US Army Corps
of Engineers

AD-A249 644

# USE OF SITE-SPECIFIC MODEL DATA
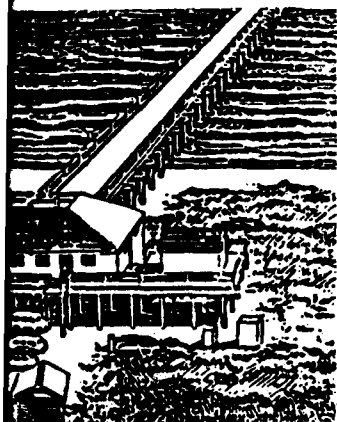# FOR GENERAL BREAKWATER DESIGN
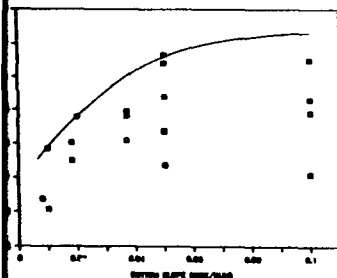
by

Robert D. Carver, Brenda J. Wright

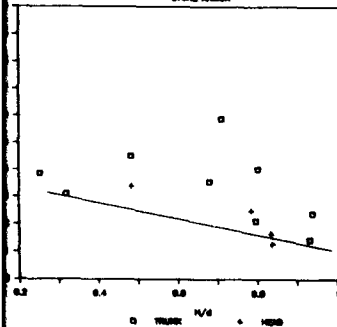Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
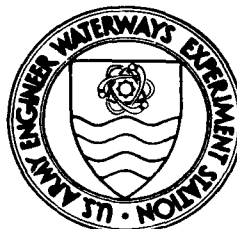3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

RELATIVE WAVE HEIGHT VS BOTTOM SLOPE

STABILITY COEFFICIENT VS H/d

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Final Report

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**13. ABSTRACT (Maximum 200 words)**

The purpose of this investigation was to obtain a better understanding of why significant variations in the stability coefficient occur. Specifically, it was hoped that functional relationships could be developed between the stability coefficient and such variables as wave height, wave period, and water depth. These functional relationships would then be used as input to an improved procedure for obtaining minimum armor unit weights required for hydraulic stability. Also, it was hoped that a link could be developed between breaking and nonbreaking wave test results.

Based on results of model tests described herein, in which tetrapod, tribar, dolos, and stone armor are used on breakwater trunks and heads, it is concluded that test results are very significant in that they show tetrapod, tribar, dolos, and stone stability to be dependent on the combined effects of wave height, wave period, and water depth with minimum stability occurring at the lower values of $d/L$ and higher values of $H/d$, i.e., longer wave periods in shallower water. An improved procedure for determining minimum armor unit weights was developed.

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PREFACE

Authority for the US Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), to conduct this study was granted by the Headquarters, US Army Corps of Engineers (HQUSACE), under Work Unit 32534, "Breakwater Stability - A New Design Approach," of the Coastal Structure Evaluation and Design Program, Coastal Engineering Area of Civil Works Research and Development. The HQUSACE Technical Monitors for this research were Messrs. John H. Lockhart, Jr.; John G. Housley; James E. Crews; and Robert H. Campbell. The CERC Program Managers were Dr. C. Linwood Vincent and Ms. Carolyn M. Holmes.

The study was conducted by personnel of CERC under the general direction of Dr. James R. Houston, Chief, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC. Direct supervision was provided by Messrs. C. E. Chatham, Chief, Wave Dynamics Division (WDD), and D. Donald Davidson, Chief, Wave Research Branch (WRB), WDD. This report was prepared by Mr. Robert D. Carver, Principal Investigator, and Mrs. Brenda J. Wright, Engineering Technician, WRB. This report was typed by Ms. Myra E. Willis, WRB, and edited by Ms. Lee T. Byrne, Information Technology Laboratory, WES.

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

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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 |
|---|---|---|
| cubic feet | 0.02831685 | cubic metres |
| degrees (angle) | 0.01745329 | radians |
| feet | 0.3048 | metres |
| pounds (mass) | 0.4535924 | kilograms |
| pounds (mass) per cubic foot | 16.01846 | kilograms per cubic metre |
| square feet | 0.09290304 | square metres |
| tons (2,000 pounds, mass) | 907.1847 | kilograms |

# USE OF SITE-SPECIFIC MODEL DATA FOR GENERAL BREAKWATER DESIGN

## PART I:   INTRODUCTION

### Background

1.   During the past decade, much consternation has arisen in the inter-
national coastal engineering community over the use of the Hudson Stability
Equation (Shore Protection Manual (SPM) 1984).  This is not surprising if one
accepts the fact that, based on the present state of the art, this approach to
breakwater design is an oversimplification of a complex problem.  Most re-
searchers have the highest respect for the pioneering work accomplished by
Hudson during the 1950's and 1960's; however, based on a detailed study of the
original work, numerous conversations with Mr. Hudson, and an attempt to
understand the physics of the problem, it has been concluded that the present
formula does not necessarily address all design parameters.  Since the stabil-
ity coefficient ($K_D$) combines the effects of over 20 wave and structure vari-
ables, it is reasonable to expect that  $K_D$  may vary from one investigation to
another (as confirmed by recent laboratory tests).

2.   Information from many US Army Engineer Waterways Experiment Station
(WES) site-specific breakwater stability studies exists, but has never been
generalized and summarized to the extent possible due to the narrow focus of
individual projects.  In the aggregate, the stable plans developed in these
studies cover a significant range of wave heights, wave periods, water depths,
and bottom slopes.  Also, many of these studies used the maximum breaking wave
condition for a given water depth, wave period, and offshore slope.  This con-
dition has not been parameterized, but it is similar to the maximum wave con-
ditions shown in the SPM.

### Purpose of Study

3.   The purpose of this investigation was to obtain a better understand-
ing of why significant variations in the stability coefficient occur.
Specifically, the objective was to develop functional relationships between
the stability coefficient and such variables as wave height, wave period, and
water depth.  These functional relationships then would be used as input to an

improved procedure for determining minimum armor unit weights required for hydraulic stability. Also, a link was sought between breaking and nonbreaking wave test results.

## Approach

4. Previous breakwater stability investigations conducted by Carver (1983) and Carver and Wright (1988a, 1988b, and 1988c) have shown that the relative depth (d/L) and relative wave height (H/d) are two of the most important dimensionless variables influencing breakwater stability. Therefore, results of the site-specific studies described herein were nondimensionalized relative to these and other pertinent variables that characterize incident wave conditions.

PART II:   RESULTS OF ARMOR STABILITY ANALYSIS

## General

5.   A review of WES reports yielded 28 site-specific, stability studies conducted between 1955 and 1988.   These studies, conducted with regular waves, are summarized by date, armor type, location, and investigator(s) in Table 1. It is interesting to note that all tests were conducted using tetrapods, tri-bars, dolos, or stone.   Tetrapods and tribars were considered during the period 1955-1971, whereas all studies conducted since 1971 have used either dolos or stone armor.   Tables 2-5 summarize important project characteristics such as armor weight, water depth, design wave period and height, and bottom slope (seaward of the structure) for each of the four armor types tested.

6.   Trial plots of the stability coefficient $K_D$ as a function of deep water $(H/L_o)$ and local wave steepness $(H/L)$, deep water $(d/L_o)$ and local rela-tive depth $(d/L)$, and local relative wave height $(H/d)$ were made.   The plots showed the stability coefficient to be best correlated by  $d/L$  and  $H/d$ ; therefore, these variables were chosen as the basis on which to build a new design procedure.

## Tetrapod Design

7.   Figures 1 and 2 present  $K_D$  as a function of  $d/L$  and  $H/d$ , respectively.   These data show tetrapod stability to be influenced by both parameters with minimum stability being observed at the lower values of  $d/L$ and higher values of  $H/d$ , i.e., longer wave periods in shallower water.   The tetrapod data set is not sufficient to develop general design curves; however, significant future interest in tetrapods is not anticipated with the advent of newer, hydraulically superior, armor units.

## Tribar Design

8.   Figures 3 and 4 present tribar stability as a function of  $d/L$   and H/d , respectively.   Again, minimum stability is observed for the longer wave periods in shallower water.   It is suggested that tribar armor be sized by entering these plots with the appropriate values of  $d/L$   and  $H/d$   and using

the <u>minimum</u> stability coefficient thus obtained.

## Dolos Design

9. Figures 5 and 6 show dolos stability to also be strongly influenced by d/L and H/d . Again, it is suggested that the lower limit curves be used to determine minimum hydraulic stability.

## Stone Design

10. Lower limit design curves for stone armor are presented as a function of d/L and H/d in Figures 7 and 8, respectively. Minimum trunk and head stabilities proved to be similar. Therefore, only one design curve for both trunks and heads is presented.

