and wave period and decrease with increase in water depths.

3. The bottom velocity was quite large for a significant wave of 24 feet (H_s) and 42.72 feet (H_{max}) even in a depth of 150 feet of water. The magnitude of bottom velocity for a 15-second wave period was of the order of 4 feet per second and 7.5 feet per second, respectively. A velocity of this magnitude is expected to cause considerable sediment movement along the bed.

4. The maximum bottom velocity for any wave occurs at the breaking region where the sediment movement would be maximum.

5. The bottom velocity drops rapidly initially from the breaker zone towards the sea up to some depth and then drops gradually till it becomes zero in the deep sea.

In order to assess the effects of wave heights and wave periods on the maximum bottom velocities, plots were made of maximum bottom velocities

versus the wave heights. These are presented in Figures 10 to 12. These plots indicated a linear relationship between maximum bottom velocities and wave heights. The velocities also showed increase with increase in wave period as would be evident from the figures. A notable feature noticed was the scatter of data for depth of water of 80 feet for 15-second waves. Two lines have been drawn to indicate the upper and lower limits of velocities for this period. The scatter however reduces when the depth increases and for a 150 foot depth of water there is negligible scatter of data (see Figure 12).

There was very little difference between the maximum horizontal bottom velocities under a wave crest and that under a wave trough for most of the wave theories except the Stokes III. This wave theory indicated considerable variation in the bottom velocities for crest and trough. In order to examine the exact nature of the variation, plots were made for maximum bottom velocities versus wave height for two typical depths of water, i.e. 40 feet and 80 feet. The variations were very high for 40-foot depths compared to that for 80-foot depths of water. The difference in the velocities increased with wave heights and wave periods and decreased with depth. The results are presented in Figures 13 and 14.

IV. CONCLUDING REMARKS

Maximum bottom velocity under a wave is one of the important aspects of wave phenomena that needs thorough study since it causes sediment movement of immense magnitude along the bed. This affects the pipelines laid along the seabed and the scour around objects placed along the bottom. Bottom velocities were determined with the aid of a digital computer on the basis of four wave theories. Plots have been made to highlight the importance of various parameters affecting the maximum bottom velocity. It is suggested that maximum bottom velocities under a wave crest be considered while estimating the sediment movement and designing offshore pipelines, platforms, and underwater objects.

REFERENCES

1. Wiegel, R.L., "Oceanographic Engineering", Englewood Cliffs, Prentice-Hall, Inc., 1964.
2. Skjelbreia, L., "Gravity Waves. Stokes' Third Order Approximation Tables of Functions", Council on Wave Research, The Engineering Foundation, 1959.
3. Masch, F.D., and Wiegel, R.L., "Cnoidal Wave Tables of Function", Council on Wave Research, The Engineering Foundation, 1961.

V. APPENDIX

TABLE NO. 1
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS Bottom velocities in ft/sec
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
1	2 ft	2.9 secs	2.3	2.7112	2.6366			1.2720	1.2121	1.2201	1.2159	
			8 ft					0.1384	0.1384	0.1301	0.1297	
			24 ft					0.0141	0.0141	0.0127	0.0126	
			40 ft					0.0004	0.0004	0.0004	0.0004	
			64 ft					0.0000	0.0000	0.0000	0.0000	
			80 ft					0.0000	0.0000	0.0000	0.0000	
			100 ft					0.0000	0.0000	0.0000	0.0000	
			150 ft					0.0000	0.0000	0.0000	0.0000	
			3.81	4.5765	4.3935							
			10 secs									
2	2 ft	8 ft	8 ft									
			24 ft					0.724	0.7665	0.7302	0.7489	
			40 ft					0.711				
			64 ft					0.5247	0.5176	0.5213	0.5212	
			80 ft					0.4260	0.4230	0.4245	0.4245	
			100 ft					0.3347	0.3337	0.3342	0.3341	
			150 ft					0.1884	0.1883	0.1882	0.1882	

TABLE NO. 2
BOTTOM VELOCITIES FOR VARIOUS WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
3	3.56 ft	2.9 secs	4.15	4.7125	4.5842			2.3738	2.1559			
			8 ft					0.2743	0.2743			
			24 ft					0.0304	0.0304			
			40 ft					0.0011	0.0011			
			64 ft					0.0001	0.0001			
			80 ft					0.000	0.000			
			100 ft					0.000	0.000			
			150 ft					0.000	0.000			
			4.06 ft	4.7872	4.6569							
			8 ft									
4	3.56 ft	10 secs	24 ft					1.3881	1.2773	1.3331	1.3331	
			40 ft					0.9391	0.9165	0.9278	0.9278	
			64 ft					0.7604	0.7512	0.7556	0.7556	
			80 ft					0.5968	0.5935	0.5948	0.5948	
			100 ft					0.3355	0.3352	0.3350	0.3350	
			150 ft									

TABLE NO. 3
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

TABLE NO. 4
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY				CNOIDAL				STOKES III				AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
7	7.12 ft	3.8 secs	8 ft					6.7331		3.7769		5.5036		5.4943				1.4629 0.3914 0.0509 0.0130
			8.90 ft							1.6482		1.6316		1.4643				
			24 ft							0.4821		0.4820		0.3918				
			40 ft							0.0729		0.0729		0.0509				
			64 ft							0.0206		0.0206		0.0130				
		10 secs	80 ft															
			100 ft															
			150 ft															
			8 ft															
			10.41 ft	8.5407	8.3642													
8	7.12 ft	8 ft	24 ft		3.8520	2.8060							3.7172	3.7169				1.8557 1.5112
			40 ft		2.4410	2.5160	2.8787						2.4207	2.6665	2.6663			
			64 ft										1.9016	1.8108	1.8557			
		10 secs	80 ft										1.5318	1.4947	1.5112			
			100 ft										0.6729	0.6716	0.6700			
			150 ft															

TABLE NO. 5
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
9	6 ft	4.6 secs	7.20 ft	6.9656	6.6691			6.4739	3.0103	5.0804	5.0750	
			8 ft					1.9520	1.8942	1.8656	1.8647	
			24 ft					0.8242	0.8224	0.7805	0.7801	
			40 ft					0.2190	0.2190	0.1998	0.1997	
			64 ft					0.0891	0.0891	0.0790	0.0789	
			80 ft					0.0289	0.0289	0.0247	0.0247	
			100 ft					0.0017	0.0017	0.0014	0.0014	
			150 ft							5.8222	5.8211	
			10 secs	8 ft	7.8608							
				9.18 ft	8.0191							
10	6 ft		24 ft	3.2630	2.5050			2.3995	2.0739	2.2470	2.2469	
			40 ft									
			64 ft					1.5962	1.5319	1.5638	1.5638	
			80 ft					1.2879	1.2615	1.2735	1.2735	
			100 ft					1.0087	0.9992	1.0024	1.0024	
			150 ft					0.5665	0.5656	0.5646	0.5646	

TABLE NO. 6
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
11	10.68 ft	4.6 secs	8 ft									
			12.35 ft	8.8421	8.7145							
			24 ft					3.6816	3.4580	3.3209	3.3192	
			40 ft					1.5987	1.5908	1.3892	1.3886	
			64 ft					0.4519	0.4519	0.3537	0.3537	
			80 ft					0.1919	0.1919	0.1406	0.1406	
			100 ft					0.0655	0.0655	0.0440	0.0440	
			150 ft					0.0044	0.0044	0.0024	0.0024	
			8 ft							10.3636	10.3615	
			14.48 ft	10.0396	9.9318							
12	10.68 ft	10 secs	24 ft		5.3470	3.653						
			40 ft		3.6120	3.6940	4.4592		3.4344	3.9997	3.9995	
			64 ft					2.8886	2.6823	2.7836	2.7835	
			80 ft					2.3158	2.2314	2.2668	2.2668	
			100 ft					1.8075	1.7770	1.7843	1.7843	
			150 ft					1.0134	1.0106	1.0050	1.0050	

