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RIPRAP DESIGN FOR TOWBOAT-INDUCED FORCES IN LOCK APPROACHES

by

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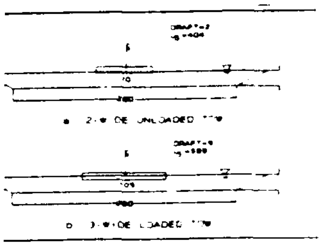

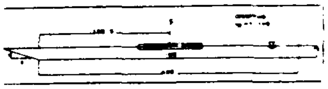

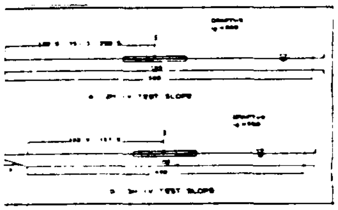

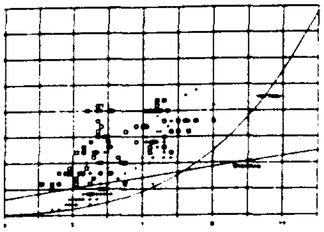

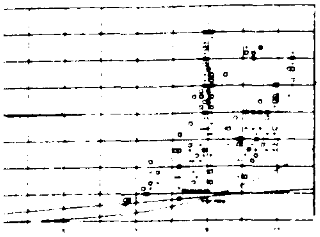

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13. ABSTRACT *(Maximum 200 words)*

Commercial towboats in navigable waterways, particularly in confined reaches, generate waves and currents which can be of significant magnitude such that stabilization of the banks with riprap is warranted. This paper focuses on stable riprap design for tows under way (here referring to those whose sailing line is parallel to the banks and whose speed is constant). Therefore, return current, wave characteristics, and channel geometry are the governing parameters for sizing the stone. Propeller jet impacts due to maneuvering tows are not addressed.

Most of the existing guidance on sizing the riprap on the banks for waves has been based on coastal waves. The riprap design guidance pertaining to waves produced by typical commercial towboats found on US waterways is limited.

Based on site-specific needs to address stone sizes due to towboat-induced forces, several studies have been conducted at the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi. The physical model

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studies include the Tennessee-Tombigbee Waterway, the Gallipolis Lock approach on the Ohio River, and some general navigation research regarding stone slope stability in confined waterways. Although these studies have been primarily devoted to the evaluation of specific stone sizes and gradations subjected to specific towboat operations, the study results lend themselves to use as general riprap design guidance. The underway tow studies have dealt with quantification of return currents and the magnitude and characteristics of secondary and transverse stern waves in lock approaches and confined channels.

While current research at WES is ultimately aimed at verification or modification of existing riprap design equations which incorporate tow-induced forces, the results to date have led to somewhat more qualitative conclusions regarding the stability of particular stone sizes subjected to tow-induced forces. This paper summarizes the physical model test conditions, makes recommendations for the stable rock size, compares these results to existing riprap design equations, and presents the limitations to which these recommendations are applicable.

PREFACE

This paper consolidates information obtained from several studies conducted to determine the stone slope protection needed for towboat-induced forces. The purpose of this paper is to document the data and results from these studies.

In addition to data collected for the Tennessee-Tombigbee Divide-Cut Section model study (Technical Report HL-86-3) and the Gallipolis lock approach study (Final data report dated September 1989), data were collected for the Navigation Hydraulics Research Work Unit 32601 funded by Headquarters, US Army Corps of Engineers, during FY90. This study was conducted by personnel of the Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station (WES), under the direction of Messrs. F.A. Herrmann, Jr., Director, HL; R.A. Sager, Assistant Director, HL; and G.A. Pickering, Chief, Hydraulic Structures Division (HSD), HL. The tests were conducted by Dr. Stephen T. Maynord, project engineer, Ms. Sandra K. Martin, and Messrs. Calvin Buie, James Cessna, and Van Stewart under the supervision of Mr. N. Randy Oswalt, Chief, Spillways and Channels Branch, and Mr. John F. George, Chief, Locks and Conduits Branch. The report was prepared by Ms. Martin, Locks and Conduits Branch, HSD.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

RIPRAP DESIGN FOR TOWBOAT-INDUCED FORCES IN LOCK APPROACHES

PART I: INTRODUCTION

1. Several site-specific studies and some general research have been conducted to address the effects of towboat-induced forces on bank stability. These studies have addressed, in particular, the problems associated with towboat traffic in shallow draft navigation channels. The studies conducted at the US Army Engineer Waterways Experiment Station (WES) in Vicksburg, Mississippi, to date have primarily been devoted to a rather narrow spectrum of specific stone gradations and towboat operating conditions. Due to the current interest in the design of riprap to protect banks from towboat currents, the intent of this paper is to provide the results of the research thus far.

2. The research analyzed the effects of two basic types of towboat operating conditions: tows maneuvering in and out of locks, and tows traveling at a constant speed and distance from the bank. The latter operating conditions are referred to as "underway tests." The former, "maneuvering tests," are rather complicated and require a more detailed description of the towboat's characteristics. The forces produced by the tow for these types of tests are a function of the tow's horsepower, propeller type, hull shape, and thrust as well as a function of the layout of the maneuver (the angle to the bank, the depth of the pool, the distance from the bank, and the angle of the slope). Due to the potential of extreme variability from location to location of towboat types and sizes as well as the site-specific geometry related to each maneuvering operation, the results of these tests are less applicable in a general sense than those obtained from the underway tests. Therefore, only the results from the underway tests are presented.

PART II: THE TESTING PROGRAM

3. Underway test conditions were used to represent normal navigation operations and assess the stability of stone slope protection in a confined channel for tows traveling at various speeds, drafts, and distances from the bank. The primary objective of these tests was to identify the most severe operational conditions in which a specific gradation of riprap remained stable. Secondarily, a relationship was sought to link these operations (sailing speed and blockage ratio) to their effects (the return current and/or waves).

4. The data presented in this paper were taken from three model studies, the Tennessee-Tombigbee Waterway (Maynord and Oswalt 1986), the Gallipolis Lock approach,* and Navigation Research work unit sponsored by Headquarters, US Army Corps of Engineers. The testing program covered a range of conditions. All tests were conducted under quiescent pool conditions, such that all flow disturbances were those created by the movement of the tow. Two different model scales were used, 1:20 and 1:25. Pool depths varied from 14 to 22 ft.** The sailing line was parallel to the bank, and the distance from the toe of the slope to the barge's edge ranged from 0 to 105 ft. The cross sections used in each test series and other pertinent geometric data are shown in Figures 1-3 for the Tennessee-Tombigbee, the Gallipolis, and the navigation research studies, respectively. Towboat sailing speeds varied from 3.7 to 11.3 mph. Two different bank slopes were tested, 3H:1V and 2H:1V. Jumbo barges with dimensions of 195 ft long by 35 ft wide were used in the testing. The barge configurations were two barge widths and three barge widths and one to five barge lengths. In some tests, the lead barges had raked bows, in others square bows. Eight different gradations of riprap were tested. Tables 1-3 contain the gradations tested in each of the three studies. A nonporous slope condition was modeled such that no seepage could occur. The model riprap was placed on filter fabric.

5. Each series of tests was repeated as few as 50 times and generally

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* Sandra K. Martin. 1989 (28 Aug). "Gallipolis Locks and Dam, Hydraulic Model Investigation to Determine Stone Slope Protection Requirements," Memorandum for Record, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