## Discussion

11. Results presented herein are very significant in that they show tetrapod, tribar, dolos, and stone stability to be dependent on the combined effects of wave height, wave period, and water depth with minimum stability occurring at the lower values of d/L and higher values of H/d , i.e., longer wave periods in shallower water. Use of the design curves presented in Figures 1-8 should provide a refinement over the procedures presently given in the SPM.

PART III:   PREDICTION OF MAXIMUM BREAKING WAVE HEIGHTS

12.   Experience in conducting model studies of the type summarized
herein has shown that breaking wave heights may significantly exceed 0.78d,
depending on bottom slope and wave period.   Figure 9, developed from data
given in Tables 2-5, presents  H/d  as a function of bottom slope.   A
correlation with wave period could not be developed, due to the limited range
of periods investigated.   However, the upper limit curve (Figure 9) should
provide a good estimate of the maximum breaking wave heights that can be
expected for the range of wave periods that are typically considered in design
of breakwaters.

PART IV:  DESIGN CURVE USE

## Example Problem 1

### Description

13.  The selected structure is a breakwater trunk with stone armor hav-ing a unit weight of 165 pcf.*  Sufficient wave energy exists to cause break-ing waves at the structure toe.  The bottom approach slope is about 1V:100H. Water depth at the toe is 20 ft, the wave period is 14 sec, and the armor slope is 1V:2H.

### Design curve use

14.  Using the water depth at 20 ft and the bottom slope of 0.01, Figure 9 indicates an  H/d  of 0.80, thus yielding a 16-ft design wave height. Calculate  $L_o$  ,  $d/L_o$  , and  $d/L$:

$$L_o = \frac{gT^2}{2\pi} = \frac{(32.17)(14)^2}{2\pi} \approx 1,004 \text{ ft} \tag{1}$$

$$d/L_o = 20/1,004 = 0.01992$$

Thus,

$$d/L = 0.0575 \tag{2}$$

Figures 7 and 8 yield a minimum stability coefficient of 1.4 for the selected design conditions.  The stable armor weight  $W_a$  is determined from the Hudson formula, i.e.,

$$W_a = \frac{\gamma_a H^3}{K_D(S_a - 1)^3 \cot\alpha}$$

$$W_a = \frac{165(16)^3}{1.4(165/64 - 1)^3 2} \tag{3}$$

$$W_a = 61,400 \text{ lb}$$

Thus, the use of 31-ton stone is recommended.

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

## Example Problem 2

### Description

15. The same structure and wave conditions described in Paragraph 14 apply; however, an alternate design using dolos armor is desired. The dolos unit weight is assumed to be 150 pcf.

### Design curve use

16. Using $d/L = 0.0575$ and $H/d = 0.80$ in concert with Figures 5 and 6 gives a minimum stability coefficient of 11. Again, application of the Hudson formula yields

$$W_a = \frac{\gamma_a H^3}{K_D (S_a - 1)^3 \cot\alpha}$$

$$W_a = \frac{150(16)^3}{11(150/64 - 1)^3 2} \qquad (4)$$

$$W_a = 11,500 \text{ lb}$$

The use of 6-ton dolos is recommended if the alternate design is chosen.

PART V: CONCLUSIONS

17. Based on the results of the site-specific model tests described herein in which tetrapod, tribar, dolos, and stone armor are used on breakwater trunks and heads, it is concluded that:

   a. Test results are very significant in that they show tetrapod, tribar, dolos, and stone stability to be dependent on the combined effects of wave height, wave period, and water depth with minimum stability occurring at the lower values of $d/L$ and higher values of $H/d$, i.e., longer wave periods in shallower water.

   b. Figures 1-8 provide a means of linking breaking and nonbreaking wave test results; i.e., they cover a range of $H/d$ and $d/L$ encountered for both types of waves.

   c. The design procedure illustrated in Part IV should provide a refinement over the approach presently given in the SPM.

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Table 1

Summary Of Site-Specific Studies

| Armor Type | Location | References |
| --- | --- | --- |
| Tetrapod | Crescent City, CA | Hudson and Jackson (1955) |
| Tetrapod | Crescent City, CA | Hudson and Jackson (1956) |
| Tribar | Nawiliwili, HI | Jackson, Hudson, and Housley (1960) |
| Stone | Siuslaw, OR | US Army Engineer Waterways Experiment Station (1963) |
| Tribar | Kahului, HI | Jackson (1964) |
| Tetrapod | Nassau, Bahamas | Jackson (1965) |
| Stone | Dana Point, CA | Dai and Jackson (1966) |
| Tribar | Nassau, Bahamas | Hudson and Jackson (1966) |
| Tetrapod | Noyo, CA | Jackson (1966) |
| Stone | Burns Harbor, IN | Jackson (1967) |
| Tribar | Monterey Harbor, CA | Davidson (1969) |
| Tribars and Dolos | Humboldt Bay, CA | Davidson (1971) |
| Dolos | Wainae, HI | Bottin, Chatham, and Carver (1976) |
| Stone and Dolos | Lahaina, HI | Carver (1976) |
| Dolos | Jubail Harbor, Saudi Arabia | Carver and Davidson (1976) |
| Stone | Masonboro Inlet, NC | Carver and Markle (1978) |
| Dolos | Nawiliwili, HI | Davidson (1978) |
| Stone | Tillamook, OR | Markle and Davidson (1979) |
| Dolos | Maalaea, HI | Carver and Markle (1981a) |
| Stone | Port Ontario, NY | Carver and Markle (1981b) |
| Stone | San Juan, Puerto Rico | Markle (1981) |
| Dolos | Kahului, HI | Markle (1982) |
| Stone and Dolos | Oregon Inlet, NC | Carver and Davidson (1983) |
| Stone | Mission Bay, CA | Markle (1983) |
| Stone | San Pedro, CA | Carver (1984) |
| Dolos | Crescent City, CA | Baumgartner, Carver, and Davidson (1985) |
| Stone | San Pedro, CA | Baumgartner, et al. (1986) |
| Stone | St. Paul, AK | Ward (1988) |

Table 2

## Summary of Results of Tetrapod Armor

| Armor Height tons | Armor Specific Weight pcf | Bottom Slope | Cot | d, ft | T, sec | H, ft | $K_D$ | Breaking Waves | Angle of Attack deg | Section of Structure | $L_o$ | $d/L_o$ | $H/L_o$ | $H/d$ | $L$ | $d/L$ | $H/L$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Crescent City, CA | | | | | | | | | |
| 17.60 | 140 | Flat | 2.000 | 69.0 | 14 | 23.0 | 14.4 | No | 90.0 | Trunk | 1004 | 0.069 | 0.023 | 0.333 | 613 | 0.1126 | 0.0375 |
| 17.60 | 140 | Flat | 3.000 | 69.0 | 14 | 25.0 | 12.4 | No | 90.0 | Trunk | 1004 | 0.069 | 0.025 | 0.362 | 613 | 0.1126 | 0.0408 |
| 17.60 | 140 | Flat | 4.000 | 69.0 | 14 | 26.0 | 10.4 | No | 90.0 | Trunk | 1004 | 0.069 | 0.026 | 0.377 | 613 | 0.1126 | 0.0424 |
| 25.00 | 150 | Flat | 1.333 | 55.0 | 14 | 20.0 | 7.4 | No | 90.0 | Trunk | 1004 | 0.055 | 0.020 | 0.364 | 555 | 0.0990 | 0.0360 |
| | | | | | | | | Novo Harbor, CA | | | | | | | | | |
| 36.00 | 150 | Flat | 3.000 | 48.0 | 14 | 29.0 | 7.0 | Yes | 90.0 | Trunk | 1004 | 0.048 | 0.029 | 0.604 | 523 | 0.0918 | 0.0555 |
| | | | | | | | | Nassau Harbor, Bahamas | | | | | | | | | |
| 7.00 | 150 | Flat | 1.500 | 25.0 | 11 | 12.0 | 5.1 | No | 90.0 | Head | 620 | 0.040 | 0.019 | 0.480 | 299 | 0.0836 | 0.0401 |
| 14.00 | 150 | Flat | 1.500 | 25.0 | 11 | 15.0 | 5.0 | No | 90.0 | Head | 620 | 0.040 | 0.024 | 0.600 | 299 | 0.0836 | 0.0502 |
| 17.00 | 150 | Flat | 1.500 | 25.0 | 11 | 16.0 | 5.0 | No | 90.0 | Head | 620 | 0.040 | 0.026 | 0.640 | 299 | 0.0836 | 0.0535 |
| | | | | | | | | Humboldt Bay, CA | | | | | | | | | |
| 28.00 | 150 | 1:10 | 5.000 | 43.0 | 16 | 23.0 | 2.7 | No | 90.0 | Head | 1311 | 0.033 | 0.018 | 0.535 | 575 | 0.0748 | 0.0400 |