TABLE NO. 7
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
13	8 ft	5.3 secs	8 ft	9.6	8.0532	7.8481						
			24 ft				3.1873	2.9237	2.9978	2.9968		
			40 ft				1.6207	1.6032	1.5495	1.5491		
			64 ft				0.6098	0.6095	0.5703	0.5701		
			80 ft				0.3126	0.3125	0.2868	0.2868		
			100 ft				0.1343	0.1343	0.1199	0.1199		
			150 ft				0.0161	0.0161	0.0135	0.0135		
			11.34 ft	8.9128	8.7574							
14	8 ft	10 secs	24 ft								4/1766	4.1763
			40 ft	2.7800	2.7840	3.2615	2.6838	2.9960	2.9959			
			64 ft			2.1433	2.0284	2.0851	2.0850			
			80 ft			1.7244	1.6774	1.6980	1.6980			
			100 ft			1.3485	1.3316	1.3366	1.3365			
			150 ft			0.7567	0.7551	0.7528	0.7528			

TABLE NO. 8

BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
15	14.24 ft	5.3 secs	8 ft	10.5784	10.4490	6.0145	5.0483	5.3361	5.3361			
			24 ft			3.0807	3.0095	2.7581	2.7573			
			40 ft			1.2081	1.2064	1.0151	1.0480			
			64 ft			0.6392	0.6391	0.5106	0.5164			
			80 ft			0.2859	0.2859	0.2135	0.2134			
			100 ft			0.0378	0.0378	0.0240	0.0240			
			150 ft									
			18.24 ft	11.2357	11.1593							
16			24 ft									
			40 ft			4.6700	4.7180	6.1181	4.3138	5.3329	5.3327	
			64 ft					3.9008	3.5296	3.7115	3.7114	
			80 ft					3.1140	2.9617	3.0225	3.0224	
			100 ft					2.4248	2.3698	2.3791	2.3791	
			150 ft					1.3585	1.3533	1.3400	1.3399	

TABLE NO. 9
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

TABLE NO. 10
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
19	17.80 ft	6.0 secs	8 ft	20.41 ft	11.7362	11.6726						
			24 ft				8.7231	6.0856	7.4624	7.4624		
			40 ft				4.8187	4.5106	4.3575	4.3567		
			64 ft				2.3012	2.2853	2.0245	2.0245		
			80 ft				1.4107	1.4085	1.1983	1.1981		
			100 ft				0.7576	0.7574	0.6141	0.6140		
			150 ft				0.1565	0.1565	0.1120	0.1120		
20	17.80 ft	10 secs	8 ft	22.16 ft	12.3341	12.2776						
			24 ft							9.2930	9.2940	
			40 ft				5.5650	5.6310	7.8445	5.0658	6.6661	6.6658
			64 ft					4.9388	4.3507	4.6394	4.6392	
			80 ft					3.9276	3.6857	3.7781	3.7780	
			100 ft					3.0520	2.9644	2.9739	2.9738	
			150 ft					1.7093	1.7010	1.6750	1.6749	

TABLE NO. 11
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
21	14 ft	7.4 secs	8 ft									6.6375
			16.9 ft	10.7119	10.6279			7.9546	4.7827	6.6385		
			24 ft					4.700	4.1404	4.3812	4.3807	
			40 ft					2.7015	2.6387	2.6008	2.6007	
			64 ft					1.9334	1.9172	1.8621	1.8261	
			80 ft					1.2753	1.2723	1.2203	1.2202	
			100 ft					0.4391	0.4390	0.4101	0.4101	
			150 ft									
22	14 ft	15 secs	8 ft									7.7564
			21.1 ft	12.1584	12.0967							
			24 ft									
			40 ft									
			64 ft			4.4200	3.8120			5.8233	5.8232	
			80 ft			3.6770	3.5030	4.1385		4.3838	4.3838	
			100 ft			2.9640	3.0460	3.4193	3.0453	3.2422	3.2422	
			150 ft				2.3930		2.3040	2.3377	2.3374	

TABLE NO. 12
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
23	24.92 ft	7.4 secs	8 ft									
			24 ft									
			31.26 ft	14.0555	14.0242							
			40 ft					8.8650	6.9025	7.7985	7.7977	
			64 ft					5.0633	4.8250	4.6295	4.6292	
			80 ft					3.6478	3.5839	3.3145	3.3143	
			100 ft					2.4391	2.4265	2.1722	2.1720	
			150 ft					0.8759	0.8757	0.7299	0.7299	
24	24.92 ft	15.0 secs	8 ft									
			24 ft									
			32.1 ft	14.9468	14.9088							
			40 ft									
			64 ft			7.4690	5.8520					
			80 ft			6.2630	5.8780	7.7722				
			100 ft			5.1300	5.3360	6.3130				
			150 ft					4.3267	4.0416	4.1788	4.1788	

TABLE NO. 13
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

TABLE NO. 14
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
27	32.04 ft	8.5 secs	8 ft									
			24 ft	39.9 ft	15.9030	15.8809		13.3515	7.9584	11.0788	11.0780	
			40 ft					7.9682	6.9905	7.2104	7.2100	
			64 ft					6.0677	5.7265	5.5609	5.5606	
			80 ft					4.4304	4.3334	4.0506	4.0505	
			100 ft					2.0583	2.0539	1.8118	1.8117	
			150 ft									
			8 ft									
			24 ft									
			39.0 ft	16.4557	16.4312							
28	32.04 ft	15 secs	40 ft					13.3270	13.3268			
			64 ft					10.0358	10.0356			
			80 ft					8.6728	8.6727			
			100 ft					6.3335	7.4200	7.4199		
			150 ft					5.6216	5.1450	5.3728	5.3727	

TABLE NO. 16

BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

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SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
31	39.16 ft	9.5 secs	40 ft									
			48.6 ft	17.7956	17.3177			11.1442	8.6099	9.8098	9.8095	
			64 ft					8.6820	7.6467	7.8768	7.8766	
			80 ft					6.126	6.2579	6.0761	6.0759	
			100 ft					3.5508	3.5212	3.2177	3.2177	
32	39.16 ft	15 secs	150 ft									
			40 ft									
			48.5 ft	18.2747	18.2574							
			64 ft									
			80 ft			8.9120	8.2330	12.8958	7.3944	10.6001	10.6000	
			100 ft			7.3950	8.1880	10.3429	7.4219	9.0689	9.0688	
			150 ft					6.9443	6.2230	6.5667	6.5667	

TABLE NO. 17
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

SL NO	WAVE HT.	WAVE PERIOD	WATER DEPTH	SOLITARY WAVE THEORY		CNOIDAL		STOKES III		AIRY		REMARKS
				CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	CREST	TOUGH	
33	24 ft	10 secs	24 ft	14.0622	14.0251							
			40 ft			10.9866	6.1131	8.9881	8.9876			
			64 ft			6.8081	5.7105	6.2553	6.2551			
			80 ft			5.3844	4.9291	5.0940	5.0939			
			100 ft			4.1713	4.0056	4.0097	4.0096			
			150 ft			2.3369	2.3211	2.2584	2.2583			
34	24 ft	15 secs	24 ft	15.0544	15.0229							
			32.5 ft			7.2640	5.6980			9.9828	9.9826	
			40 ft			6.0390	5.702	7.4548	5.2768	7.5151	7.5150	
			64 ft			4.9580	5.1710	6.0622	4.9673	6.4965	6.4964	
			80 ft							5.5580	5.5580	
			100 ft							4.1614	3.8937	4.0246
			150 ft									4.0245