** A table of factors for converting US customary units of measurement to metric (SI) is presented on page 3.

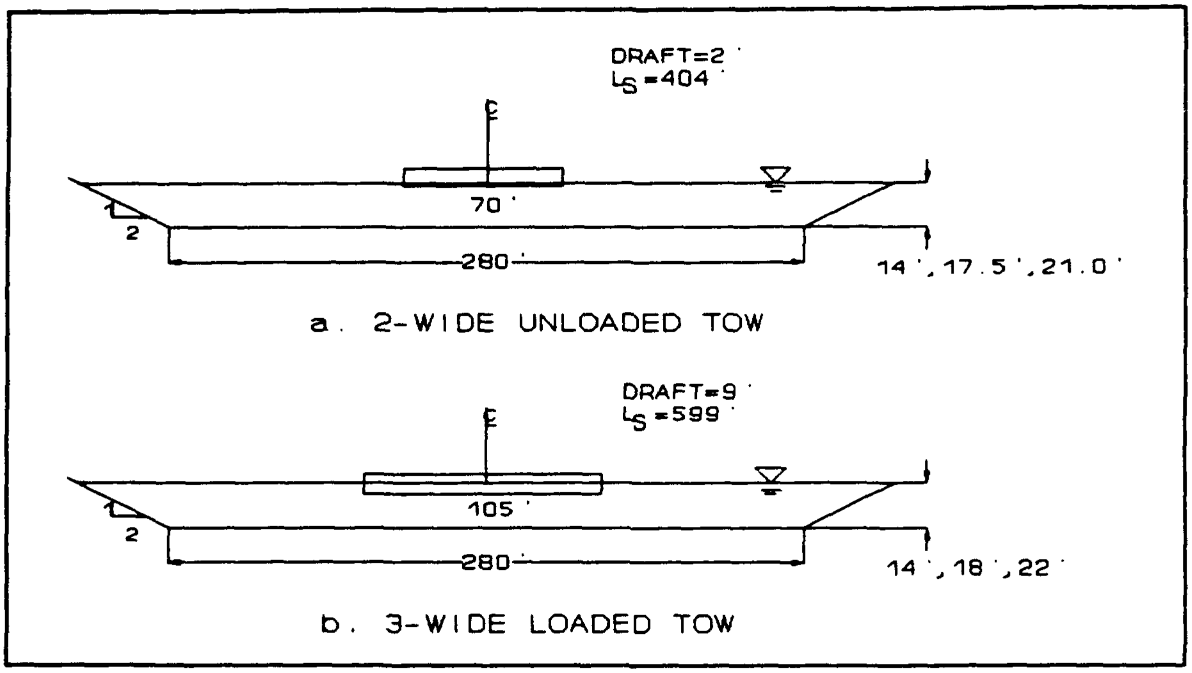


Figure 1. Tennessee-Tombigbee study

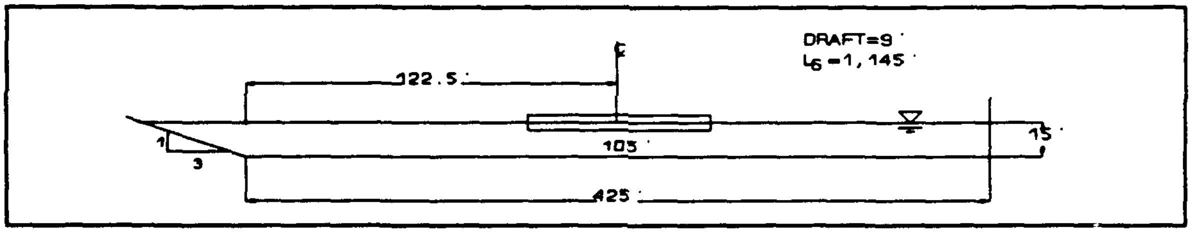
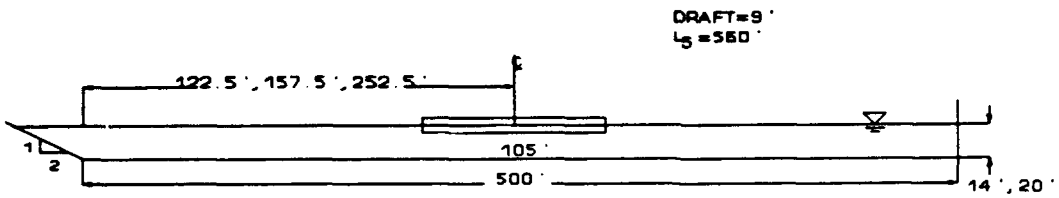
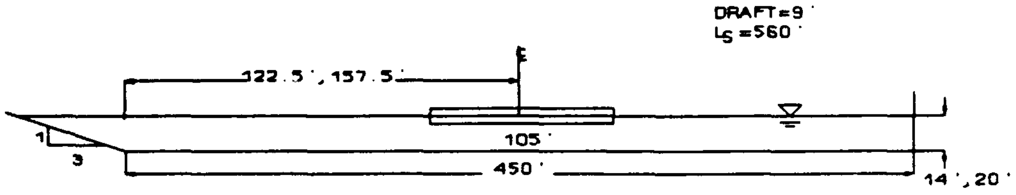


Figure 2. Gallipolis study

100 times. Table 4 summarizes the test conditions for these studies. In this table, D_{50} and W_{50} refer to the equivalent spherical diameter (inches) and weight (pounds) of the riprap for which 50 percent is lighter by weight. The column entitled "Depth" is the undisturbed depth of water in the channel in feet. The column entitled "Distance" is defined as the distance from the center line of the barge train to the toe of the slope in feet. The average velocity of the tow "Speed" is given in miles per hour. Under the column for stability, F stands for failed, S for stable, and M for marginal. Failure, also called incipient failure, is defined as the condition in which the filter cloth is exposed (Maynord, Ruff, and Abt 1989). The category "stable" indicates that while some individual stones may have overturned or moved, the general thickness of the riprap was not affected. The category "marginal" was



a. 2H:1V TEST SLOPE



b. 3H:1V TEST SLOPE

Figure 3. Navigation Research study

not added until the tests for the research work unit were conducted. During these tests relatively small and previously untested stone sizes were used, and although the filter fabric was not exposed, the riprap thickness showed signs of thinning in the zone of wave action. A safety factor will be added back into the stone size for stable design conditions.

6. For each series of tests the blockage ratio N was calculated such that:

$$N = \frac{\text{Cross-sectional area of the channel}}{\text{Cross-sectional area of the submerged tow}} \tag{1}$$

The areas were calculated for the entire section. The sailing line is the distance from the center line of the tow to the waterline of the test embankment. Table 5 summarizes the blockage ratios and sailing lines for each test series.

PART III: RIPRAP DESIGN METHODS

Existing Guidance

7. The design of stone protection on banks for tows under way is either dependent upon the magnitude of secondary waves, the transverse stern wave (related to the drawdown), or the intensity of the return currents produced by the moving vessel. While equations sizing riprap protection can be based on shear stress, they are typically based on either a design wave height or current velocity. Therefore, existing methods which employ wave height or velocities will be discussed.

Wave-height-based equations

8. Previous recommendations for stone slope protection from waves have been based on various versions of the following general equations which relate wave height to stone size (Hudson 1958):

$$W_{50} = K_1 \frac{\gamma_R H^3}{\left(\frac{\gamma_R}{\gamma_W} - 1\right)^3} \tag{2}$$

where

W_{50} = weight of rock in which 50 percent is lighter by weight

K_1 = coefficient

γ_R = specific weight of the rock

H = wave height

γ_w = specific weight of the water

Assuming spherical stones, the nominal diameter D_{50} is related to the stone weight as follows:

$$D_{50} = \left(\frac{6W_{50}}{\pi\gamma_R}\right)^{1/3} \tag{3}$$

Combining Equations 2 and 3:

$$D_{50} = K_2 \frac{H}{\left(\frac{\gamma_R}{\gamma_W} - 1\right)} \tag{4}$$

9. The various stone slope equations result in a wide variation in stone sizes. The coefficients K_1 and K_2 are functions of various parameters depending upon the data for which they were developed. Some of the parameters for which these coefficients were derived include bank slope, vessel speed, wave length, angle of incidence to the bank, waves rushing up the slope, waves rushing down the slope, type of wave (i.e., plunging or surging), frequency of waves, etc.

10. The use of these equations is predicated on knowing the design wave height. This means that either a historical record exists which reflects an upper limit for the design wave or a predictive equation must be used to determine the wave height. Predictive equations have been developed for determining the drawdown (or the transverse stern wave) and the height of the secondary waves produced by the vessel. The equations produce a wide range of results depending upon the assumptions and parameters used to develop the equations.

11. Several wave equations taken from the literature are plotted with the Tennessee-Tombigbee model data in Figures 4-11 (modified from Maynord and Oswalt 1986). Two wave types were considered, secondary waves and the height of the transverse stern wave (drawdown). The data from the Tennessee-Tombigbee study include both the maximum wave height and the average drawdown.

12. For Figures 4 and 5, secondary wave height relationships are represented with data separated by loaded and empty barges. Secondary wave equations used in these comparisons were developed as a function of the draft of the boat. As a comparison of how the data fit, an equation developed by Bhowmik, Demissie, and Guo (1982) and an equation by Verhey and Bogaerts (1989) were overplotted with the data. In both equations the wave height is presented as a function of the vessel draft. The equation developed by Bhowmik, Demissu, and Guo (1982) relating boat speed to secondary wave height is linear and of the following form:

$$H = 0.133 d F_d \tag{5}$$

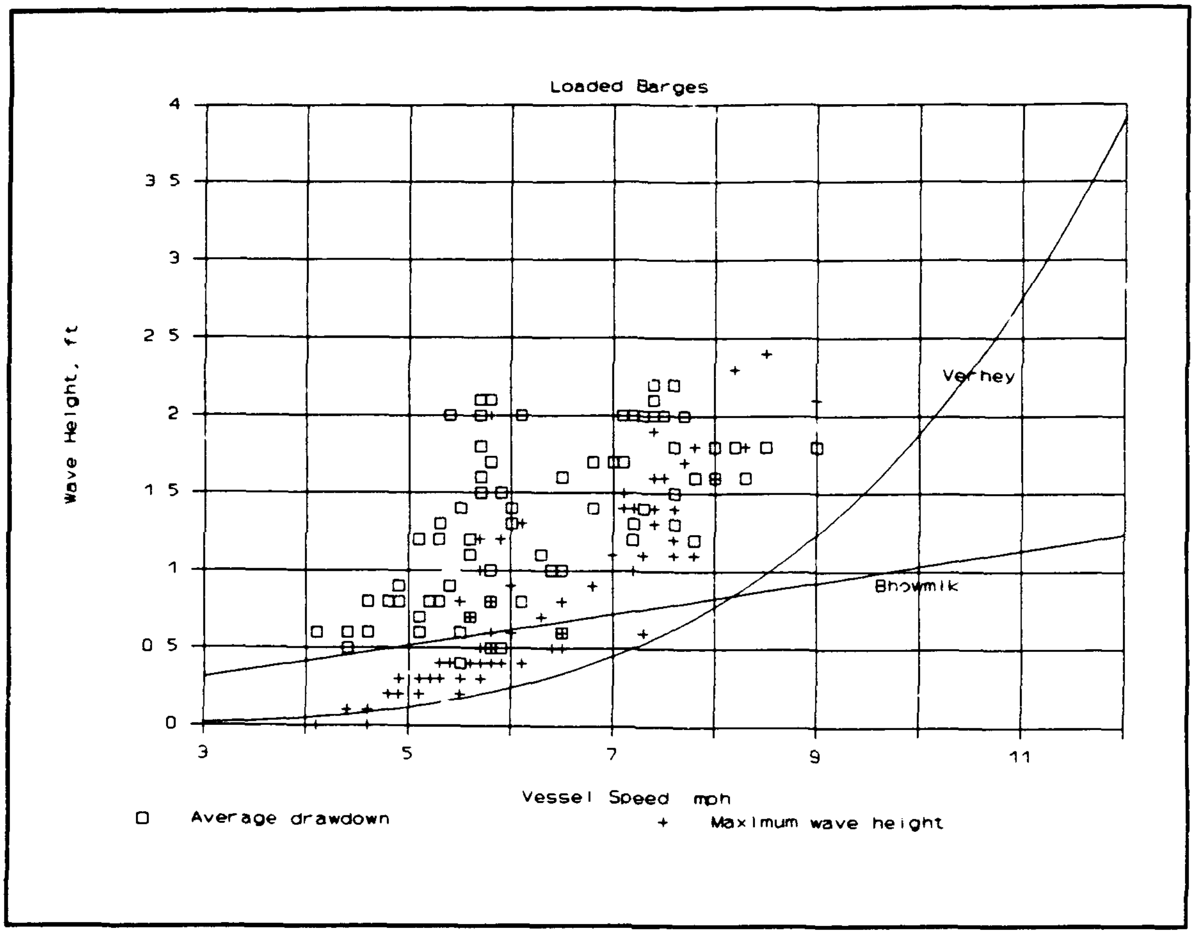


Figure 4. Secondary wave height relationships for loaded barges

where:

d = draft of the towboat

$$F_d = \frac{V_s}{\sqrt{gd}}$$

V_s = speed of vessel

g = acceleration due to gravity

The equation presented by Verhey and Bogaerts (1989) relates the wave height to the sailing line, the vessel Froude number (here presented as a function of water depth), and a coefficient α_1 based on empty or loaded vessels. The values given in their paper for α_1 are 0.35 for empty conventional vessels, 0.5 for empty barges, and 1.0 for loaded conventional vessels. No value was given for loaded barges; therefore, the value was assumed to be proportional