Table 3

Summary of Results for Tribar Armor

| Armor Height tons | Armor Specific Weight pcf | Bottom Slope | Cot | d, ft | T, sec | H, ft | $K_D$ | Breaking Waves | Angle of Attack deg | Section of Structure | $L_o$ | $d/L_o$ | $H/L_o$ | $H/d$ | L | $d/L$ | $H/L$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | **Morro Bay, CA** | | | | | | | |
| 20.00 | 150 | 1:50 | 1.5 | 38.0 | 13 | 24.0 | 14.2 | No | 90.0 | Trunk | 865 | 0.044 | 0.028 | 0.632 | 434 | 0.0876 | 0.0553 |
| | | | | | | | | | | **Nassau Harbor, Bahamas** | | | | | | | |
| 10.00 | 150 | Flat | 1.5 | 25.0 | 11 | 19.0 | 14.1 | Yes | 90.0 | Trunk | 620 | 0.040 | 0.031 | 0.760 | 299 | 0.0836 | 0.0636 |
| 19.00 | 150 | Flat | 1.5 | 30.0 | 11 | 23.0 | 13.2 | Yes | 90.0 | Trunk | 620 | 0.048 | 0.037 | 0.767 | 325 | 0.0924 | 0.0709 |
| | | | | | | | | | | **Kahului Harbor, Maui** | | | | | | | |
| 35.00 | 156 | 1:125 | 2.0 | 58.0 | 18 | 37.0 | 19.0 | Yes | 90.0 | Trunk | 1659 | 0.035 | 0.022 | 0.638 | 749 | 0.0774 | 0.0494 |
| 35.00 | 146 | 1:27 | 3.6 | 42.0 | 18 | 34.0 | 10.8 | Yes | 90.0 | Trunk | 1659 | 0.025 | 0.020 | 0.810 | 644 | 0.0652 | 0.0528 |
| 19.00 | 146 | 1:27 | 2.6 | 29.0 | 18 | 25.6 | 11.8 | Yes | 90.0 | Trunk | 1659 | 0.017 | 0.015 | 0.883 | 540 | 0.0537 | 0.0474 |
| 10.00 | 146 | 1:27 | 2.0 | 24.0 | 18 | 21.5 | 17.2 | Yes | 90.0 | Trunk | 1659 | 0.014 | 0.013 | 0.896 | 493 | 0.0487 | 0.0436 |
| 35.00 | 156 | 1:125 | 3.0 | 58.0 | 14 | 30.0 | 6.8 | No | 90.0 | Head | 1004 | 0.058 | 0.030 | 0.517 | 569 | 0.1020 | 0.0528 |
| 50.00 | 156 | 1:125 | 4.0 | 58.0 | 18 | 35.0 | 5.6 | No | 90.0 | Head | 1659 | 0.035 | 0.021 | 0.603 | 749 | 0.0774 | 0.0467 |
| 35.00 | 156 | 1:125 | 3.0 | 58.0 | 18 | 36.0 | 11.7 | No | 50.0 | Head | 1659 | 0.035 | 0.022 | 0.621 | 749 | 0.0774 | 0.0480 |
| 50.00 | 156 | 1:125 | 3.0 | 58.0 | 18 | 36.0 | 8.2 | No | 50.0 | Head | 1659 | 0.035 | 0.022 | 0.621 | 749 | 0.0774 | 0.0480 |
| | | | | | | | | | | **Nawilihili Harbor, Hawaii** | | | | | | | |
| 17.80 | 158 | 1:55 | 1.5 | 32.0 | 16 | 24.0 | 12.9 | Yes | 90.0 | Trunk | 1311 | 0.024 | 0.018 | 0.750 | 500 | 0.0639 | 0.0480 |
| | | | | | | | | | | **Humboldt Bay, CA** | | | | | | | |
| 23.00 | 150 | 1:10 | 5.0 | 43.0 | 16 | 29.0 | 6.6 | No | 45.0 | Head | 1311 | 0.033 | 0.022 | 0.674 | 575 | 0.0748 | 0.0504 |
| 33.00 | 150 | 1:10 | 5.0 | 43.0 | 16 | 36.0 | 8.7 | No | 45.0 | Head | 1311 | 0.033 | 0.027 | 0.837 | 575 | 0.0748 | 0.0626 |
| 44.00 | 150 | 1:10 | 5.0 | 43.0 | 16 | 36.0 | 6.6 | No | 45.0 | Head | 1311 | 0.033 | 0.027 | 0.837 | 575 | 0.0748 | 0.0626 |

Table 4
Summary of Results for Dolos Armor

| Armor Height tons | Armor Specific Weight pcf | Bottom Slope | Cot | d, ft | T, sec | H, ft | $K_D$ | Breaking Waves | Angle of Attack deg | Section of Structure | $L_o$ | $d/L_o$ | $H/L_o$ | $H/d$ | $L$ | $d/L$ | $H/L$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lahaina Harbor, Hawaii | | | | | | | | | | | | | | | | | |
| 0.75 | 150 | 1:20 | 2.0 | 7.5 | 16 | 8.0 | 10.6 | Yes | 90.0 | Trunk | 1311 | 0.006 | 0.006 | 1.067 | 247 | 0.0304 | 0.0324 |
| Maalaea Harbor, Maui, Hawaii | | | | | | | | | | | | | | | | | |
| 6.00 | 147 | 1:50 | 1.5 | 19.0 | 16 | 16.7 | 17.4 | Yes | 90.0 | Trunk | 1311 | 0.014 | 0.013 | 0.879 | 390 | 0.0488 | 0.0429 |
| Waianae Harbor, Oahu, Hawaii | | | | | | | | | | | | | | | | | |
| 1.50 | 150 | 1:20 | 2.0 | 16.0 | 16 | 11.8 | 16.9 | Yes | 90.0 | Trunk | 1311 | 0.012 | 0.0009 | 0.738 | 358 | 0.0446 | 0.0329 |
| Kahului, Maui Hawaii | | | | | | | | | | | | | | | | | |
| 30.00 | 146 | 1:100 | 1.7 | 49.0 | 18 | 29.8 | 18.0 | Yes | 90.0 | Trunk | 1659 | 0.030 | 0.018 | 0.508 | 693 | 0.0707 | 0.0430 |
| Nawiliwili Harbor, Hawaii | | | | | | | | | | | | | | | | | |
| 2.00 | 146 | 1:10 | 1.5 | 10.0 | 16 | 8.9 | 8.2 | Yes | 90.0 | Trunk | 1311 | 0.008 | 0.007 | 0.890 | 285 | 0.0351 | 0.0313 |
| Oregon Inlet, North Carolina | | | | | | | | | | | | | | | | | |
| 9.50 | 150 | 1:20 | 1.5 | 16.5 | 15 | 15.5 | 8.1 | Yes | 90.0 | Trunk | 1152 | 0.014 | 0.013 | 0.939 | 340 | 0.0485 | 0.0455 |
| 14.00 | 150 | 1:20 | 3.0 | 28.0 | 15 | 22.0 | 7.8 | No | 45.0 | Head | 1152 | 0.024 | 0.019 | 0.786 | 439 | 0.0638 | 0.0501 |
| 14.00 | 150 | 1:20 | 3.0 | 21.0 | 15 | 17.6 | 4.0 | Yes | 0.0 | Head | 1152 | 0.018 | 0.015 | 0.838 | 383 | 0.0549 | 0.0460 |
| 14.00 | 150 | 1:20 | 3.0 | 21.0 | 15 | 17.6 | 4.0 | Yes | 22.5 | Head | 1152 | 0.018 | 0.015 | 0.838 | 383 | 0.0549 | 0.0460 |
| 14.00 | 150 | 1:20 | 3.0 | 21.0 | 15 | 17.6 | 4.0 | Yes | 45.0 | Head | 1152 | 0.018 | 0.015 | 0.838 | 383 | 0.0549 | 0.0460 |
| 14.00 | 150 | 1:20 | 3.0 | 21.0 | 15 | 17.6 | 4.0 | Yes | 67.5 | Head | 1152 | 0.018 | 0.015 | 0.838 | 383 | 0.0549 | 0.0460 |
| 14.00 | 150 | 1:20 | 3.0 | 21.0 | 15 | 17.6 | 4.0 | Yes | 90.0 | Head | 1152 | 0.018 | 0.015 | 0.838 | 383 | 0.0549 | 0.0460 |
| 14.00 | 150 | 1:20 | 3.0 | 23.0 | 15 | 19.2 | 5.2 | Yes | 45.0 | Head | 1152 | 0.020 | 0.017 | 0.835 | 400 | 0.0576 | 0.0480 |
| Atlantic Station, New Jersey | | | | | | | | | | | | | | | | | |
| 43.00 | 150 | 1:10 | 2.0 | 56.3 | 16 | 40.0 | 23.0 | Yes | 90.0 | Trunk | 1311 | 0.043 | 0.031 | 0.710 | 651 | 0.0865 | 0.0615 |
| 62.00 | 150 | 1:10 | 3.0 | 56.3 | 16 | 40.0 | 10.6 | Yes | Var | Head | 1311 | 0.043 | 0.031 | 0.710 | 651 | 0.0865 | 0.0615 |
| Jubail Harbor, Saudi Arabia | | | | | | | | | | | | | | | | | |
| 5.50 | 150 | Flat | 2.0 | 29.5 | 9 | 15.4 | 10.3 | No | 54.0 | Head | 415 | 0.071 | 0.037 | 0.522 | 257 | 0.1149 | 0.0600 |
| 5.50 | 150 | Flat | 2.0 | 29.5 | 9 | 15.4 | 10.3 | No | 68.0 | Head | 415 | 0.071 | 0.037 | 0.522 | 257 | 0.1149 | 0.0600 |
| Humboldt Bay, California | | | | | | | | | | | | | | | | | |
| 45.00 | 155 | 1:10 | 5.0 | 43.0 | 16 | 40.0 | 7.7 | Yes | 45.0 | Head | 1311 | 0.033 | 0.031 | 0.930 | 575 | 0.0748 | 0.0696 |