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TABLE NO. 18
BOTTOM VELOCITIES FOR DIFFERENT WAVE THEORIES

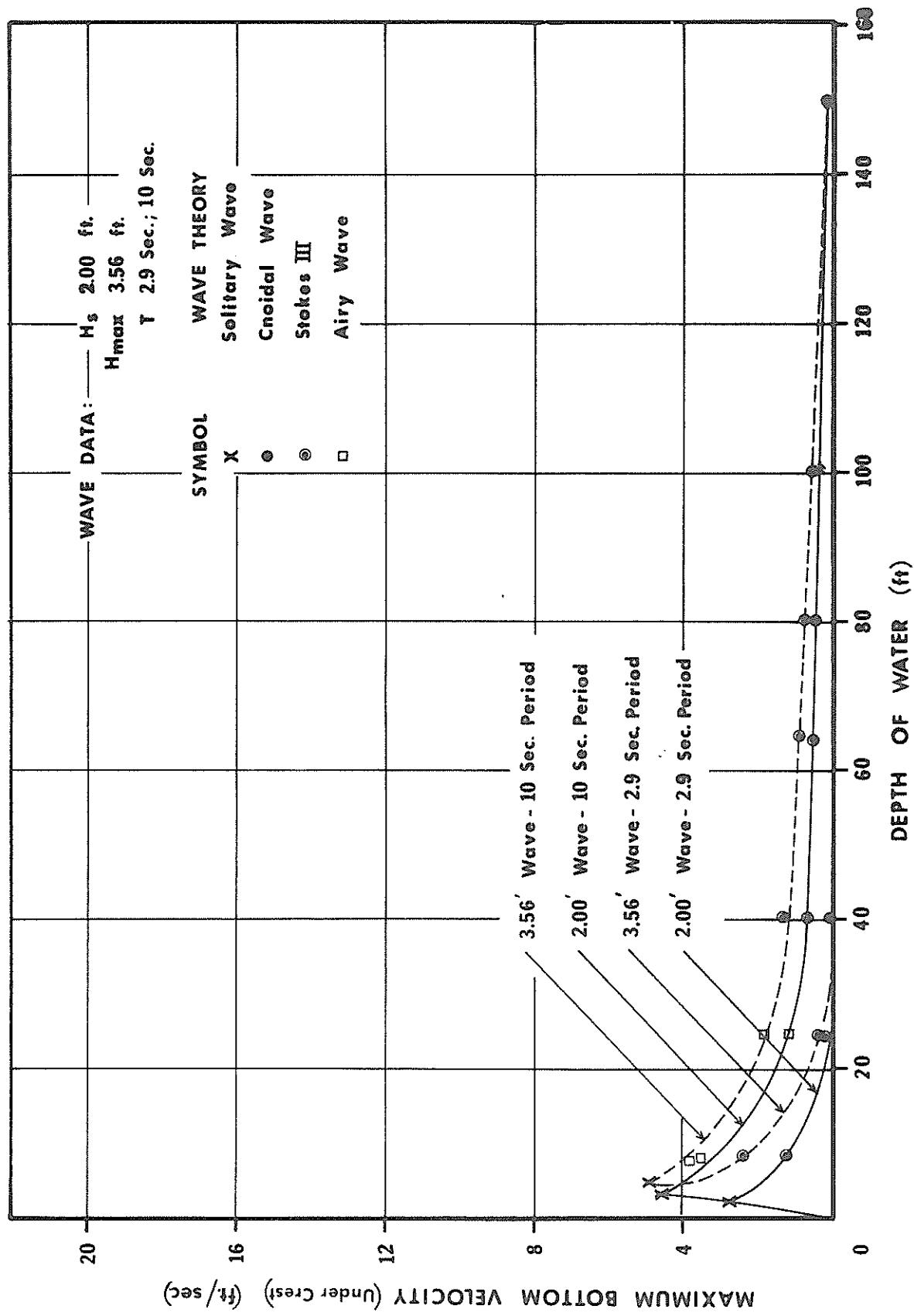


Figure 1. Maximum Bottom Velocities under Wave Crest

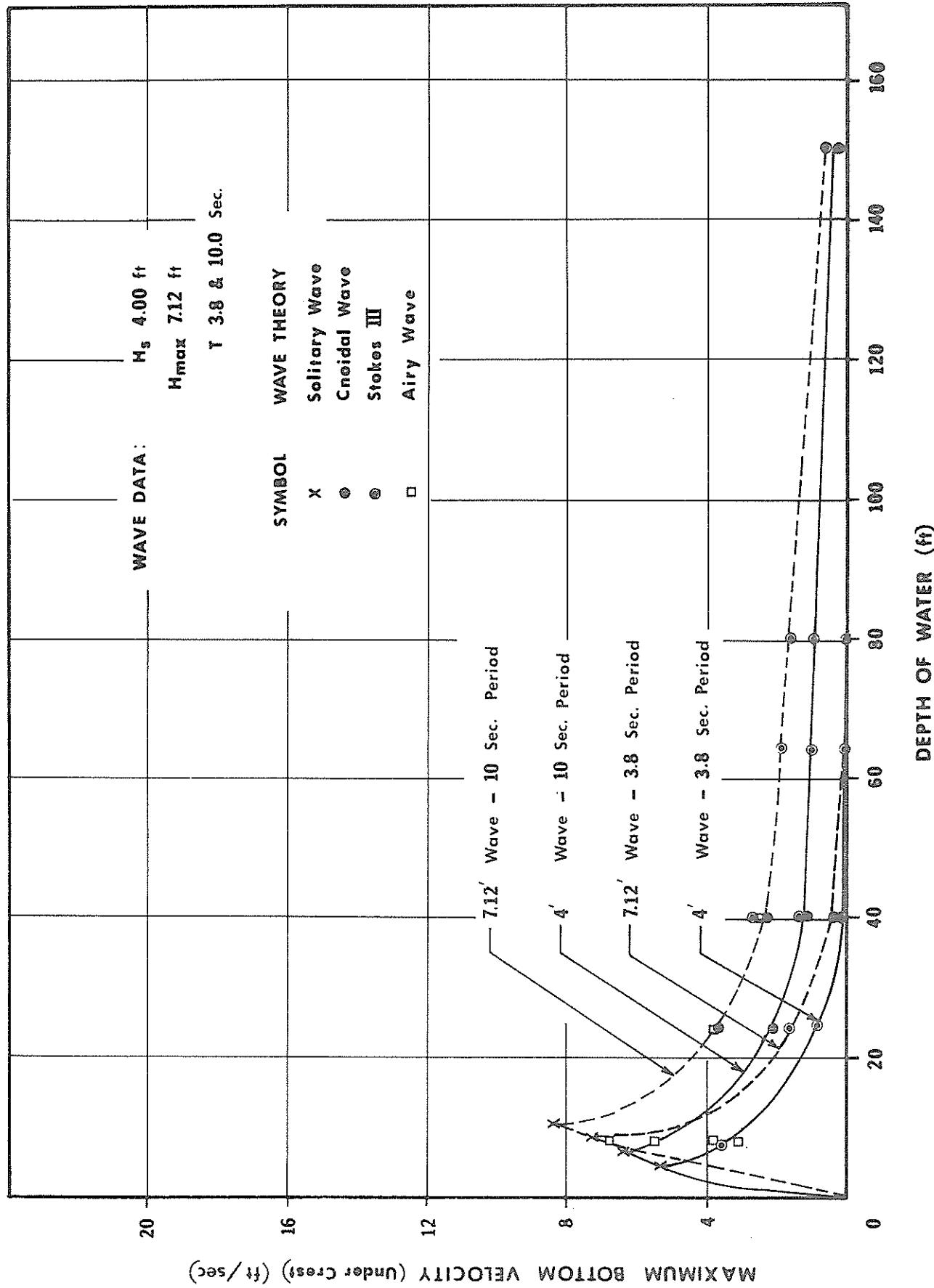


Figure 2. Bottom Velocities under Wave Crest

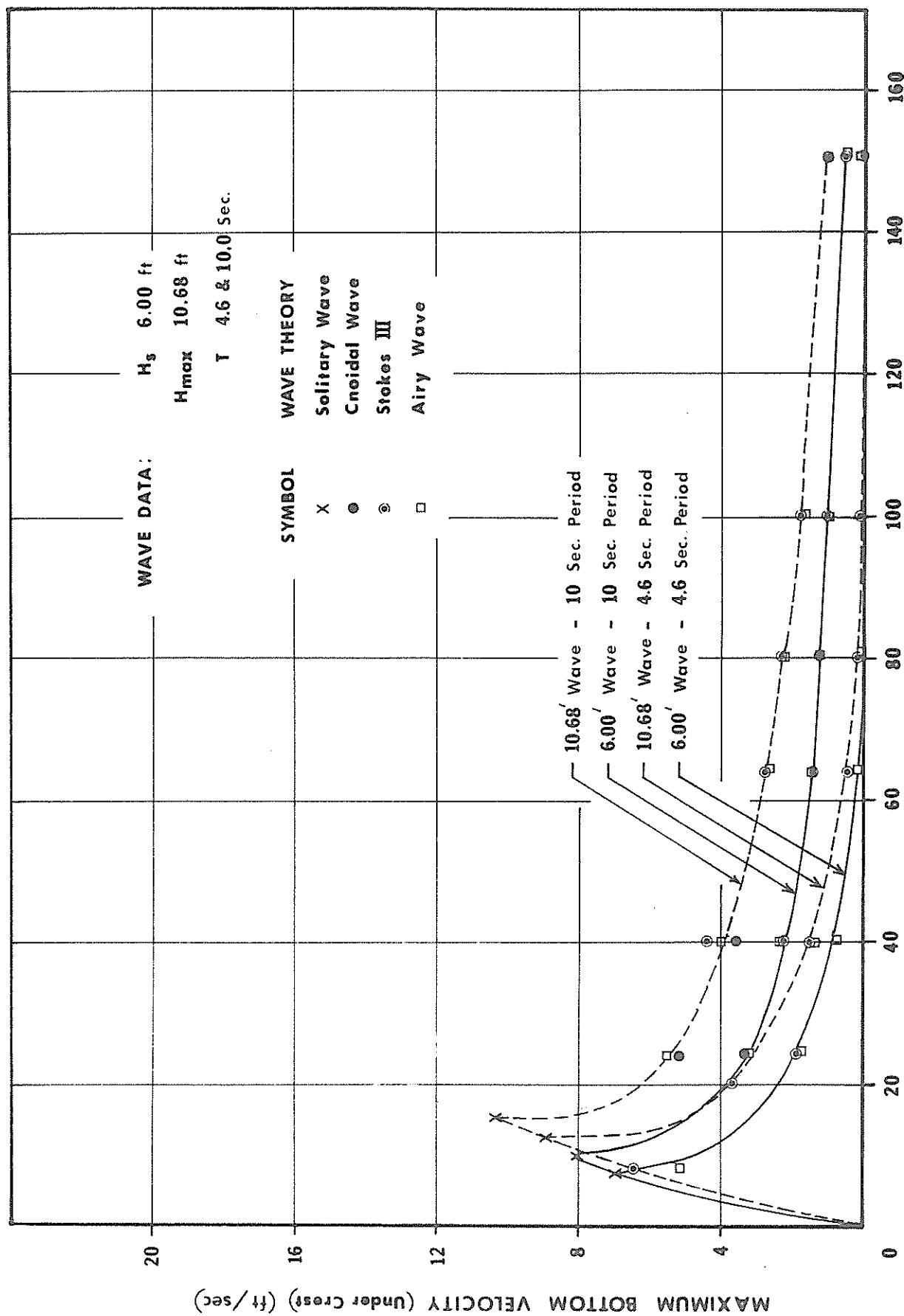


Figure 3. Maximum Bottom Velocities under Wave Crest
DEPTH OF WATER (ft)