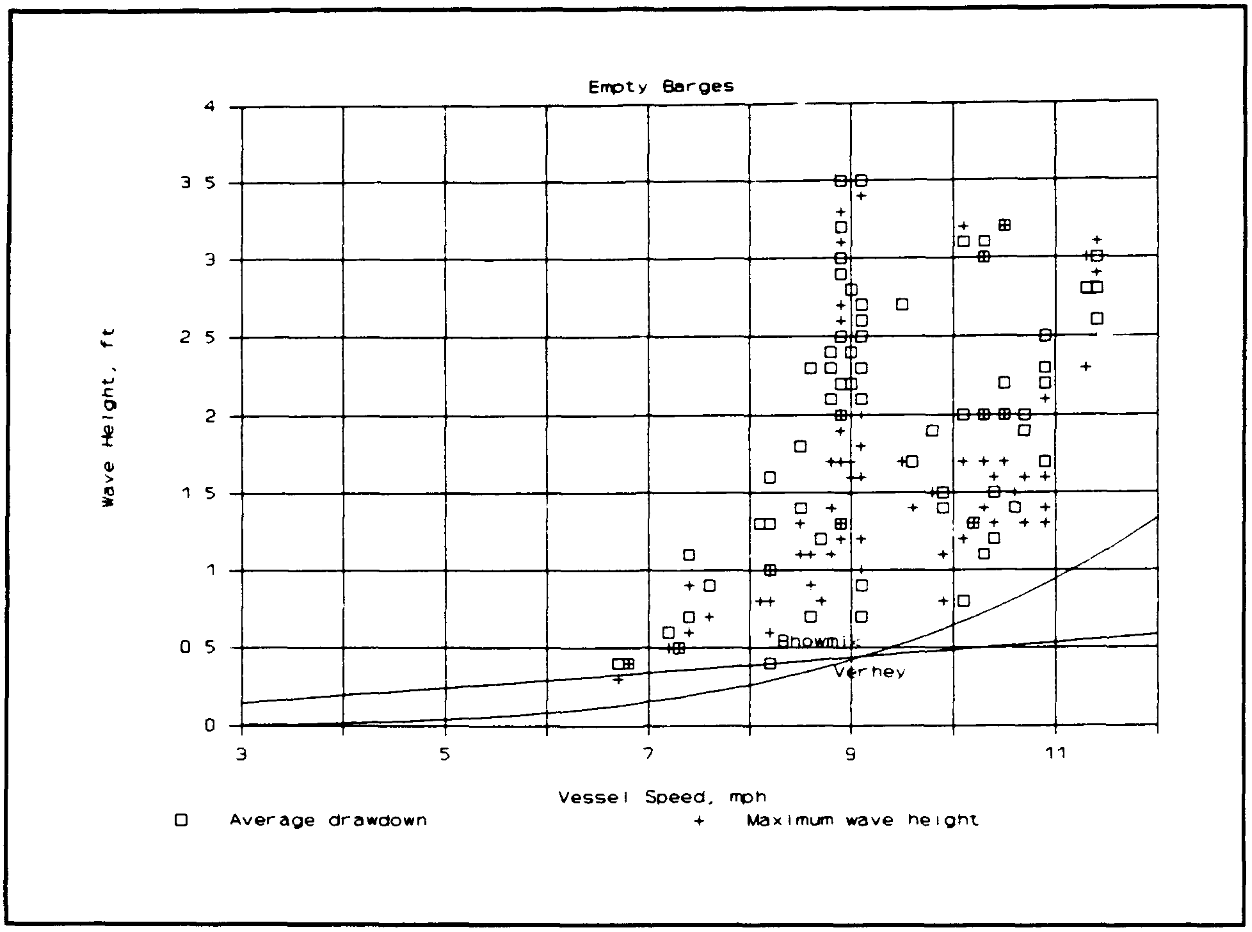


Figure 5. Secondary wave height relationships for empty barges

to the ratio of the loaded to unloaded conventional vessels, or 1.43. Verhey and Bogaerts used a value of 4.0 for the coefficient α_3. The equation given for estimating wave height is:

$$H = \alpha_1 h \left(\frac{S}{h}\right)^{-0.33} F_h^{\alpha_3} \qquad (6)$$

where:

h = water depth

S = distance between ship's side and bank

$$F_h = \frac{V_s}{\sqrt{gh}}$$

As can be seen in Figures 4 and 5, at lower vessel speeds the data points come closer to the empirical equations. As these speeds approach the limiting

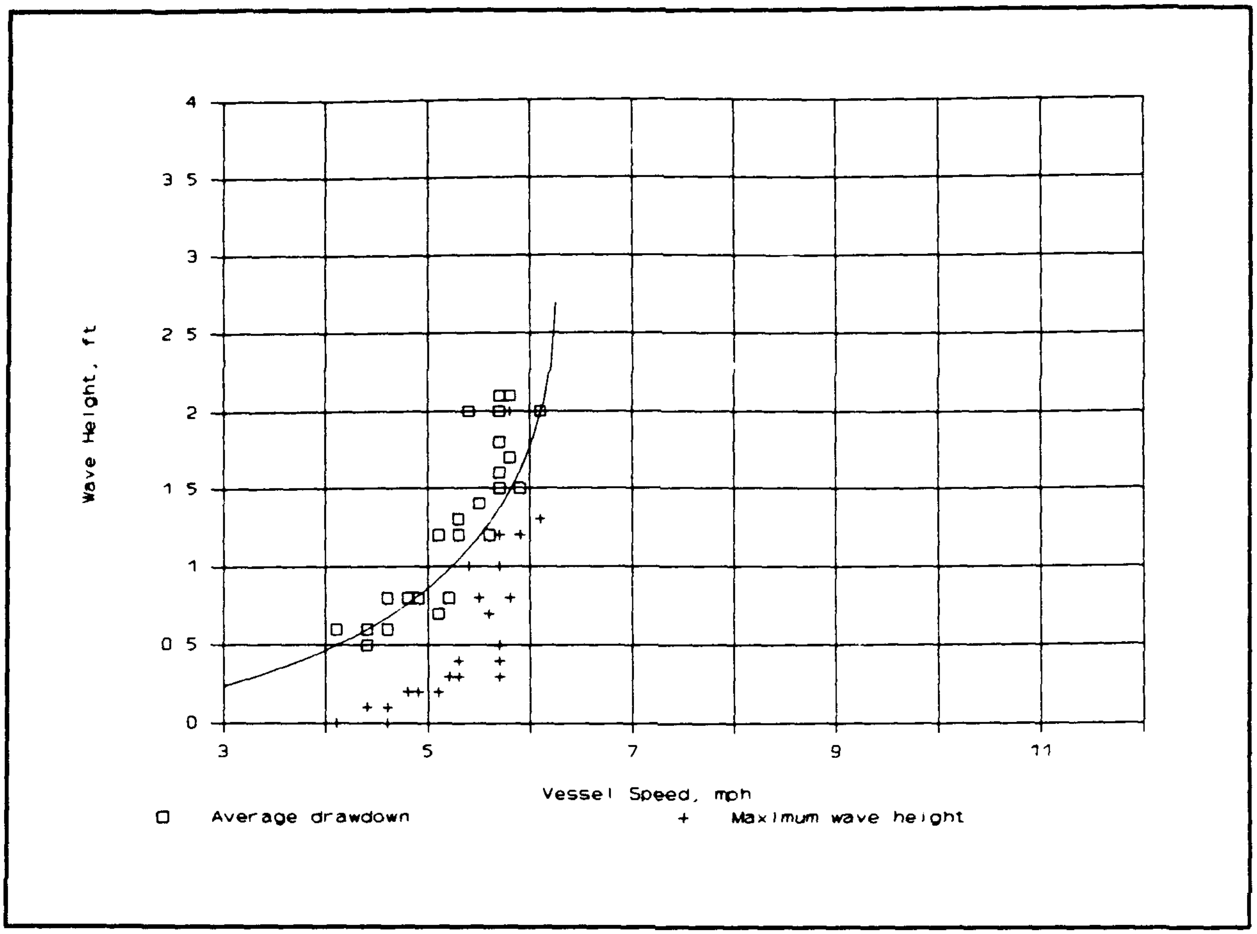


Figure 6. Wave height relationships for N = 4.6

speeds and as the blockage ratios decrease, the equations fall further and further from the data points. It is important to state that these equations and the coefficients in them were developed for specific data sets.

13. In the second set of graphs (Figures 6-11), each graph represents data taken for a specific blockage ratio and is plotted with the Jansen and Schijf (1953) relationship for drawdown which uses the conservation of energy approach. Equations for drawdown appear to better reflect the model conditions as the vessel speed approaches the limiting speed. The same data from the Tennessee-Tombigbee Study are used in these plots. The theoretical equations are presented in the discussion of return currents. Bouwmeester et al. (1977) also developed equations for drawdown and return currents, but based his approach on conservation of momentum. Since these equations are a function of the blockage ratio, each figure represents the data and curve corresponding to a specific blockage ratio.