Table 5

Summary of Results for Rough Angular Stone Armor

| Armor Height tons | Armor Specific Weight pcf | Bottom Slope | Cot | d, ft | T, sec | H, ft | $K_D$ | Breaking Waves | Angle of Attack deg | Section of Structure | $L_o$ | $d/L_o$ | $H/L_o$ | $H/d$ | $L$ | $d/L$ | $H/L$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Burns Harbor, IN** | | | | | | | | | | | | | | | | | |
| 13.50 | 165 | 1:100 | 1.5 | 47.0 | 11 | 15.0 | 3.1 | No | 90.0 | Trunk | 620 | 0.076 | 0.024 | 0.319 | 394 | 0.1193 | 0.0381 |
| **Long Beach (Sohio), CA** | | | | | | | | | | | | | | | | | |
| 7.50 | 165 | Flat | 2.0 | 55.4 | 13 | 14.0 | 3.8 | No | 90.0 | Trunk | 865 | 0.064 | 0.016 | 0.253 | 512 | 0.1081 | 0.0273 |
| **Mission Bay, CA** | | | | | | | | | | | | | | | | | |
| 14.50 | 165 | Flat | 1.5 | 34.6 | 9 | 16.7 | 4.5 | No | 90.0 | Trunk | 415 | 0.083 | 0.040 | 0.483 | 274 | 0.1262 | 0.0609 |
| 14.50 | 165 | Flat | 1.5 | 34.6 | 15 | 16.7 | 4.5 | No | 90.0 | Trunk | 1152 | 0.030 | 0.014 | 0.483 | 485 | 0.0714 | 0.0344 |