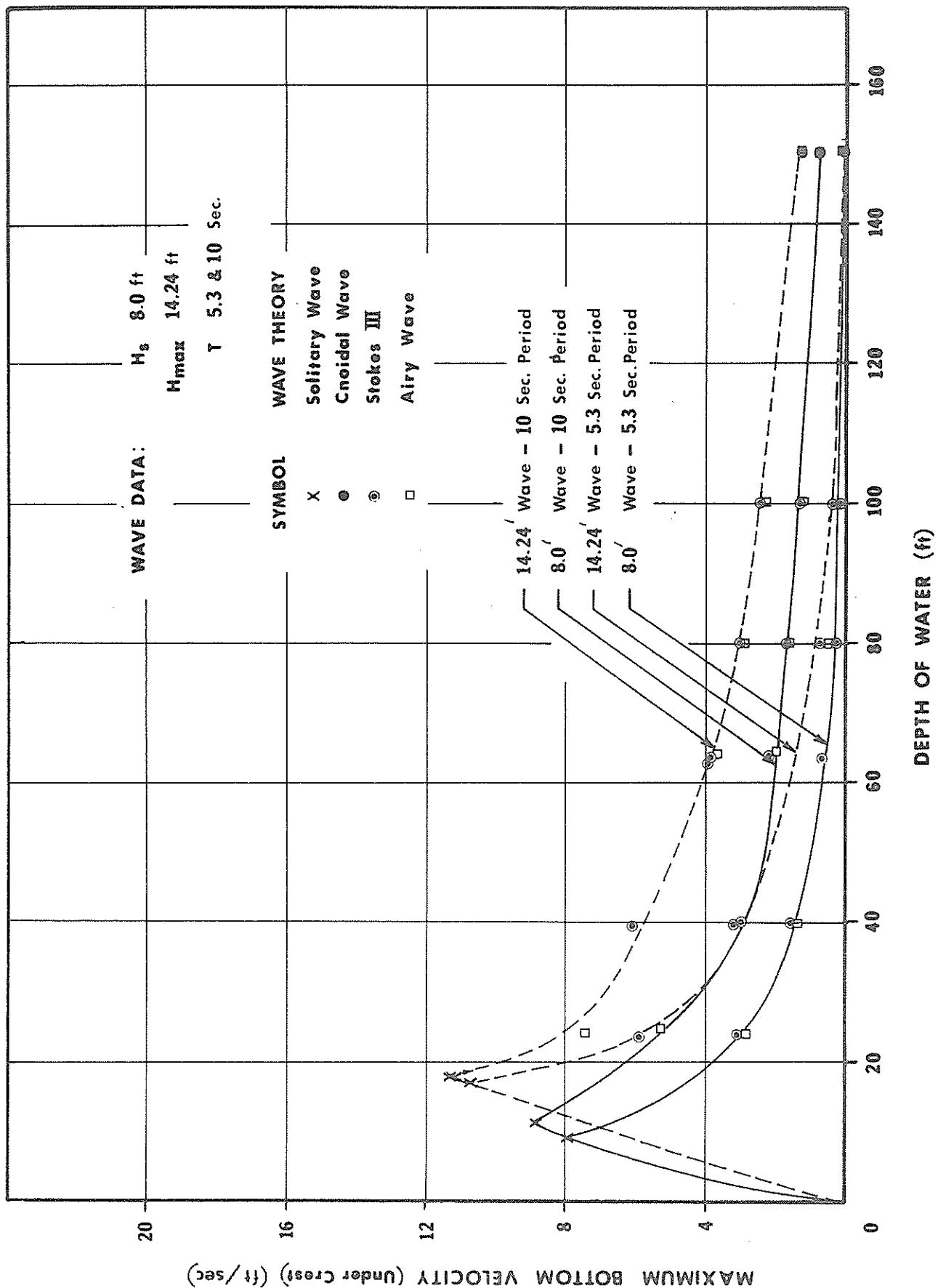


Figure 4. Maximum Bottom Velocities under Wave Crest

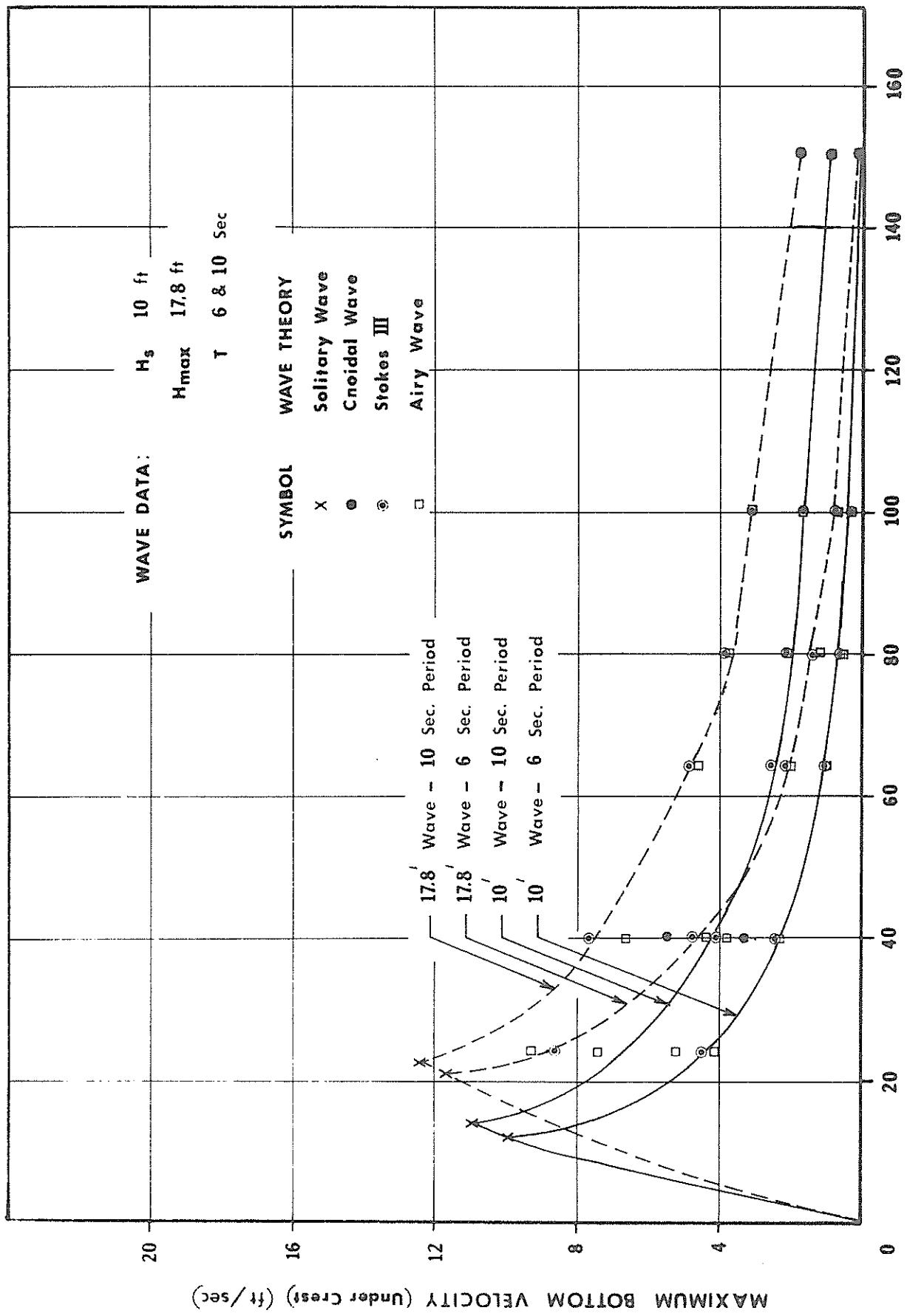


Figure 5. Maximum Bottom Velocities under Wave Crest

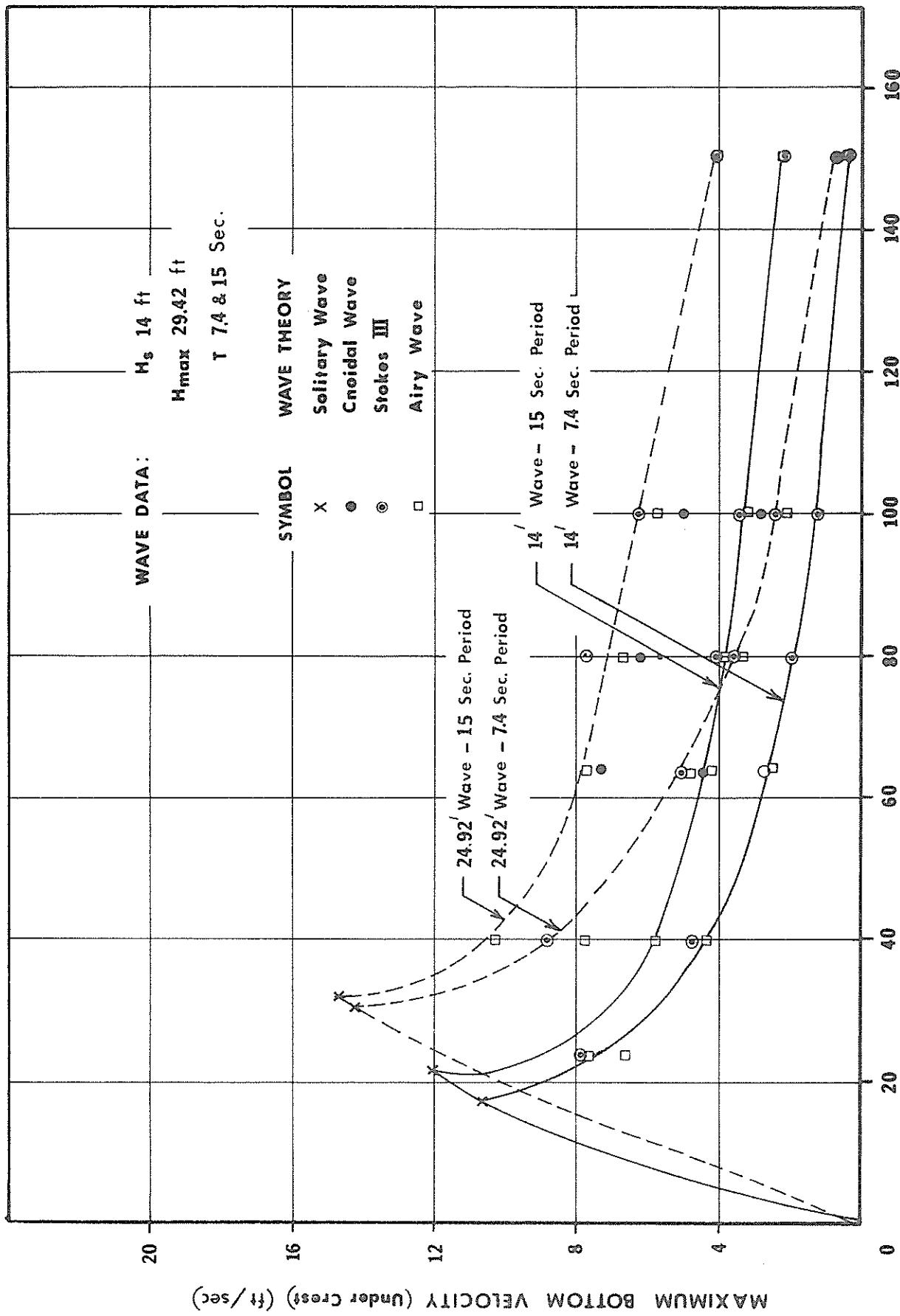