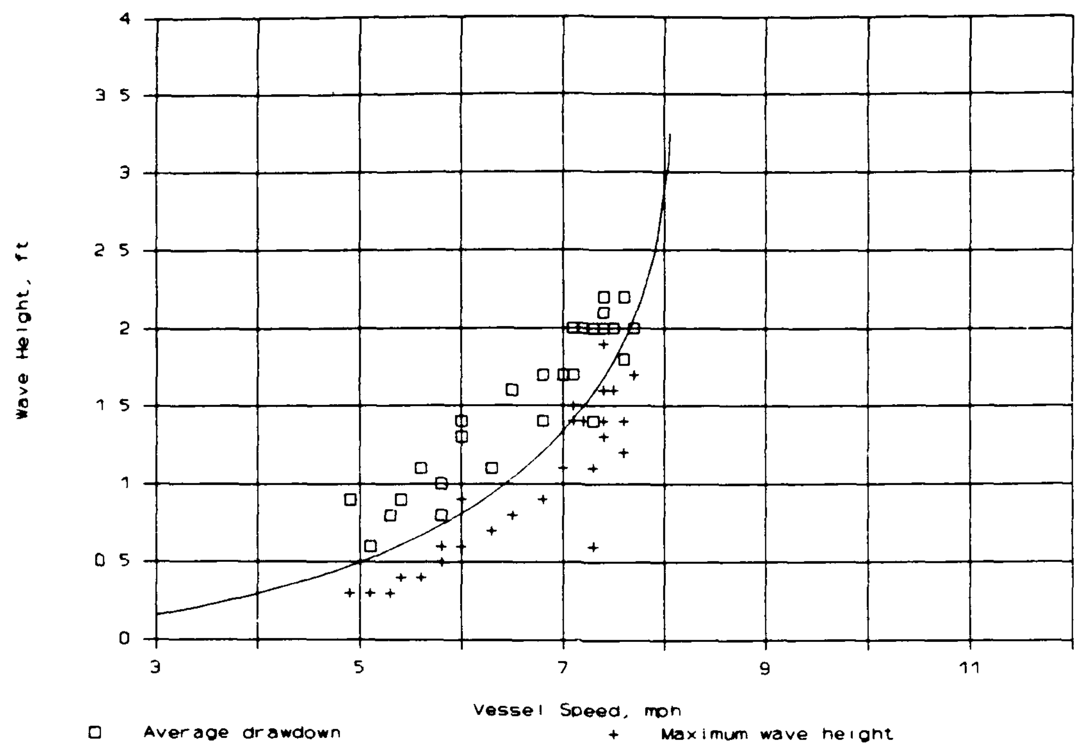


Figure 7. Wave height relationships for N = 6.0

14. Two points can be concluded from this comparison of existing equations and the Tennessee-Tombigbee data. First, many researchers have developed predictive equations for wave height as a function of vessel speed, only a few of which have been presented here. These equations do not necessarily apply to the conditions which may prevail on US inland waterways. More research is needed to modify these equations for broader conditions. Secondly, regardless of the method chosen to obtain the wave height, for the design of the stone slope protection it is important to select the greater of the two waves, transverse or secondary.

Velocity-based equations

15. Just as the design stone size equations, above, were based on the assumption that the wave height was known, the current velocities near the slope produced by the moving tow must also be known to use velocity-based riprap design equations. Much research has been conducted to determine the

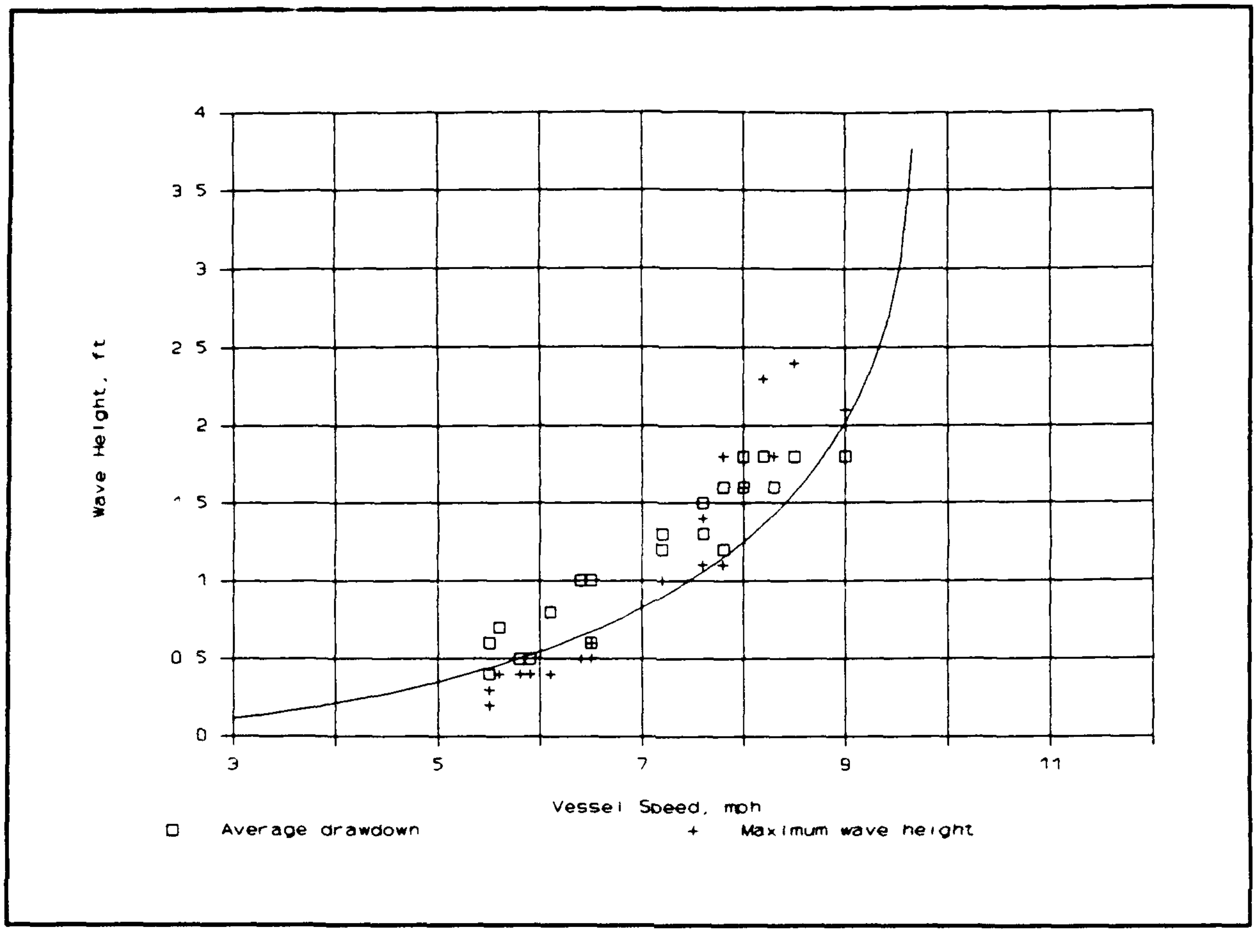


Figure 8. Wave height relationships for N = 7.5

current velocities produced by a towboat. Even though propeller jet velocities can be a critical consideration in the design of riprap, especially for maneuvering tows, return currents in confined channels for tows under way dominate the velocity-induced forces.

16. Modified versions of Jansen and Schijf's original equations (1953) relating return current to towboat speed and blockage are fair estimates of the magnitude of the return currents. Their method is based on the energy approach and can be solved graphically or by trial and error. Based on continuity

$$V_s A_c = (V_r + V_s) A_w \tag{7}$$

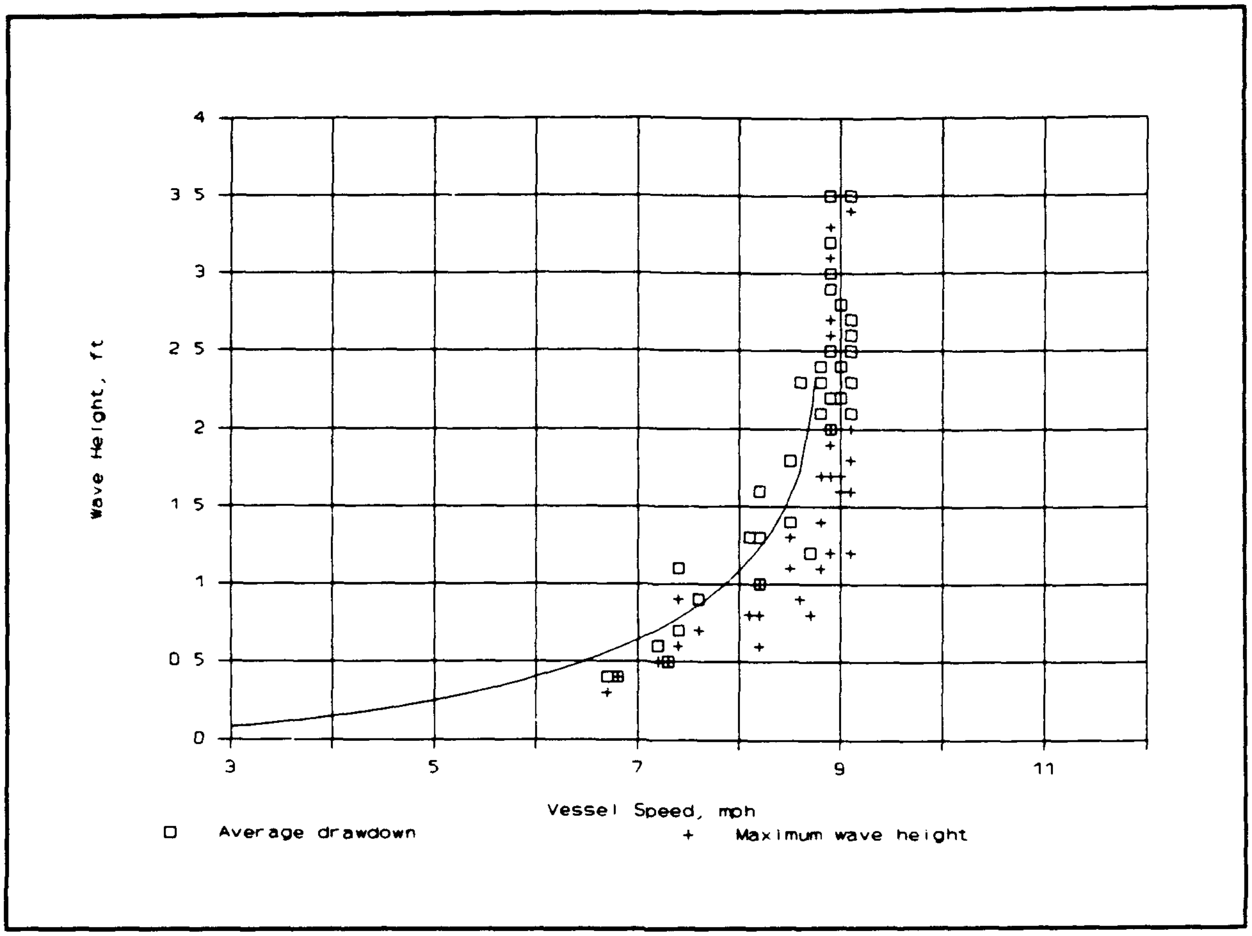


Figure 9. Wave height relationships for N = 10.5

where:

A_c = channel cross-sectional area before drawdown

V_r = return current

A_w = channel cross-sectional area at mid-section of barges

Conservation of energy results in

$$z = \frac{V_s^2}{2g}\left[\left(\frac{A_c}{A_w}\right)^2 - 1\right] \tag{8}$$

These two equations relate drawdown z to return current and vessel speed. Several studies present modifications to the above equations. In one such study, conducted by Maynord and Siemsen (1991), a method is presented for

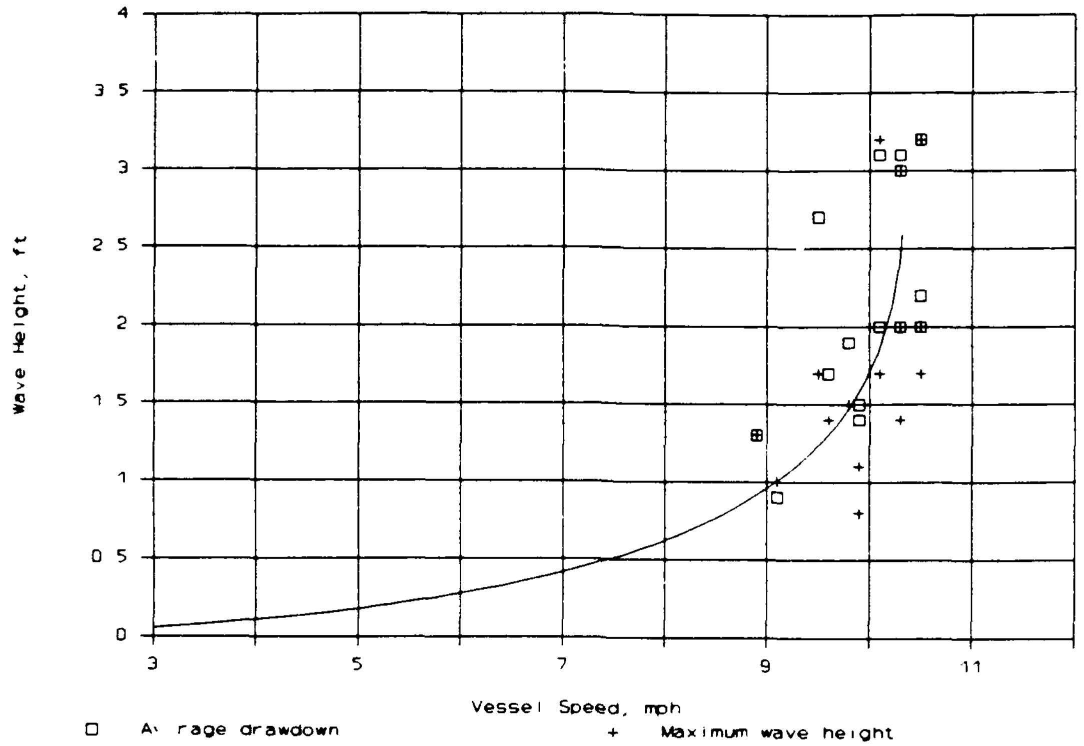


Figure 10. Wave height relationships for N = 13.4

distributing the return current in the channel. (See also Maynord 1990.)

17. A more essential problem than determining the magnitude of the current is characterizing the velocity profile produced by the moving towboat. Since the boundary layer does not fully develop during the passage of the tow, the resulting velocity profile is affected. Adaptation of the riprap design equations to the condition of the undeveloped boundary layer is needed. Tests should be conducted to determine the critical design velocity.

18. Most of the velocity-based equations, such as the one presented by Maynord, Ruff, and Abt (1989), assume a representative velocity over the slope for a fully developed profile. Maynord's equation for the design of riprap was based on the D_{30} stone size (30 percent finer by weight) and is as follows:

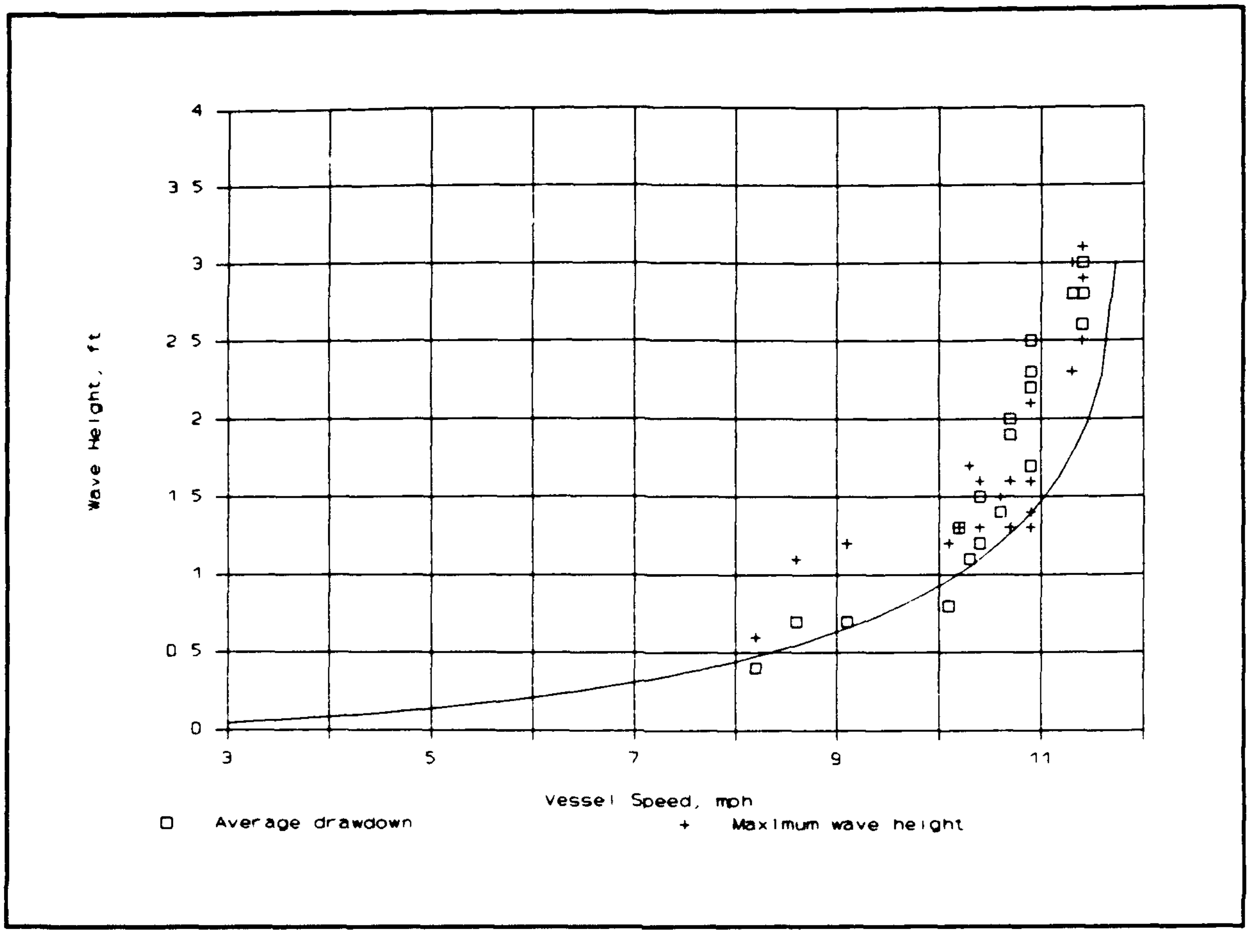


Figure 11. Wave height relationships for N = 16.4

$$D_{30} = SF * 0.3h \left[\left(\frac{\gamma_w}{\gamma_R - \gamma_w} \right)^{0.5} \frac{V}{\sqrt{gh}} \right]^{2.5} \tag{9}$$

where SF is the safety factor. The velocity V in this equation refers to the "local" average velocity, i.e., the depth-averaged velocity above the slope. In his paper, Maynord suggested an SF of 1.2 to be used since this value separated stable prototype sites from failed prototype sites. Correction factors are also applied to the equation based on the unit weight of the stone and the side slopes.

19. The velocity profile for return velocity has an undeveloped boundary, and the Isbash (1935) equation should be used for sizing riprap for return velocity protection. The Isbash equation is

$$C_3 = \frac{V}{\left[g \left(\frac{\gamma_w}{\gamma_R - \gamma_w} \right) D_{50} \right]^{0.5}} \qquad (10)$$

where

C_3 = 1.2 for return velocity Blaau et al. (1984)

V = maximum return velocity

D_{50} = the rock size of which 50 percent is lighter by weight

Also shown in Blaauw et al. is a method relating return velocity to shear stress which can be used in sediment transport functions.

Proposed Guidance

20. Ideally, to design riprap in navigation channels due to underway tows, the maximum secondary wave, the transverse stern wave (or average drawdown), and the return current near the bank should be determined. Then, using an appropriate equation as presented in this section, the stone size should be determined for each condition and the largest (most conservative) stone should be selected (Permanent International Association of Navigation Congresses (PIANC) 1987). However, the variability of the design coefficients in the wave-based equations makes these equations difficult to apply to inland vessels in US waterways. And, as indicated in the previous discussion of the undeveloped velocity profile produced by the moving tow, there is a degree of uncertainty in the appropriateness of the velocity-based equations. Therefore, this research has, and is, attempting to address these discrepancies in order that this type of approach can be used. However, in the interim, testing to date has revealed some specific stone sizes which exhibit stability under typical operating conditions and channel configurations for towboats in US waterways.