| 14.50 | 165 | Flat | 2.0 | 34.6 | 9 | 16.7 | 3.4 | No | 33.0 | Head | 415 | 0.083 | 0.040 | 0.483 | 274 | 0.1262 | 0.0609 |
| 14.50 | 165 | Flat | 2.0 | 34.6 | 15 | 16.7 | 3.4 | No | 33.0 | Head | 1152 | 0.030 | 0.014 | 0.483 | 485 | 0.0714 | 0.0344 |
| **Morro Bay, CA** | | | | | | | | | | | | | | | | | |
| 25.00 | 175 | 1:50 | 2.25 | 38.0 | 15 | 27.0 | 5.9 | No | 90.0 | Trunk | 1152 | 0.033 | 0.023 | 0.711 | 507 | 0.0750 | 0.0533 |
| **Lahaina Harbor, HI** | | | | | | | | | | | | | | | | | |
| 2.75 | 170 | 1:20 | 2.00 | 7.5 | 16 | 8.0 | 1.7 | Yes | 90.0 | Trunk | 1311 | 0.006 | 0.006 | 1.067 | 247 | 0.0304 | 0.0324 |
| **Jubail Harbor, Saudi Arabia** | | | | | | | | | | | | | | | | | |
| 7.15 | 165 | 1:10 | 2.00 | 19.7 | 9 | 13.4 | 3.5 | Yes | 90.0 | Trunk | 415 | 0.048 | 0.032 | 0.680 | 215 | 0.0914 | 0.0622 |
| **Port Ontario Harbor, NY** | | | | | | | | | | | | | | | | | |
| 5.30 | 155 | 1:50 | 2.00 | 12.3 | 11 | 9.8 | 2.1 | Yes | 90.0 | Trunk | 620 | 0.020 | 0.016 | 0.797 | 214 | 0.0574 | 0.0457 |
| **San Juan, Puerto Rico** | | | | | | | | | | | | | | | | | |