Figure 6. Maximum Bottom Velocities under Wave Crest

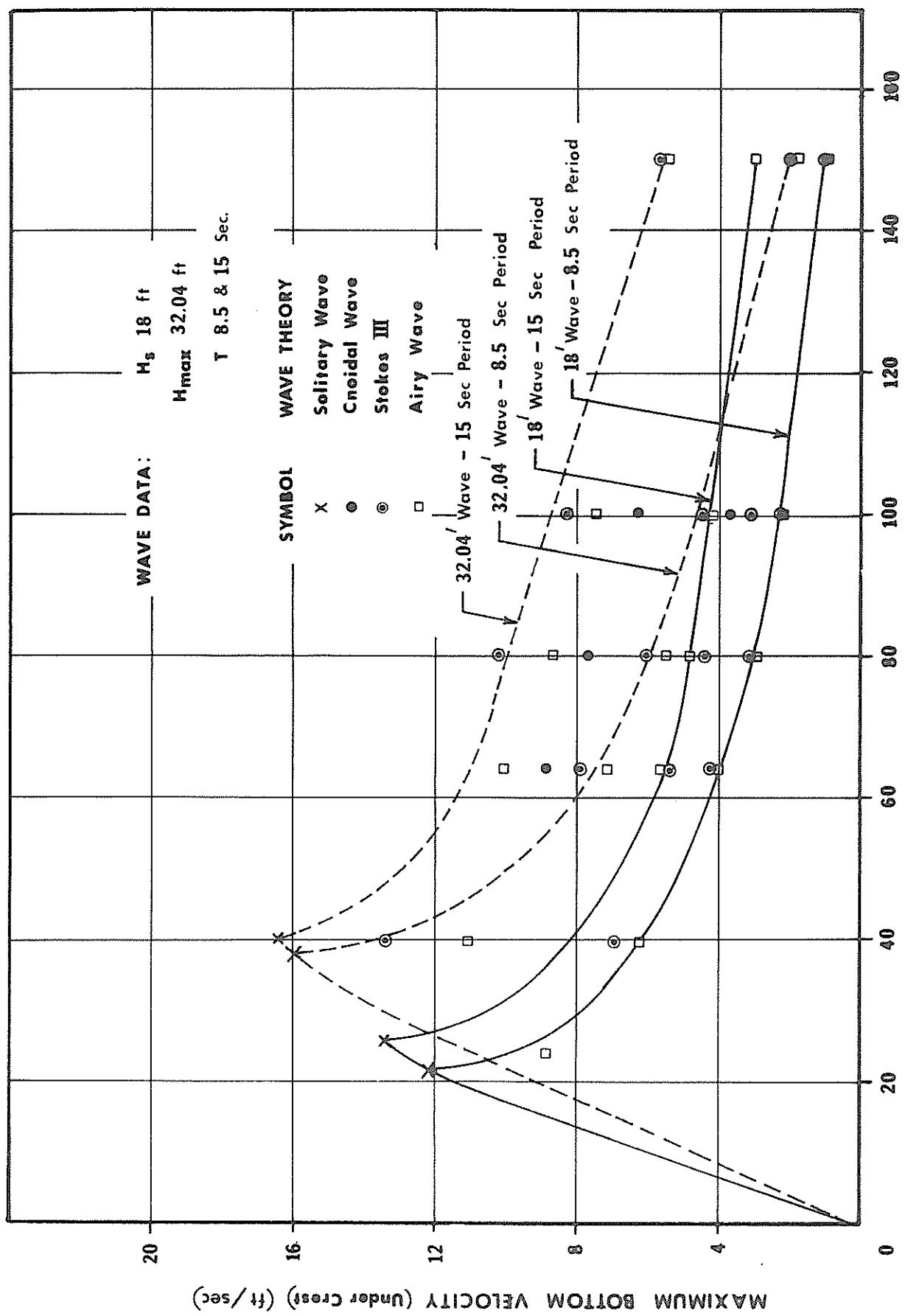


Figure 7. Maximum Bottom Velocities under Wave Crest

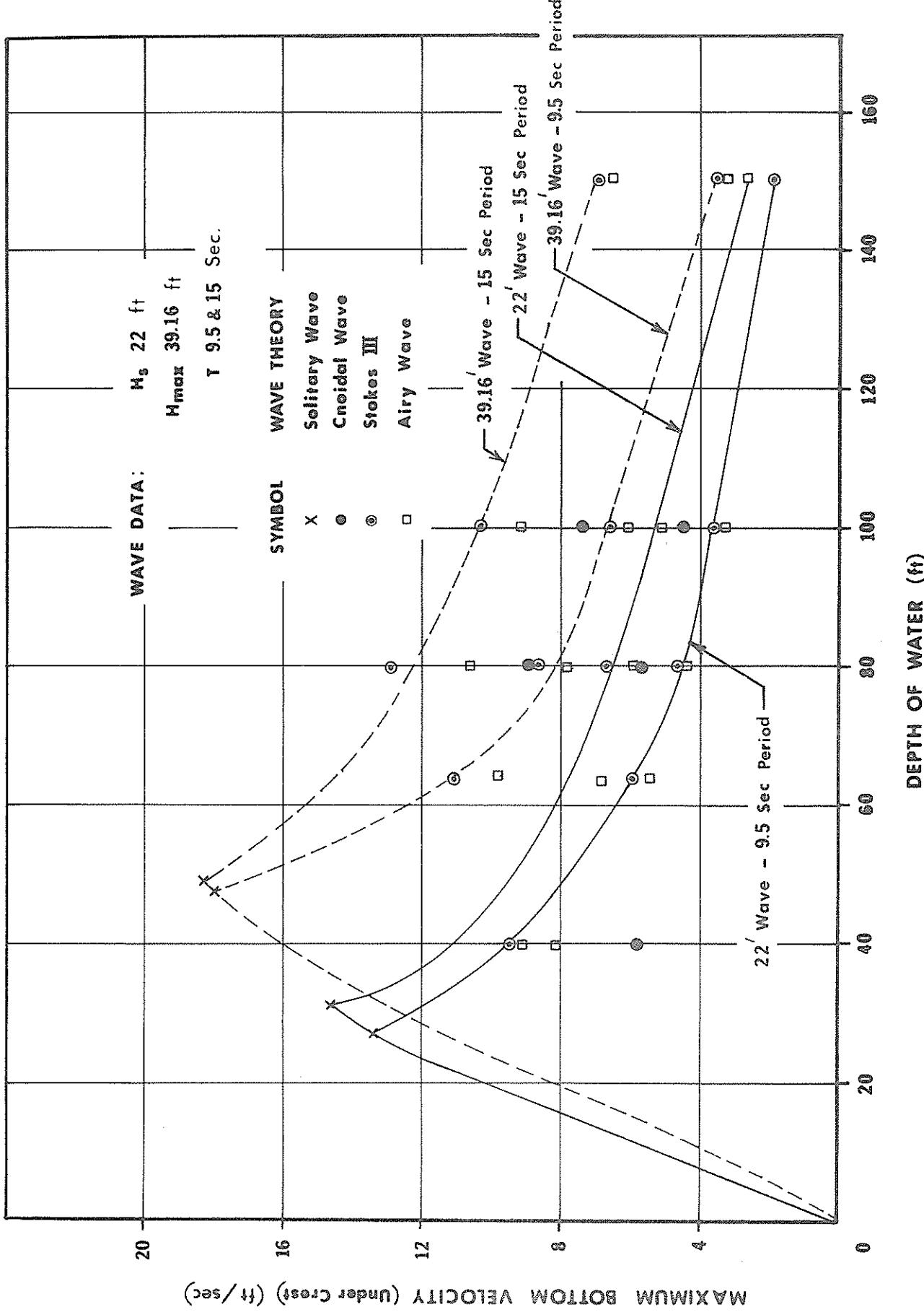