21. Preliminary guidance resulting from the testing program is based on what actually worked. The test data plotted in Figures 12 and 13 relate towboat speed to the average stone size for 2H:1V and 3H:1V slopes, respectively. Minimum values for stable stone sizes were established based on a threshold

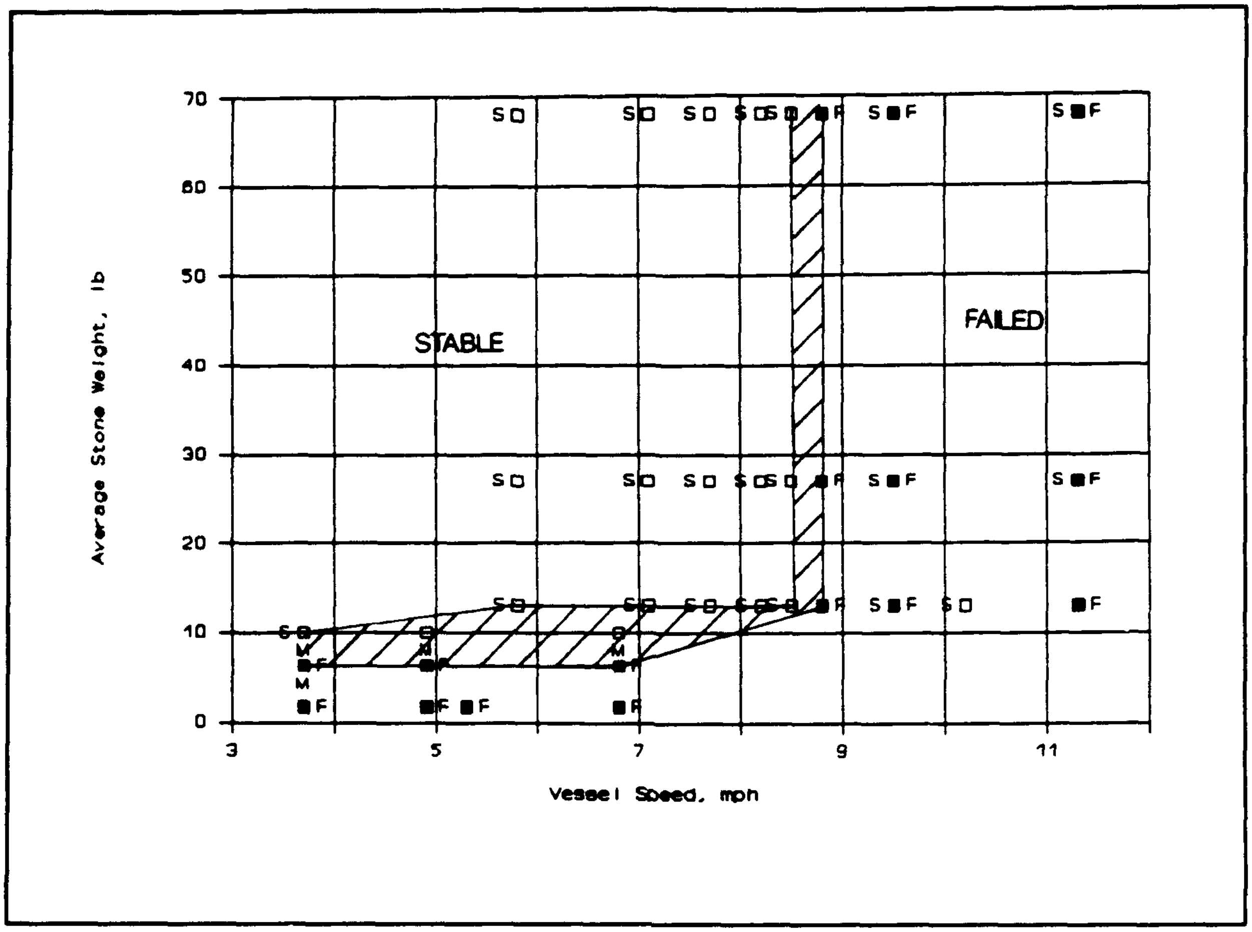


Figure 12. Stone size as a function of vessel speed for a 2H:1V slope

between the stable and failed conditions. Furthermore, the stable stone size for a range of boat speeds was assumed to be valid only within the bounds of the blockage ratios that were tested.

22. From Figures 14 and 15 it can be seen that as the vessel Froude number F_h increases, the stable stone size becomes less and less apparent. This occurs because as the Froude number approaches approximately 0.6 and the vessel approaches its limiting speed, the wave heights and their characteristics become highly erratic. More data are needed to determine the stability criteria in the Froude number range beyond approximately 0.5 and to determine the dominant wave type and magnitude.

23. The testing also indicated that the flatter slope, 3H:1V, was more stable than the steeper slope, 2H:1V. However, since the flat slope was not tested to failure, the stable stone sizes resulting from investigation of the 2H:1V slopes are recommended for tow speeds greater than 6.8 mph. These

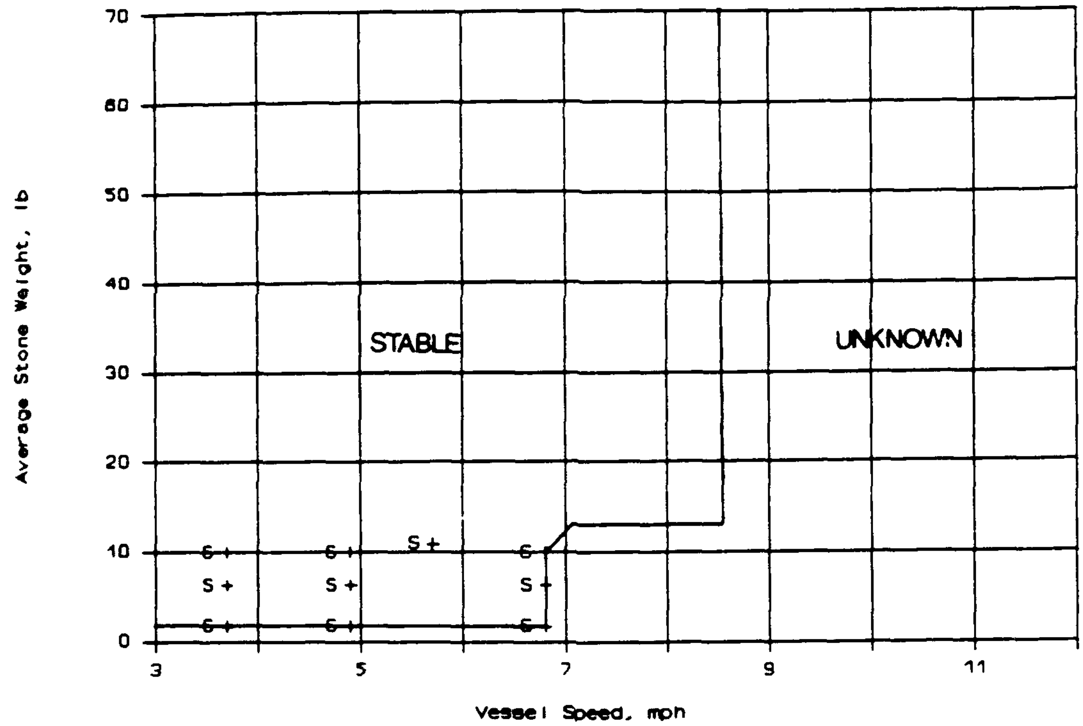


Figure 13. Stone size as a function of vessel speed for a 3H:1V slope

values are conservative and will be modified as necessary upon completion of further testing.

24. As a result, the following procedure is recommended to select the required stone size for slope protection in quiescent pools for tows under way:

a. Determine the maximum expected speed of the tows in the reach. This maximum may be based on known operations for the design channel reach or may be selected as 90 percent of the limiting speed. Based on the approach to the lock, record a minimum sailing distance. This should be based on reasonable operations into and out of the approach.

b. Assume a bank slope. If the slope is 2H:1V, use Table 6; if the slope is 3H:1V, use Table 7. (Note: A safety factor has not been applied to the values in these tables. See step d below.) If the slope is to be something other than these two slopes, select the more conservative condition. For example, if the slope is 2.5H:1V, use the 2H:1V criteria.

