TP 13046E

# Mooring Selection Guide
# Software Development

Prepared for
Canadian Coast Guard
Marine Navigation Services and
Transportation Development Centre
Safety and Security
Transport Canada
March 1997

Prepared by:

A.S. Dinovitzer
M. Steele
Fleet Technology Limited
311 Legget Drive
Kanata, Ontario
K2K 1Z8

## Disclaimer

The contents of this manual and the processes and data that are embedded in the program reflect the views of the above named contractors and do not necessarily reflect the official view or opinions of the Transportation Development Centre of Transport Canada or the Canadian Coast Guard.

The Transportation Development Centre does not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

## FTL Document Quality Control Data Sheet

| | |
|---|---|
| Report: | **DEVELOPMENT OF A MOORING SELECTION GUIDE SOFTWARE** |
| Project No. | 4706 |
| Date: | March 1997 |

Prepared by:

A. Dinovitzer, Senior Engineer

Checked by:

L. Malik, Director of Materials Research

Approved for
Release by:

I. Glen, President - Fleet Technology Limited

Un sommaire français se trouve avant la table des matières.

Transport Canada Transports Canada

# PUBLICATION DATA FORM

1. Transport Canada Publication No.
TP 13046E

2. Project No.
8835

3. Recipient's Catalogue No.

4. Title and Subtitle
Mooring Selection Guide Software Development

5. Publication Date
March 1997

6. Performing Organization Document No.

7. Author(s)
Aaron Dinovitzer, Mike Steele

8. Transport Canada File No.
ZCD1460-349-2

9. Performing Organization Name and Address
Fleet Technology Limited
311 Legget Drive
Kanata, Ontario
K2K 1Z8

10. PWGSC File No.
XSD95-00132-(671)

11. PWGSC or Transport Canada Contract No.
T8200-5-5525/01-XSD

12. Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
800 René Lévesque Blvd. West
6th Floor
Montreal, Quebec
H3B 1X9

13. Type of Publication and Period Covered
Final

14. Project Officer
J.-L. René

15. Supplementary Notes (Funding programs, titles of related publications, etc.)
Co-sponsored by Department of Fisheries and Oceans Marine Navigation Services.
See also TP 13049E, Mooring Selection Guide (MSG) Program Manual.

16. Abstract

A computer program known as the Mooring Selection Guide (MSG) has been developed to provide the Coast Guard with a tool for designing long life buoy mooring systems. The software considers the hydrodynamic loads, the long-term degradation (wear/corrosion) and residual strengths of the riding and thrash chains. In addition, the loads applied to the sinker are used to calculate a minimum required anchor size to hold the buoy on station. The software operates in either French or English, includes a complete menu-driven help system, and allows the user to store and retrieve mooring design data.

This report presents the technical algorithms and design decisions employed by the Mooring Selection Guide software.

17. Key Words
Mooring, buoy, anchor, sinker, chain mooring system

18. Distribution Statement
Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)
Unclassified

20. Security Classification (of this page)
Unclassified

21. Declassification (date)
—

22. No. of Pages
xiv, 32

23. Price
—

CDT/TDC 79-005
Rev. 96

Canada

Transports Canada
Transport Canada

# FORMULE DE DONNÉES POUR PUBLICATION

1\. N° de la publication de Transports Canada
TP 13046E

2\. N° de l'étude
8835

3\. N° de catalogue du destinataire

4\. Titre et sous-titre
Mooring Selection Guide Software Development

5\. Date de la publication
Mars 1997

6\. N° de document de l'organisme exécutant

7\. Auteur(s)
Aaron Dinovitzer, Mike Steele

8\. N° de dossier - Transports Canada
ZCD1460-349-2

9\. Nom et adresse de l'organisme exécutant
Fleet Technology Limited
311 Legget Drive
Kanata, Ontario
K2K 1Z8

10\. N° de dossier - TPSGC
XSD95-00132-(671)

11\. N° de contrat - TPSGC ou Transports Canada
T8200-5-5525/01-XSD

12\. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
800, boul. René-Lévesque Ouest
6e étage
Montréal (Québec)
H3B 1X9

13\. Genre de publication et période visée
Final

14\. Agent de projet
J.-L. René

15\. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)
Coparrainé par Pêches et Océans Canada - Services de la navigation maritime.
Voir également le document TP 13049F, Guide de sélection des systèmes de mouillage (GSSM) Manuel de l'utilisateur.