Figure 8. Maximum Bottom Velocities under Wave Crest

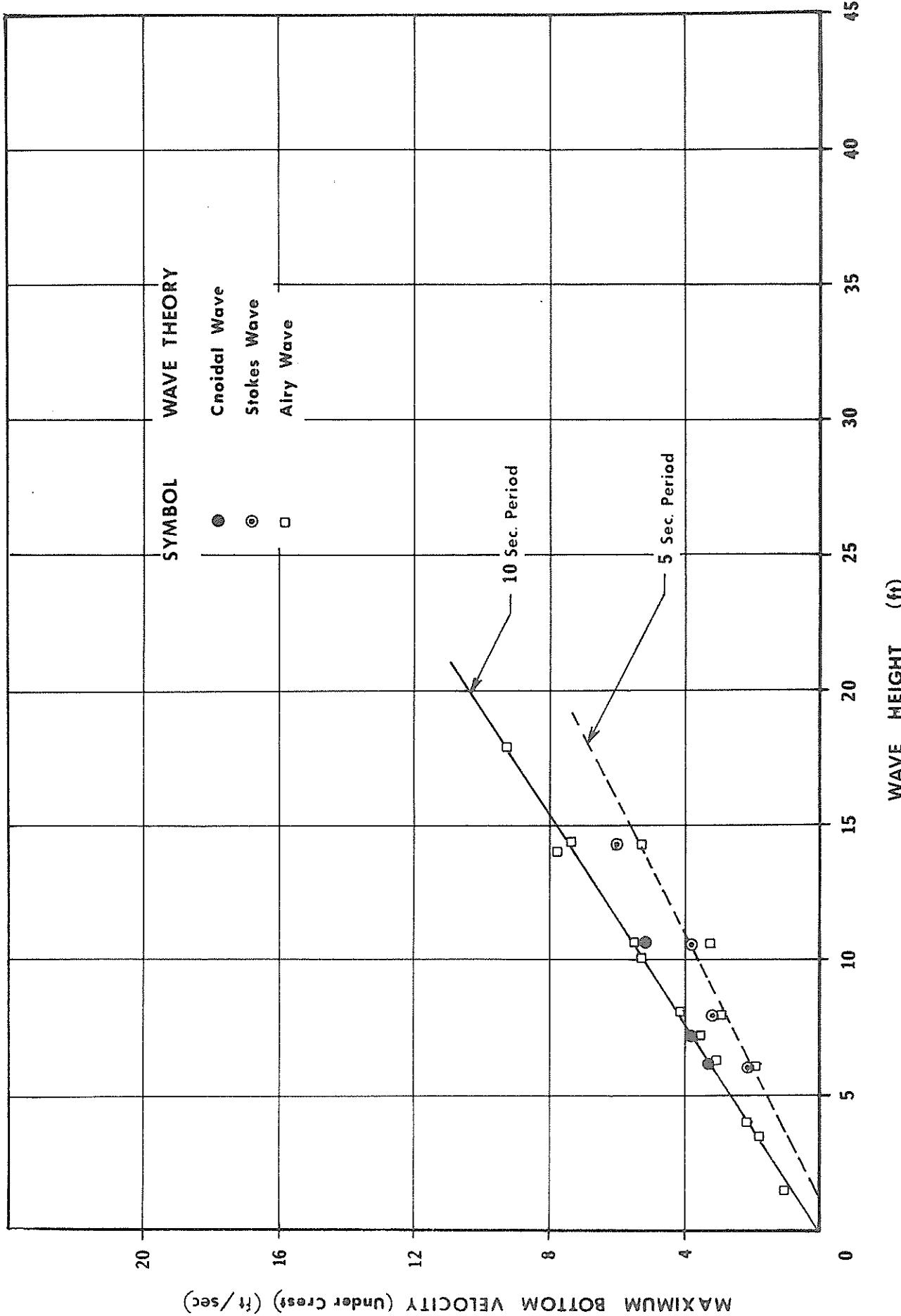


Figure 10. Maximum Bottom Velocities under Wave Crest
in 24 Feet Depth of Water

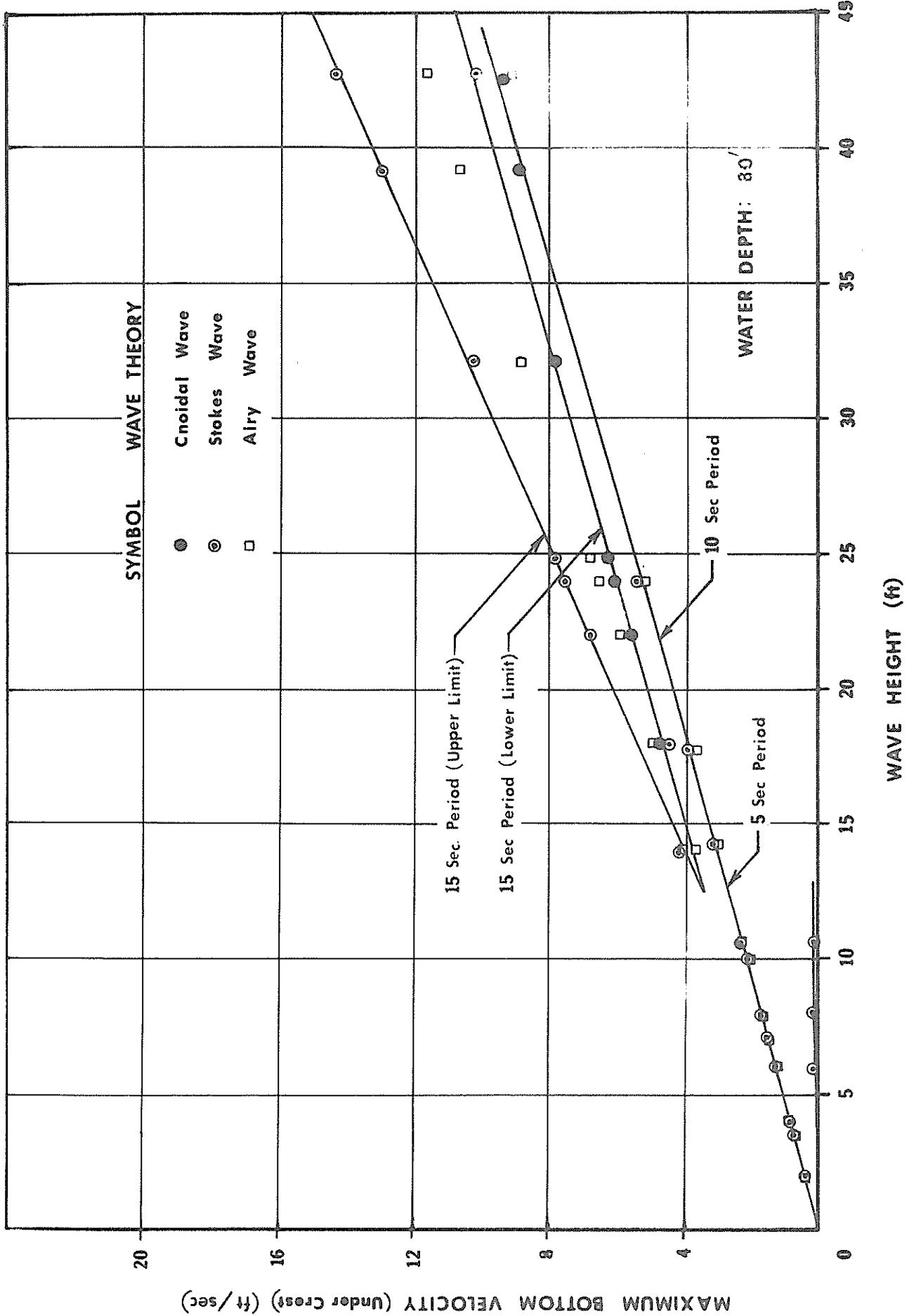