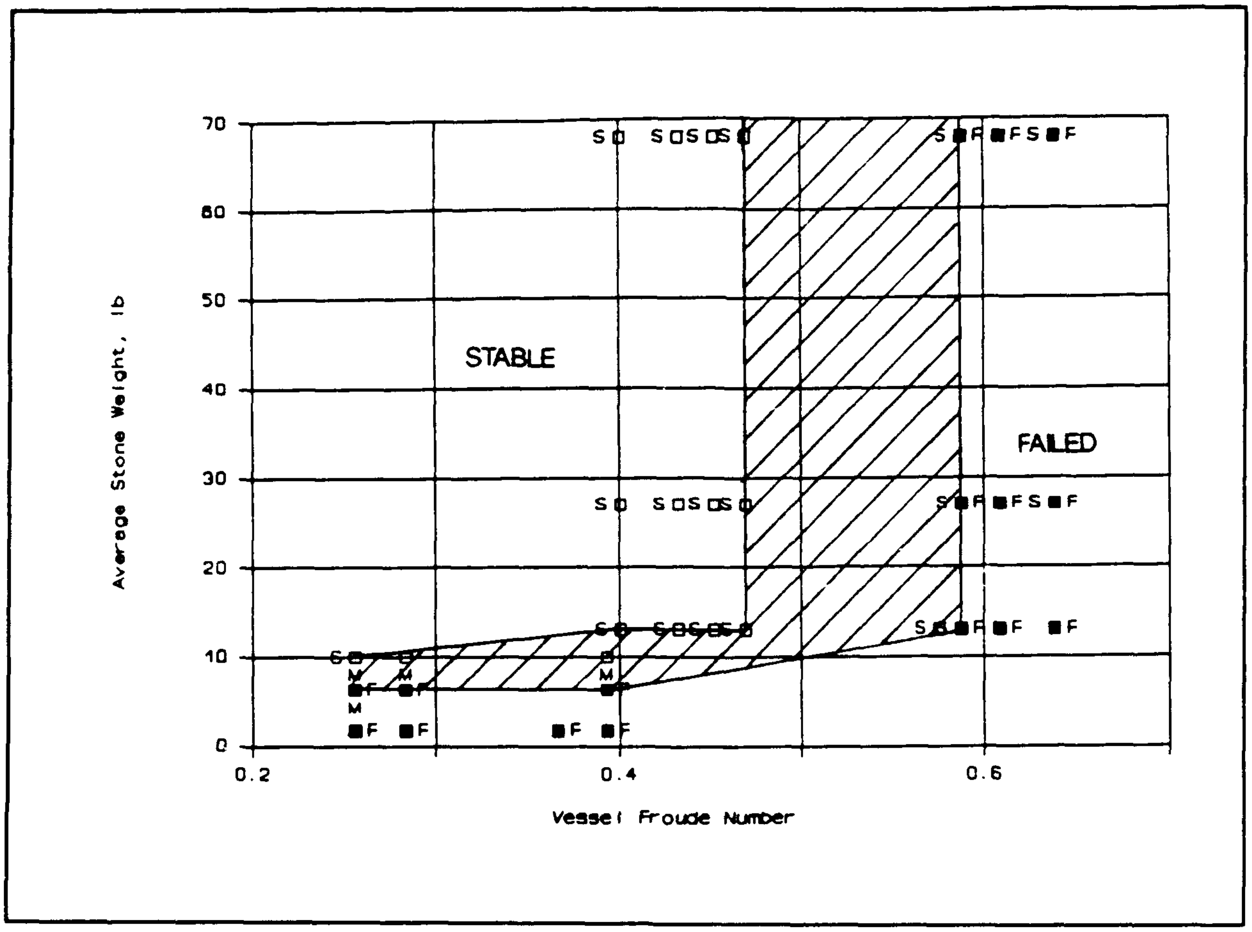


Figure 14. Stone size as a function of the Froude number for a 2H:1V slope

c. Calculate the blockage ratio. To do this pick the minimum pool condition. Calculate the cross-sectional area of the channel. Calculate the submerged cross-sectional area of the barges. (Also, determine the cross-sectional area of the towboat. Use the larger of the two.) Recall that the blockage ratio N is the cross section of the channel over the submerged cross section of the tow.

d. From the appropriate table, determine the minimum value for D_{50}. Multiply D_{50} (not W_{50}) by a safety factor of 1.25. A conservative safety factor should be used until verification of this guidance is validated with prototype data.

e. If the speed of the tow exceeds the conditions in the table, use the existing methods such as those found in PIANC (1987). If the tow speed is within the limits of the table, but the blockage ratio or minimum distance does not meet the criteria, select a conservative stone size from the table or use an existing method for stone selection.

f. Determine gradation, thickness, and extent of protection according to accepted methods.

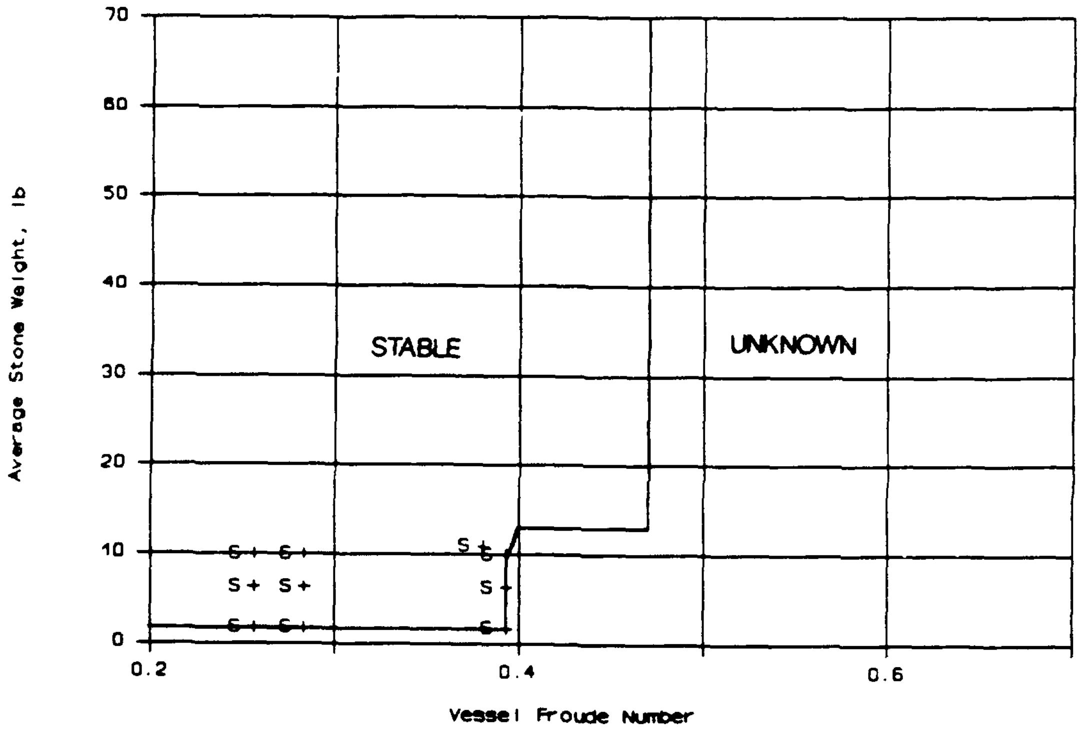


Figure 15. Stone size as a function of the Froude number for a 3H:1V slope

PART IV: DISCUSSION

Existing Guidance

25. As stated, the existing guidance can result in a veritable array of results. The variations, especially regarding boat waves, are not just related to the design equations for the riprap, but are highly dependent upon the predictive equations which relate vessel speed to wave height. Therefore, selecting the appropriate predictive equation for wave height and the appropriate design equation for stone size can be a difficult task.

Proposed Guidance

26. Recognizing that the ultimate thrust of the research will be to relate towboat speed, eccentricity, and blockage ratio to a stable riprap design, the interim guidance indirectly achieves this goal for the conditions tested. This guidance, however, does have limitations. It does not begin to cover all potential gradations of riprap, assumes quiescent pool conditions, explores only two slope conditions and only one type of channel (trapezoidal), and certainly does not begin to test all the conceivable navigation operating conditions.

27. Considering the fact that the guidance was at least partially developed from investigating the stone slope requirements in a lock approach, the limitations do not present a tremendous problem. The underway vessel speeds in a lock approach do not typically approach a limiting value and in fact operations rarely exceed, even in a long approach, 6 mph. Furthermore, assuming a quiescent pool and a trapezoidal channel is valid in this location. Consequently, the results are quite useful and, not withstanding any maneuvering problems, indicate that a relatively small stone size may be appropriate in an area such as this.

Other Considerations

28. In addition to the average stone size, there are a number of other considerations in the design of stone slope protection. These considerations include stone gradation, thickness of the blanket, filters (both stone and

cloth), and protection limits due to wave runup. The fact that this paper does not make any specific recommendations regarding these parameters does not minimize their importance. Existing design guidance should be followed regarding these design considerations.

29. Regarding phenomena that produce waves, this study has strictly limited its research to one source of waves: navigation towboats typically found in US waters. Specifically, these tows were limited to a horsepower range between 2,000 and 5,600. It is important to note that pleasure craft can, and do, produce adverse waves and currents which may require bank protection. These effects are not considered in this guidance, and neither are the effects of wave setup due to wind.

30. Determining the need for and the design of stone slope protection is complex. Prior to design, all potential sources of bank erosion, whether waves or currents, should be considered, including those caused by towboats, ecreation boats, wind setup, ambient currents, and flow fields around strucures. Bank conditions should be carefully evaluated with regard to existing bank materials, the extent of fluctuations in the water surface, historical records of stability or failure, and geometric conditions.

PART V: CONCLUSIONS

31. The following conclusions can be drawn from the research to date:

- a. Relatively small stone sizes are stable for moderate boat speeds, say less than 6 to 8 mph.
- b. This holds true even for blockage ratios in the range of 5 to 15.
- c. Flatter slopes have smaller stone requirements.
- d. As the vessel speed approaches the limiting speed and/or as the Froude number approaches 0.6, the accuracy of predicting wave heights, and, consequently, stable stone size dramatically decreases.
- e. A need exists to develop a predictive equation for wave heights, especially as the vessel Froude number increases to above approximately 0.5 at low blockage ratios.
- f. A need exists to modify existing riprap equations to reflect the characteristics of the forces produced by US inland towboats.

32. The focus of the research being conducted at WES is on developing guidance for design of navigation channel protection and guidance for determining vessel-generated forces produced by towboats in the US inland waterway system. The final products of this research will be twofold. First, mathematical relationships will be developed or modified from existing equations which will quantify the waves and currents produced by a towboat. These equations will not only provide the input to riprap design equations, but will also be useful in evaluating environmental issues related to fish and wildlife in navigation channels. The second major product of this research will be riprap design guidance for the protection of navigation channels, lock approaches, or other reaches where tows navigate near bank lines.

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Table 1

Gradations for the Tennessee-Tombigbee Study

	Type II Gradation	Type X Gradation	Type Y Gradation
Thickness, in.	18.0	15.0	10.0
D_{50}, in.	11.1	8.1	6.4

$\gamma_R = 166$ pcf

Percent Finer by Weight	Type II		Type X		Type Y	
	Weight lb	Size* in.	Weight lb	Size in.	Weight lb	Size in.
100	360.0	19.3	170.0	15.0	50.0	10.0
80	170.0	15.0	75.0	11.4	28.0	8.2
60	92.0	12.2	37.0	9.0	16.0	6.8
50	68.0	11.1	27.0	8.1	13.0	6.4
40	50.0	10.0	21.0	7.5	10.0	5.8
30	33.0	8.7	13.5	6.4	7.9	5.4
20	21.0	7.5	8.8	5.6	6.0	4.9
10	9.0	5.6	5.6	4.8	4.8	4.6
0	3.6	4.2	3.6	4.2	3.6	4.2

* Equivalent stone diameter.