| 33.90 | 165 | 1:20 | 2.00 | 22.9 | 17 | 23.3 | 3.9 | Yes | 90.0 | Trunk | 1480 | 0.015 | 0.016 | 0.017 | 454 | 0.0504 | 0.0513 |
| 27.70 | 165 | 1:20 | 2.00 | 26.9 | 17 | 28.0 | 8.3 | Yes | 72.0 | Head | 1480 | 0.018 | 0.019 | 1.041 | 491 | 0.0548 | 0.0571 |
| 27.70 | 165 | 1:20 | 2.00 | 26.9 | 17 | 28.0 | 8.3 | Yes | 42.0 | Head | 1480 | 0.018 | 0.019 | 1.041 | 491 | 0.0548 | 0.0571 |
| **Masonboro Inlet, NC** | | | | | | | | | | | | | | | | | |
| 18.00 | 165 | 1:20 | 2.00 | 14.5 | 15 | 13.5 | 1.4 | Yes | 90.0 | Trunk | 1152 | 0.013 | 0.012 | 0.931 | 320 | 0.0453 | 0.0422 |
| **Oregon Inlet, NC** | | | | | | | | | | | | | | | | | |
| 22.00 | 165 | 1:20 | 1.5 | 16.5 | 15 | 15.5 | 2.4 | Yes | 90.0 | Trunk | 1152 | 0.014 | 0.013 | 0.939 | 340 | 0.0485 | 0.0455 |
| 30.00 | 165 | 1:20 | 3.0 | 28.0 | 15 | 22.0 | 2.5 | No | 45.0 | Head | 1152 | 0.024 | 0.019 | 0.786 | 439 | 0.0638 | 0.0501 |
| 30.00 | 165 | 1:20 | 3.0 | 21.0 | 15 | 17.6 | 1.3 | Yes | 90.0 | Head | 1152 | 0.018 | 0.015 | 0.838 | 383 | 0.0549 | 0.0460 |
| 30.00 | 165 | 1:20 | 3.0 | 23.0 | 15 | 19.2 | 1.7 | Yes | 45.0 | Head | 1152 | 0.020 | 0.017 | 0.835 | 400 | 0.0576 | 0.0480 |