Figure 11. Maximum Bottom Velocities under Wave Crest
in 80 Feet Depth of Water

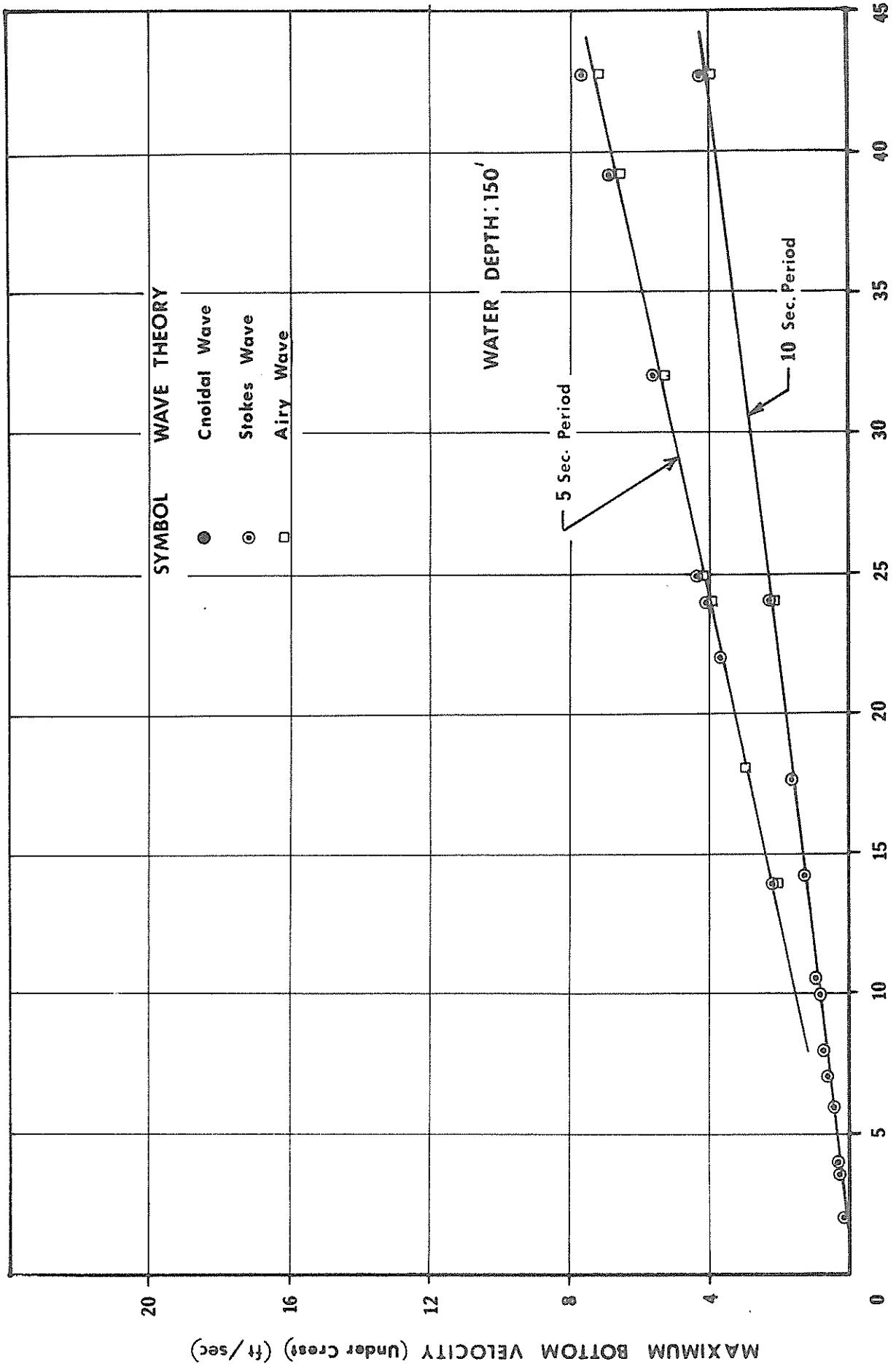


Figure 12. Maximum Bottom Velocities under Wave Crest
in 150 Feet Depth of Water

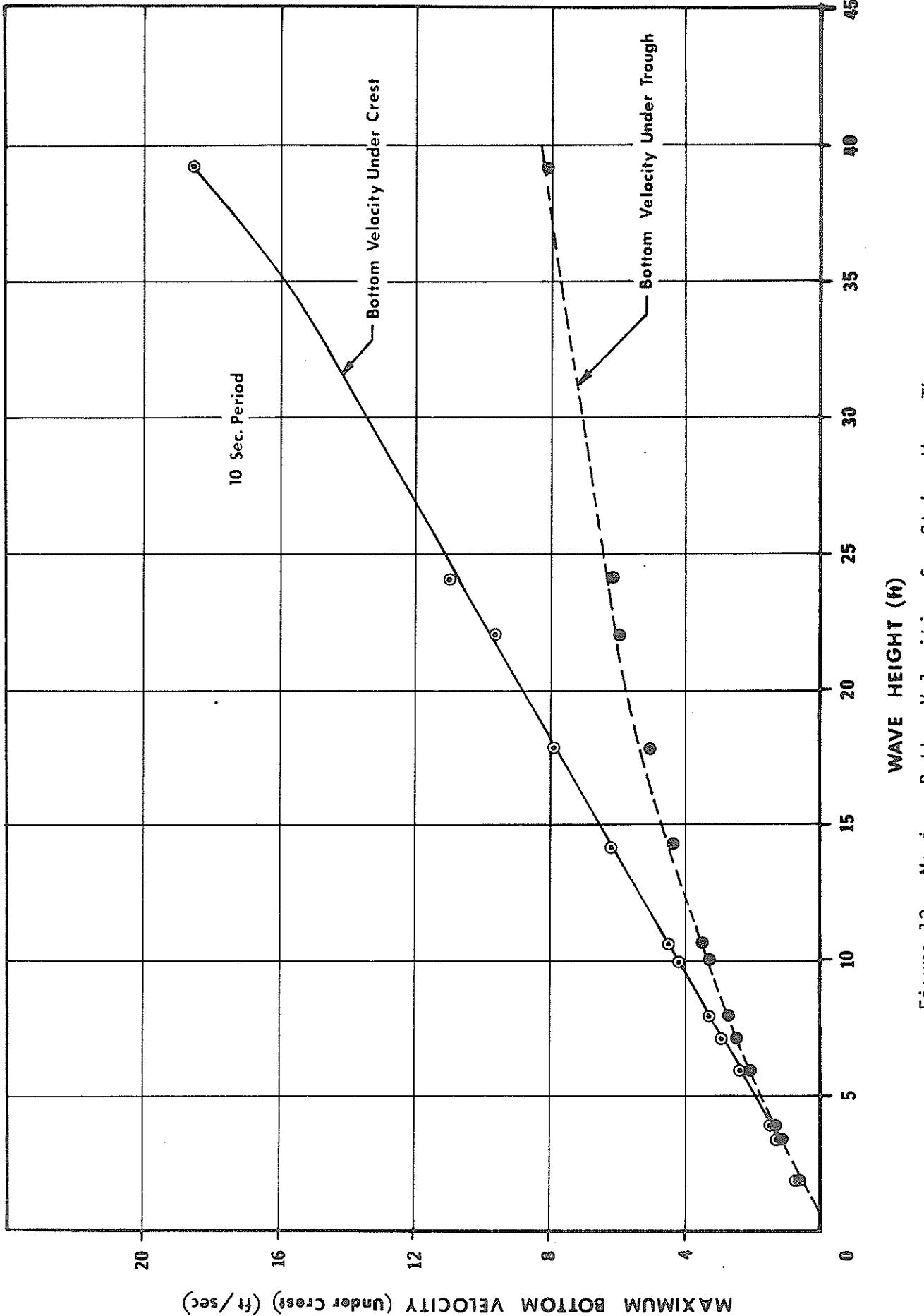