Table 2

Gradations for the Gallipolis Study

	Original	Proposed
Thickness, in.	24.0	12.0
D_{50}, in.	13.0	6.0

$\gamma_R = 167$ pcf

Percent Finer by Weight	Original		Proposed	
	Weight lb	Size in.	Weight lb	Size in.
100	347.0	19.0	41.7	9.4
80	217.0	16.3	25.0	7.9
60	139.0	14.0	14.0	6.5
50	111.0	13.0	10.9	6.0
40	87.0	12.0	8.3	5.5
30	64.0	10.8	6.2	5.0
20	40.0	9.2	4.8	4.6
10	25.0	7.9	---	---
0	10.9	6.0	0.6	2.3

Table 3

Gradations for the Navigation Research Study

	Type 1		Type 2		Type 3	
Thickness, in.	9.0		9.0		12.0	
D_{50}, in.	3.3		5.0		5.8	
γ_R = 167 pcf						
Percent Finer by Weight	**Type 1** Weight lb	Size in.	**Type 2** Weight lb	Size in.	**Type 3** Weight lb	Size in.
100	5.4	4.8	12.4	6.3	41.7	9.4
80	3.5	4.1	9.5	5.7	23.0	7.7
60	2.2	3.5	7.1	5.2	12.4	6.3
50	1.7	3.3	6.3	5.0	10.0	5.8
40	---	---	5.4	4.8	8.2	5.5
30	---	---	3.1	3.9	6.7	5.1
20	---	---	1.7	3.3	5.4	4.8
10	---	---	---	---	---	---
0	0.6	2.3	0.6	2.3	0.6	2.3

Table 4

Summary Test Conditions

Barge Configuration	D_{50} in.	W_{50} lb	Wave (max) ft	Bank Slope	Depth ft	Distance ft	Vessel Speed mph*	Stability
				Tennessee-Tombigbee				
3 Wide Loaded	11.1	68.0	1.5	2:1	14	140.0	5.2(5.8)	S
	8.1	27.0	1.5	2:1	14	140.0	5.2(5.8)	S
	6.3	13.0	1.5	2:1	14	140.0	5.2(5.8)	S
2 Wide Unloaded	11.1	68.0	3.1	2:1	14	140.0	8.5(8.8)	F
	8.1	27.0	3.1	2:1	14	140.0	8.5(8.8)	F
	6.4	13.0	3.1	2:1	14	140.0	8.5(8.8)	F
	11.1	68.0	1.5	2:1	14	140.0	8.5(8.5)	S
	8.1	27.0	1.5	2:1	14	140.0	8.5(8.5)	S
	6.4	13.0	1.5	2:1	14	140.0	8.5(8.5)	S
2 Wide Unloaded	11.1	68.0	3.0	2:1	17.5	140.0	9.95(9.5)	F
	8.1	27.0	2.3	2:1	17.5	140.0	9.95(9.5)	F
	6.4	13.0	2.3	2:1	17.5	140.0	9.95(9.5)	F
	11.1	68.0	2.3	2:1	17.5	140.0	9.95(9.5)	S
	8.1	27.0	1.7	2:1	17.5	140.0	9.95(9.5)	S
	6.4	13.0	1.7	2:1	17.5	140.0	9.95(9.5)	S
3 Wide Loaded	11.1	68.0	1.8	2:1	18	140.0	6.7(7.7)	S
	8.1	27.0	1.8	2:1	18	140.0	6.7(7.7)	S
	6.4	13.0	1.8	2:1	18	140.0	6.7(7.7)	S
	11.1	68.0	1.5	2:1	18	140.0	6.7(7.1)	S
	8.1	27.0	1.5	2:1	18	140.0	6.7(7.1)	S
	6.4	13.0	1.5	2:1	18	140.0	6.7(7.1)	S
2 Wide Unloaded	11.1	68.0	2.9	2:1	21	140.0	10.5(11.3)	F
	8.1	27.0	2.9	2:1	21	140.0	10.5(11.3)	F
	6.4	13.0	2.5	2:1	21	140.0	10.5(11.3)	F
	11.1	68.0	2.5	2:1	21	140.0	10.5(11.3)	S
	8.1	27.0	2.5	2:1	21	140.0	10.5(11.3)	S
	6.4	13.0	1.7	2:1	21	140.0	10.5(10.2)	S
3 Wide Loaded	11.1	68.0	2.2	2:1	22	140.0	7.1(8.2)	S
	8.1	27.0	2.2	2:1	22	140.0	7.1(8.2)	S
	6.4	13.0	2.2	2:1	22	140.0	7.1(8.2)	S
	11.1	68.0	1.9	2:1	22	140.0	7.1(8.2)	S
	8.1	27.0	1.9	2:1	22	140.0	7.1(8.2)	S
	6.4	13.0	1.9	2:1	22	140.0	7.1(8.2)	S

(Continued)

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* The first vessel speed given is an arithmetic average of all the vessel speeds corresponding to the wave data for a particular test condition taken on the Tennessee-Tombigbee. The number in parentheses is a conservative value taken from the data curves given in Plates 14-16 of Maynord and Oswalt (1986).

Table 4 (Concluded)

Barge Configuration	D_{50} in.	W_{50} lb	Wave (max) ft	Bank Slope	Depth ft	Distance ft	Vessel Speed mph	Stability
				Gallipolis				
3 Wide Loaded	13.0	111.0	---	3:1	15	----	---	S
	6.0	10.9	1.2	3:1	15	122.5	5.7	S
				Navigation Research				
3 Wide Loaded	3.3	1.7	---	2:1	14	252.5	5.3	F
	3.3	1.7	---	2:1	20	157.5	4.9	F
	5.0	6.3	---	2:1	20	157.5	4.9	F
	5.8	10.0	---	2:1	20	157.5	4.9	M
	3.3	1.7	---	3:1	20	157.5	4.9	S
	5.0	6.3	---	3:1	20	157.5	4.9	S
	5.8	10.0	---	3:1	20	157.5	4.9	S
	3.3	1.7	---	2:1	20	157.5	6.8	F
	5.0	6.3	---	2:1	20	157.5	6.8	F
	5.8	10.0	---	2:1	20	157.5	6.8	M
	3.3	1.7	---	3:1	20	157.5	6.8	S
	5.0	6.3	---	3:1	20	157.5	6.8	S
	5.8	10.0	---	3:1	20	157.5	6.8	S
	3.3	1.7	---	2:1	14	157.5	3.7	F
	5.0	6.3	---	2:1	14	157.5	3.7	M
	5.8	10.0	---	2:1	14	157.5	3.7	S
	3.3	1.7	---	3:1	14	157.5	3.7	S
	5.0	6.3	---	3:1	14	157.5	3.7	S
	5.8	10.0	---	3:1	14	157.5	3.7	S
	3.3	1.7	---	2:1	14	122.5	3.7	F
	5.0	6.3	---	2:1	14	122.5	3.7	F
	5.8	10.0	---	2:1	14	122.5	3.7	M
	3.3	1.7	---	3:1	14	122.5	3.7	S
	5.0	6.3	---	3:1	14	122.5	3.7	S
	5.8	10.0	---	3:1	14	122.5	3.7	S

Table 5

Blockage Ratio

Barge Configuration	Bank Slope	Depth of water ft	Sailing Line Distance ft	Total Barge Area sq ft	Channel Area Left* sq ft	Total Channel Area sq ft	Blockage Ratio
			Tennessee-Tombigbee				
2 Wide-Unloaded	2:1	14.0	168.0	412	2156	4312	10.5
3 Wide-Loaded	2:1	14.0	168.0	945	2156	4312	4.6
3 Wide-Loaded	2:1	18.0	176.0	945	2844	5688	6.0
3 Wide-Loaded	2:1	22.0	188.0	945	3564	7128	7.5
2 Wide-Unloaded	2:1	17.5	175.0	412	2756	5513	13.4
2 Wide-Unloaded	2:1	21.0	182.0	412	3381	6762	16.4
			Gallipolis				
3 Wide-Loaded	3:1	15.0	167.5	945	2175	6713	7.1
			Navigation Research				
3 Wide Loaded	2:1	14.0	280.5	945	3731	7196	7.6
	2:1	20.0	197.5	945	3550	10400	11.0
	3:1	20.0	217.5	945	3750	9600	10.2
	2:1	14.0	185.5	945	2401	7196	7.6
	3:1	14.0	199.5	945	2499	6594	7.0
	2:1	14.0	150.5	945	1911	7196	7.6
	3:1	14.0	164.5	945	2009	6594	7.0

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* This is the cross-sectional area of the channel from the center line of the barge train to the waterline of the test embankment.

Table 6

Underway Tows - Bank Slope = 2H:1V

Allowable Tow Speed mph	Blockage Ratio N	Minimum Sailing Line Distance ft	Minimum W_{50} Stone Size lb	Minimum D_{50} Stone Size in.
$V_s < 3.7$				Use Permissible Velocity Criteria
$V_s = 3.7$	≥ 7.6	185.5	10	5.8
$3.7 < V_s \le 5.8$	≥ 4.6	168.0	13	6.4
$5.8 < V_s \le 7.7$	≥ 6.0	176.0	13	6.4
$7.7 < V_s \le 8.2$	≥ 7.5	188.0	13	6.4
$8.2 < V_s \le 8.5$	≥ 10.5	168.0	13	6.4
$8.5 < V_s$				Determine Wave or Return Current

Table 7

Underway Tows - Bank Slope = 3H:1V

Allowable Tow Speed mph	Blockage Ratio N	Minimum Sailing Line Distance ft	Minimum W_{50} Stone Size lb	Minimum D_{50} Stone Size in.
$V_s < 3.7$				Use Permissible Velocity Criteria
$3.7 \le V_s \le 6.8$	≥ 10.2	217.5	1.7	3.3
$6.8 < V_s \le 7.7$	≥ 6.0	176.0	13	6.4
$7.7 < V_s \le 8.2$	≥ 7.5	188.0	13	6.4
$8.2 < V_s \le 8.5$	≥ 10.5	168.0	13	6.4
$8.5 < V_s$				Determine Wave or Return Current

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