| **Fort Fisher, NC** | | | | | | | | | | | | | | | | | |
| 4.30 | 165 | 1:55 | 2.00 | 14.7 | 10 | 11.8 | 4.0 | Yes | 90.0 | Trunk | 512 | 0.029 | 0.023 | 0.803 | 211 | 0.0697 | 0.0559 |
| **St. Paul, AK** | | | | | | | | | | | | | | | | | |
| 18.00 | 166 | 1:100 | 2.5 | 27.0 | 14 | 21.2 | 4.3 | Yes | 90.0 | Trunk | 1004 | 0.027 | 0.021 | 0.785 | 401 | 0.0673 | 0.0529 |
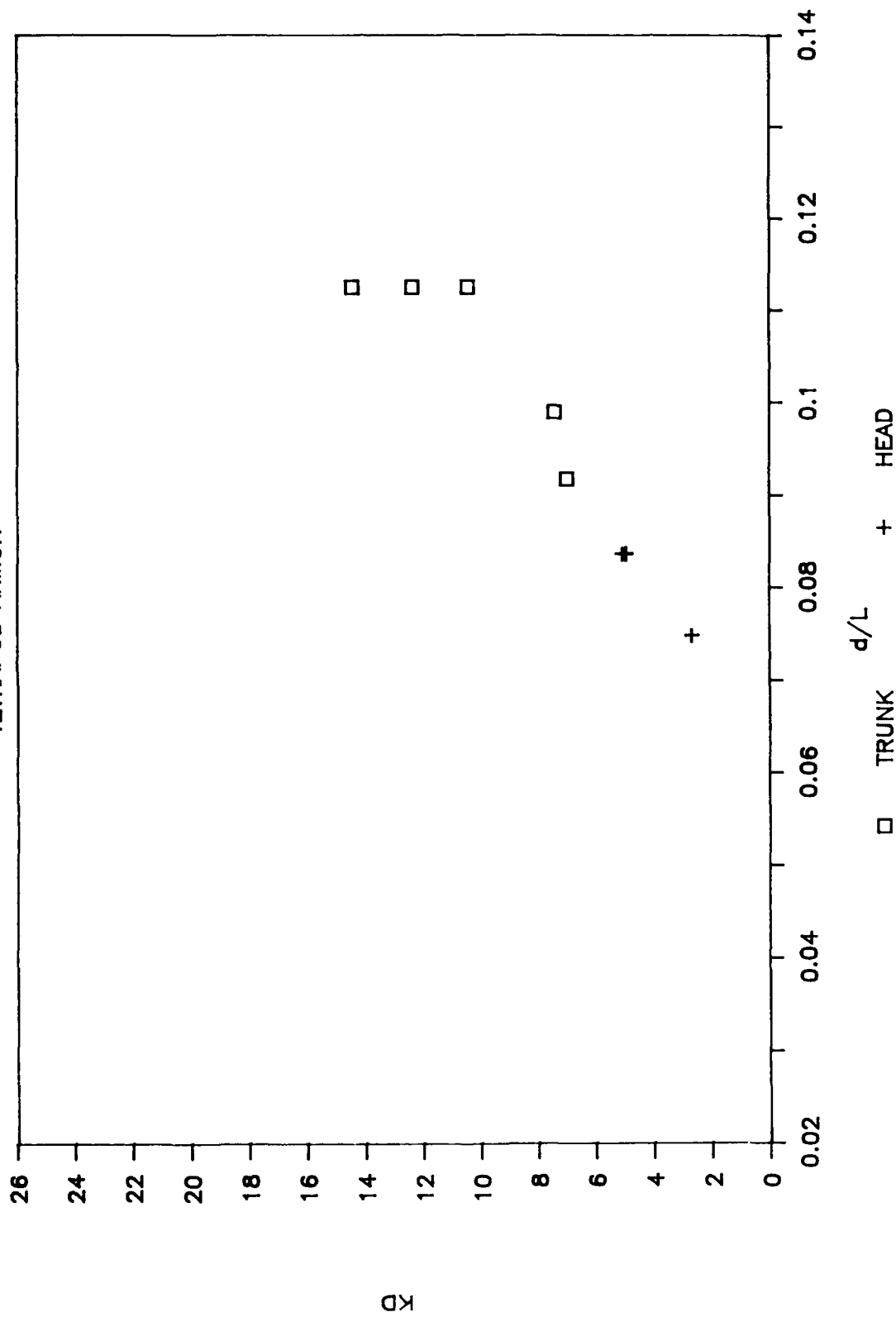
Figure 1. $K_D$ as a function of d/L
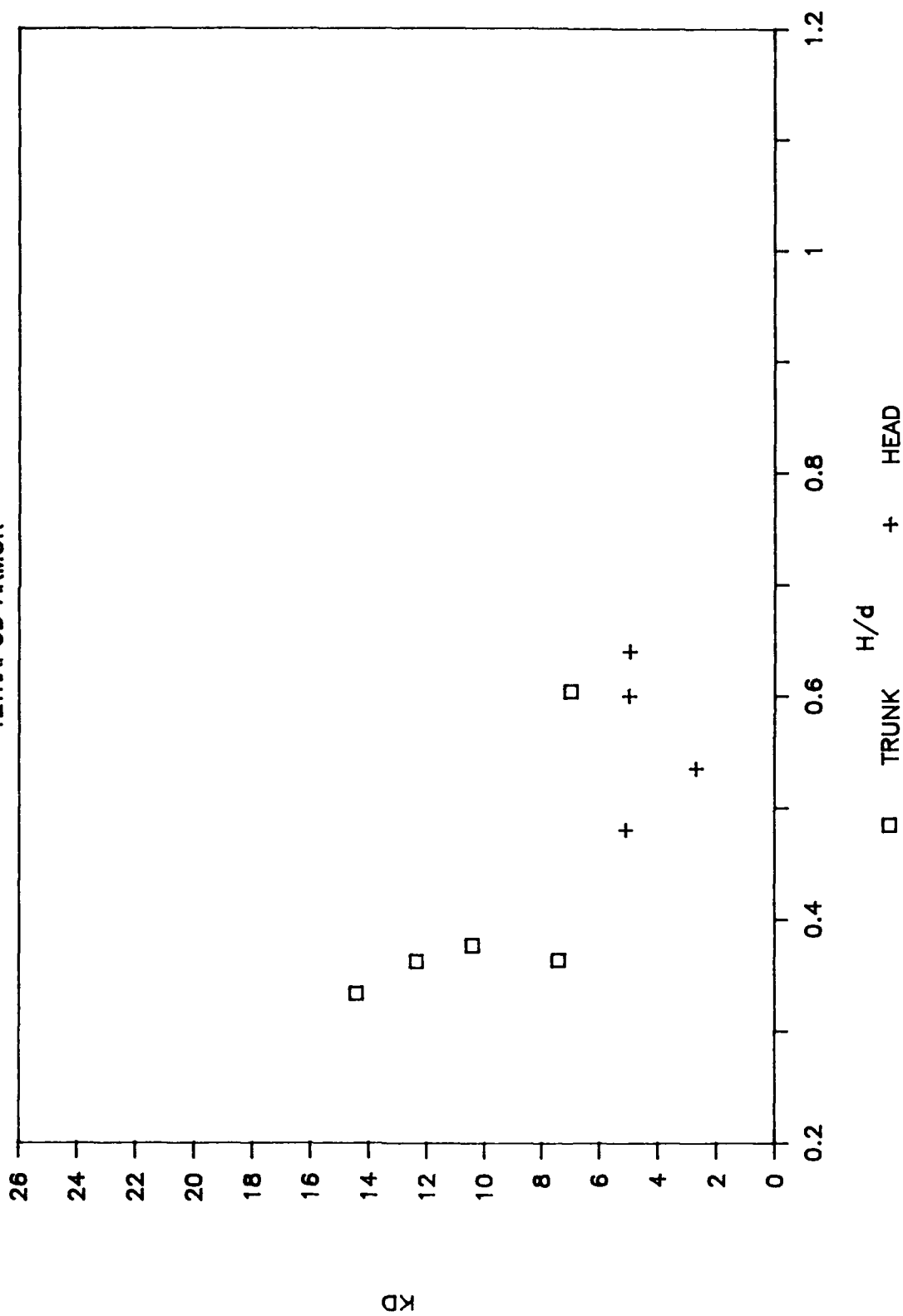
Figure 2. $K_D$ as a function of H/d
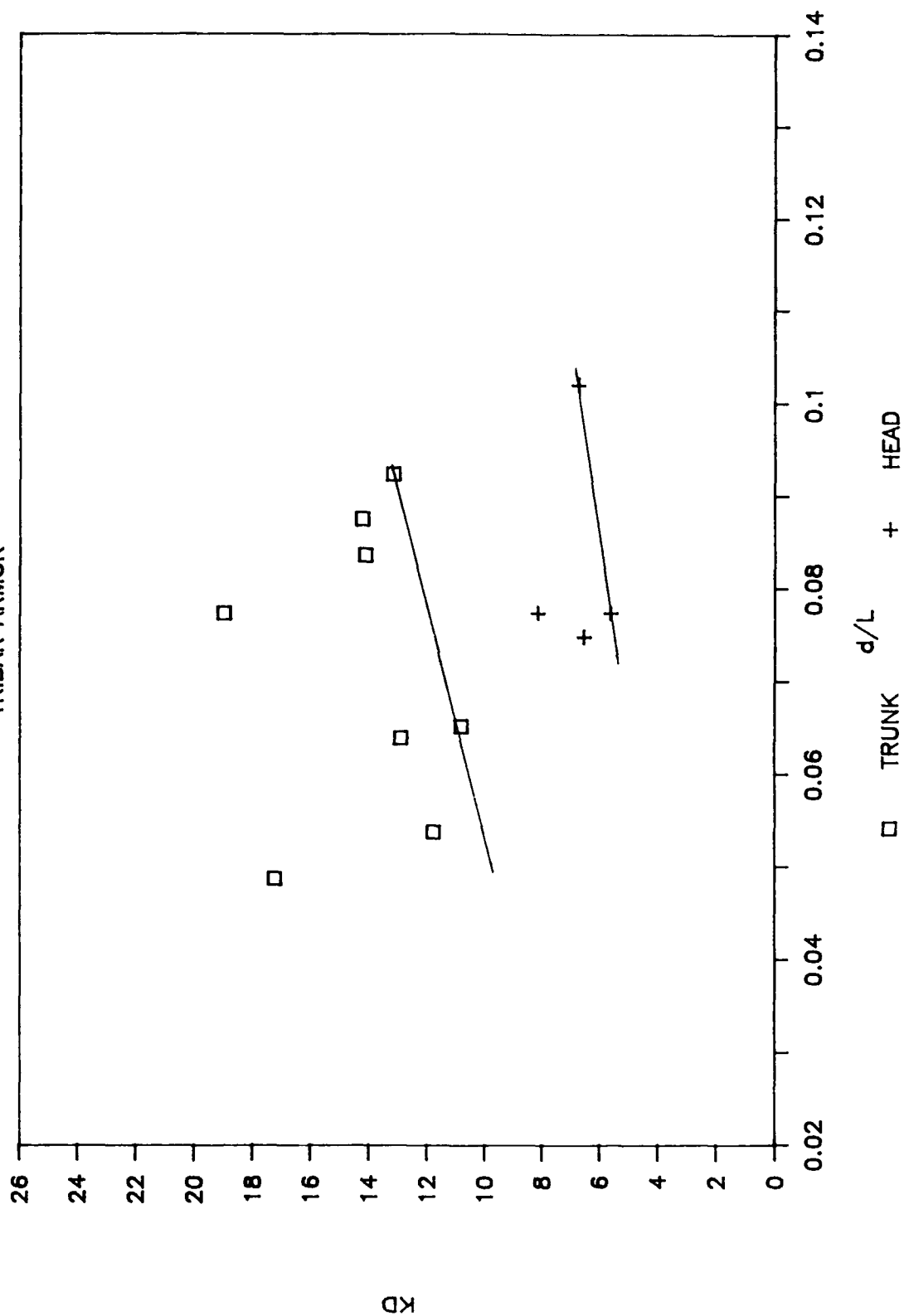
Figure 3. Tribar stability as a function of d/L
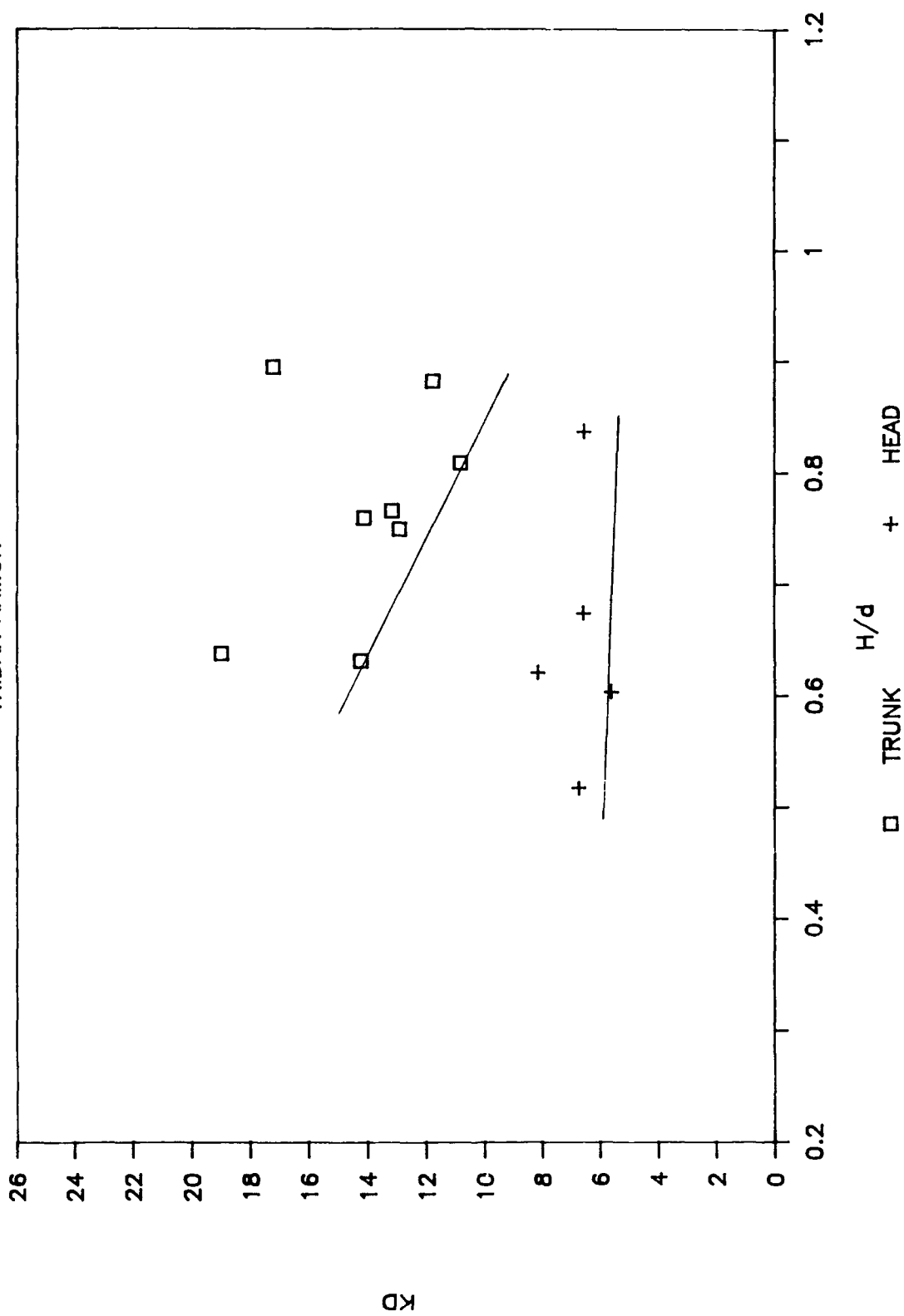
Figure 4. Tribar stability as a function of H/d
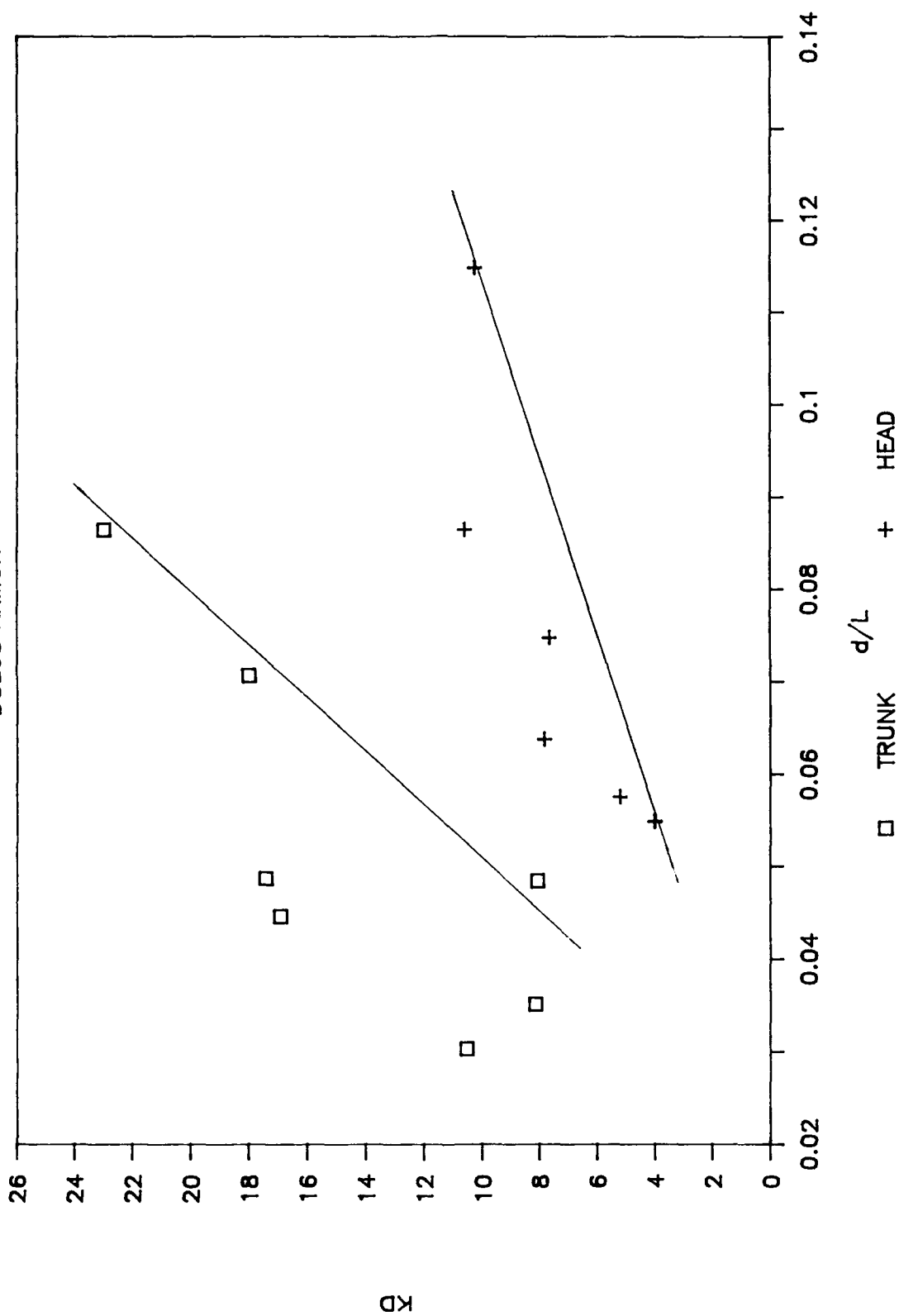
Figure 5.  Dolos stability as a function of  d/L
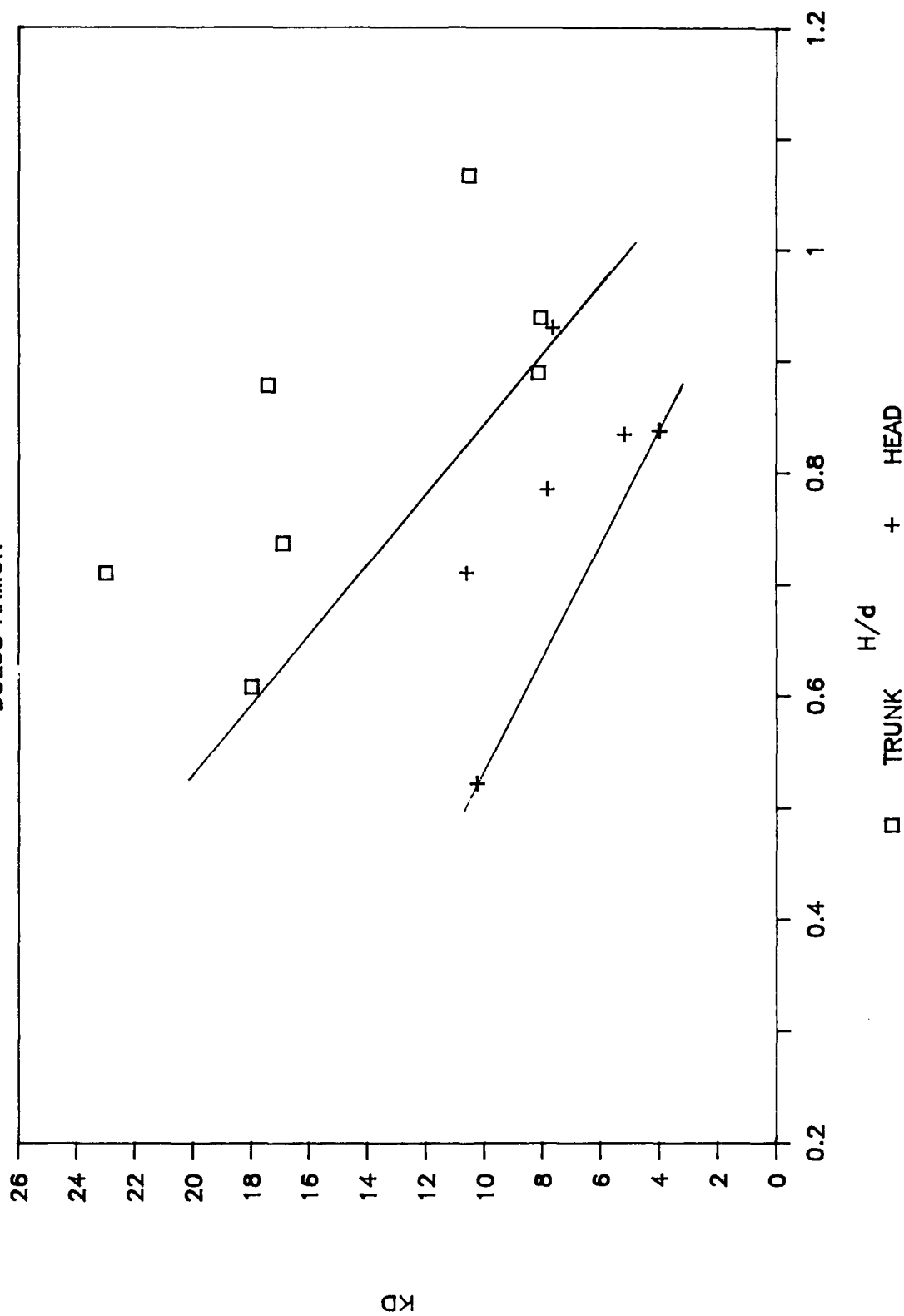
Figure 6. Dolos stability as a functioon of H/d
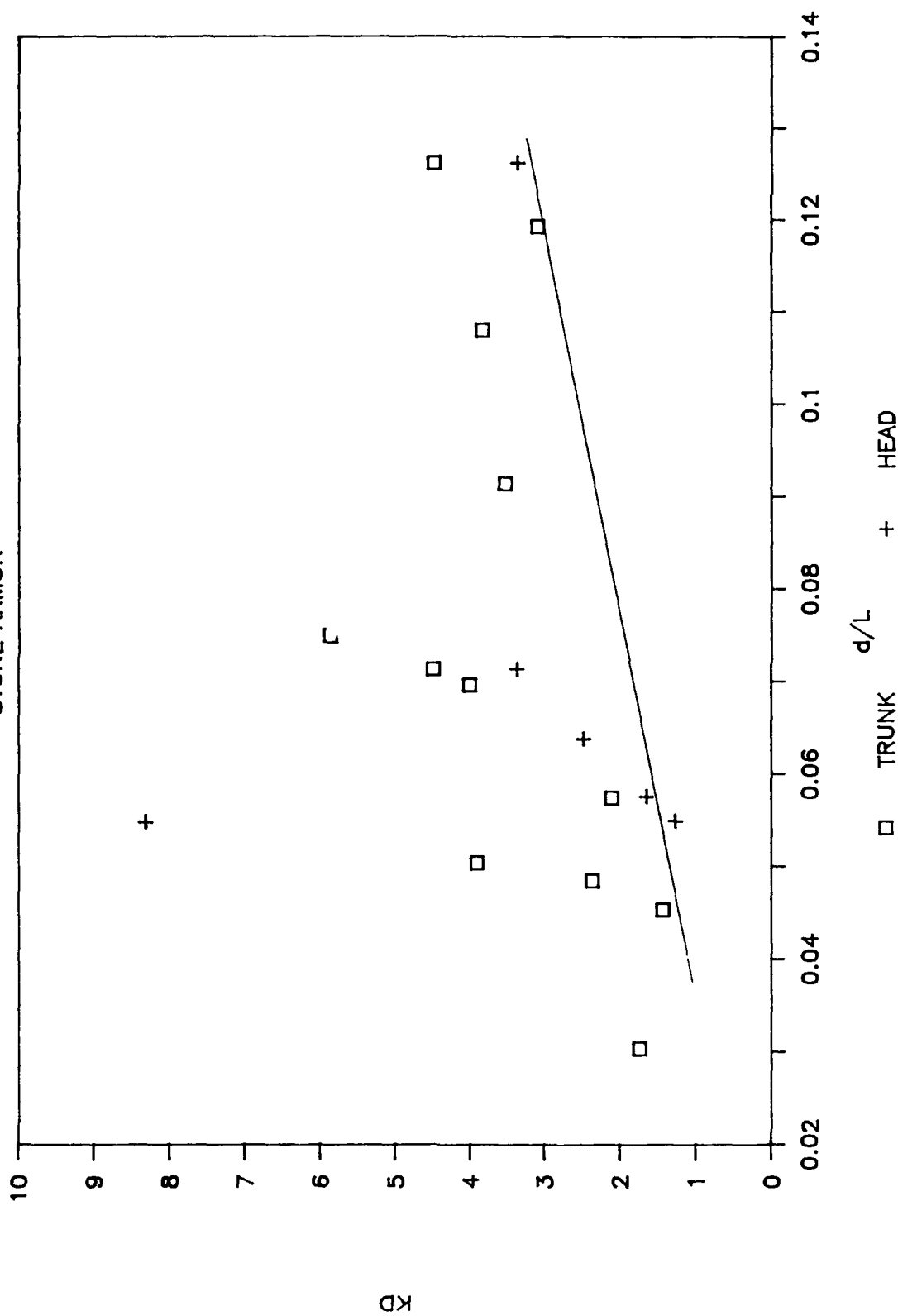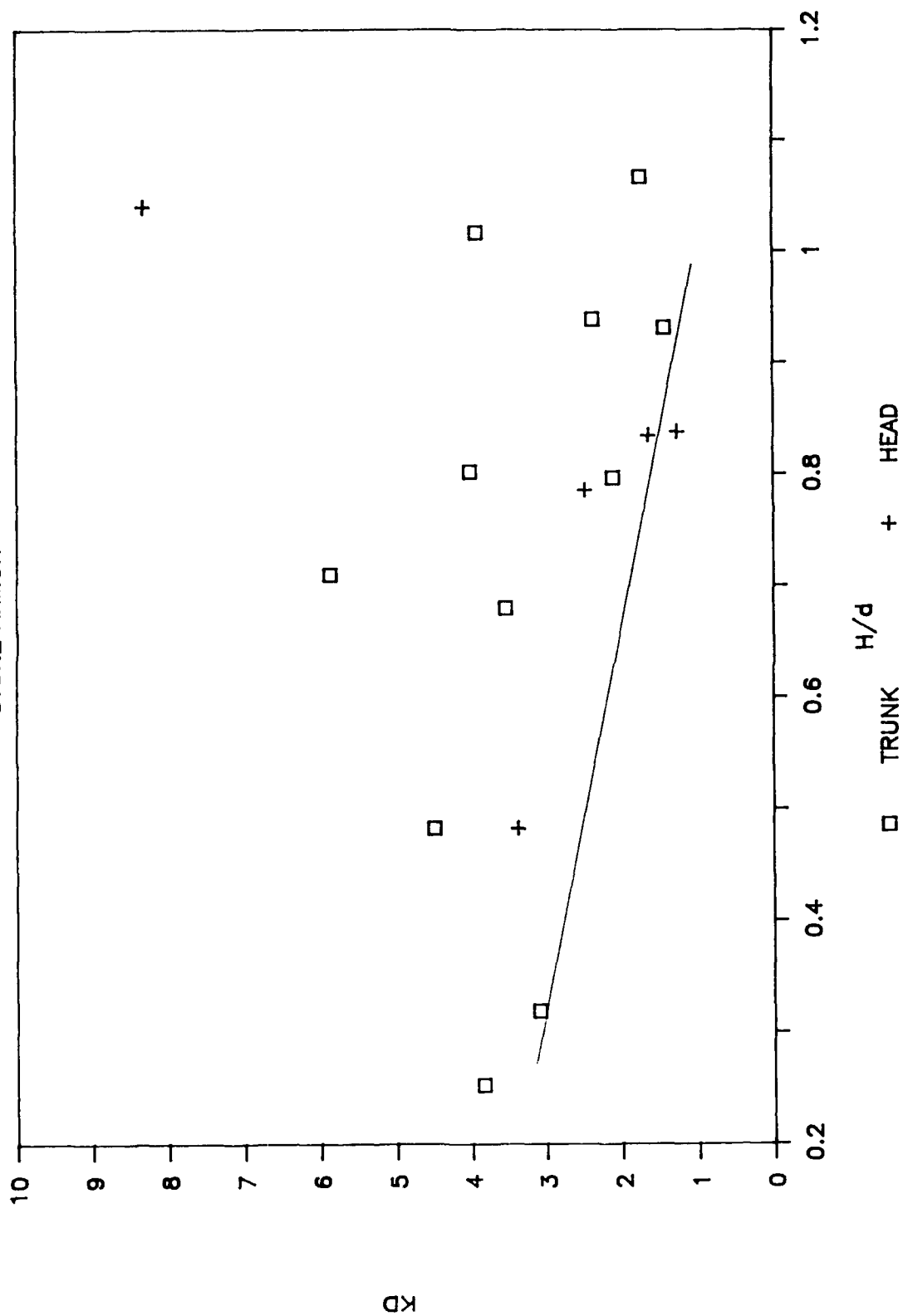
Figure 7. Stone armor stability as a function of d/L