Figure 13. Maximum Bottom Velocities for Stokes Wave Theory
in 40 Feet Depth of Water

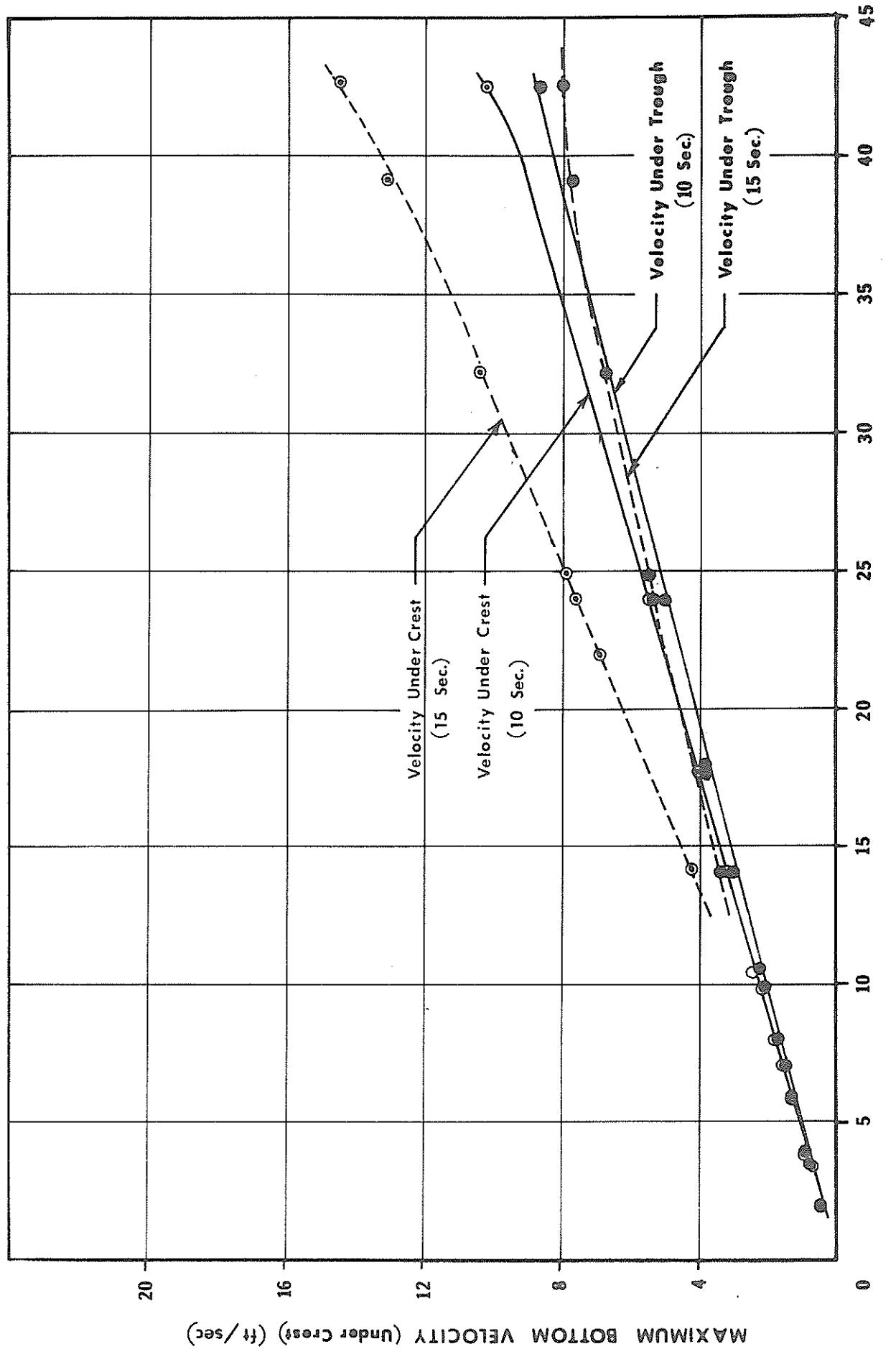


Figure 14. Maximum Bottom Velocities for Stokes Wave Theory
in 80 Feet Depth of Water