Figure 8.  Stone armor stability as a function of H/d

# RELATIVE WAVE HEIGHT VS BOTTOM SLOPE
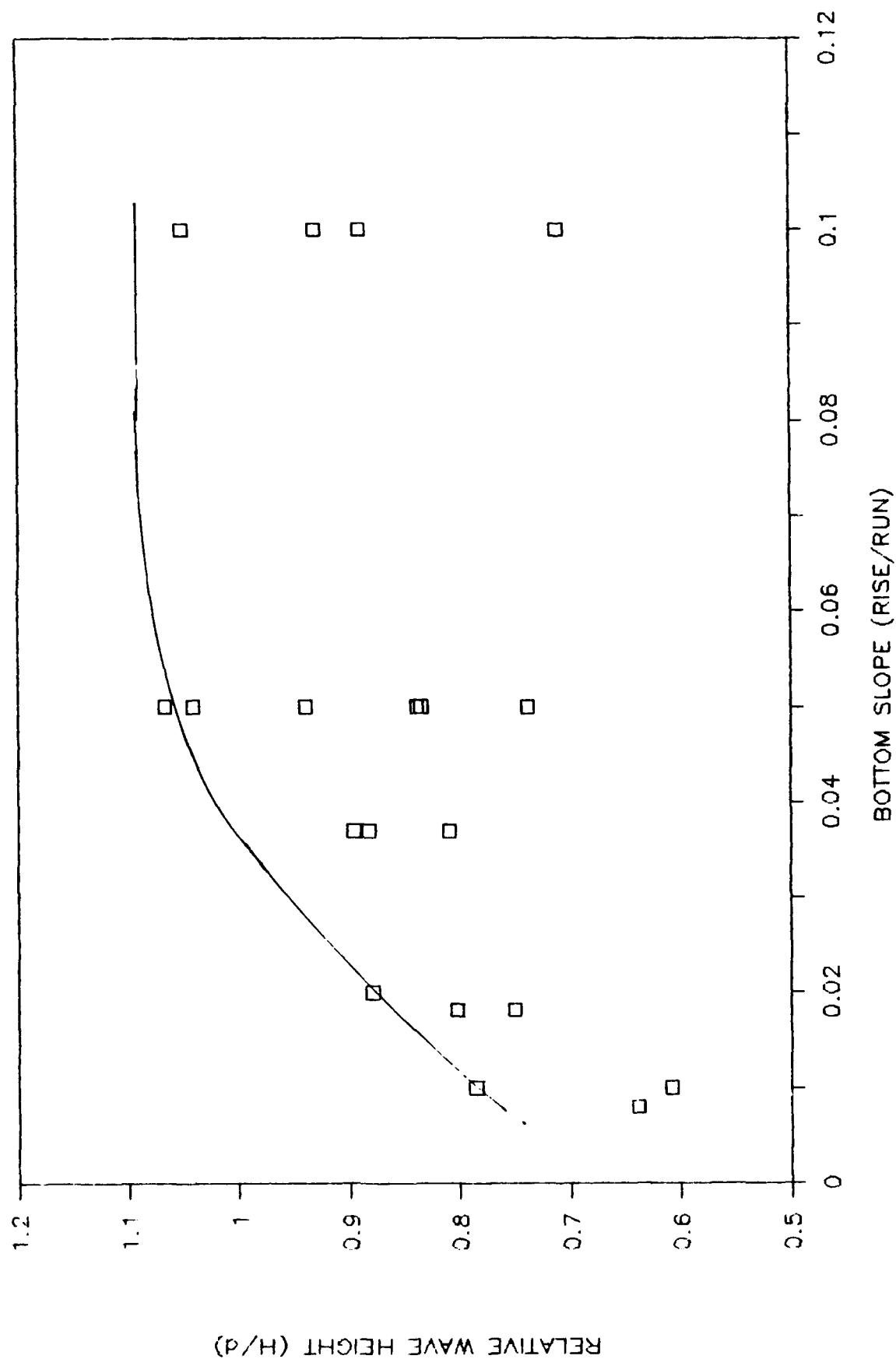


Figure 9.  H/d  as a function of bottom slope

# APPENDIX A: NOTATION

| | |
|---|---|
| $d$ | Water depth, ft |
| $d/L$ | Relative depth, dimensionless |
| $g$ | Acceleration due to gravity, $ft/sec^2$ |
| $H$ | Wave height, ft |
| $H/d$ | Relative wave height, dimensionless |
| $K_D$ | Stability coefficient, dimensionless |
| $L$ | Wave length at a given water depth, ft |
| $L_o$ | Deepwater wavelength, ft |
| $T$ | Wave period, sec |
| $W_a$ | Weight of an armor unit, lb |
| $\alpha$ | Angle of breakwater slope, measured from horizontal, deg |
| $\cot \alpha$ | Reciprocal of breakwater slope |
| $\gamma_a$ | Specific weight of armor unit, pcf |