16\. Résumé

Le «Guide de sélection des systèmes de mouillage (GSSM)» est un logiciel mis au point pour la Garde côtière canadienne en tant qu'outil destiné à la conception de systèmes de mouillage à chaînes pour bouées à cycle de vie long. Ce logiciel tient compte de la détérioration à long terne (usure et corrosion) et de la résistance résiduelle des chaînes flottantes et de marnage ainsi que des charges hydrodynamiques imposées à celles-ci. Il utilise en outre les charges imposées aux crapauds pour déterminer la grosseur minimale du corps-mort qui servira à maintenir la bouée en place. Le logiciel peut être utilisé en français ou en anglais, comporte un système d'aide complet piloté par menu et permet à l'utilisateur d'emmagasiner ou de récupérer des données sur les calculs relatifs aux systèmes de mouillage.

Ce rapport présente les algorithmes techniques et les décisions conceptuelles utilisés dans le logiciel «Guide de sélection des systèmes de mouillage (GSSM)»

17\. Mots clés
Mouillage, bouée, corps-mort, crapaud, systèmes de mouillage à chaînes

18\. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

| | | | | |
|---|---|---|---|---|
| 19. Classification de sécurité (de cette publication) | 20. Classification de sécurité (de cette page) | 21. Déclassification (date) | 22. Nombre de pages | 23. Prix |
| Non classifiée | Non classifiée | — | xiv, 32 | — |

## Project Review Committee

This work has been guided by a project review committee comprising:

| | |
|---|---|
| D. Long | Canadian Coast Guard, Marine Aids Division |
| J.-L. René | Transportation Development Centre - Project Officer |
| R. Silberhorn | Canadian Coast Guard, Marine Aids Division |

Their input to the project throughout its development has been most useful and encouraging.

The project team would also like to acknowledge the CCG headquarters and regional staff from across Canada whose cooperation and input throughout the development process provided practical guidance in the development of this software. In particular:

R. Beauchesne
K. Sanford
E. Rotgans
Keith Taylor
Phil Nelson
R. Flemming

## Project Team

The development of the theory and software included in the Mooring Selection Guide are the result of the efforts of:

**Fleet Technology Limited:**

| | |
|---|---|
| Lalit Malik | Project Manager |
| Aaron Dinovitzer | Principal Investigator |
| Mike Steele | Programmer |
| Rosemary Gardner | Technical Illustrator |
| James Luffman | Mech. Eng. Technician |
| Reagan McIssac | Student Engineer |

**Subcontractors:**

| | |
|---|---|
| Balji Menon | Menon Inc. |

## Summary

The Marine Aids Division of the Canadian Coast Guard has the responsibility for design, installation and maintenance of navigation buoys. One of the important load carrying components in the buoy system is the mooring chain. As a matter of routine practice, the mooring chains have been inspected frequently and if the wastage due to corrosion and/or wear is considered unacceptable, then the chain is replaced. As a consequence of this proactive inspection and maintenance approach, the chain failures have been infrequent and the overall experience to date with mooring chains is considered to be a success. However, this record of success may not have been entirely cost effective due to chain inspection and replacement costs.

The Canadian Coast Guard set a long term goal of achieving a minimum of five years of unattended service from year round navigation buoys and their mooring chains. In order to achieve this goal Fleet Technology Limited (FTL) of Kanata, Ontario was contracted to investigate the feasibility of designing a mooring system to provide five years of unattended service.

The study involved estimation and comparison of the peak steady state and dynamic loads on the riding chain under severe sea conditions and of residual strength of the riding chains of different sizes and qualities after 5 years of service. The dynamic load estimation was performed for a 10 year wave using the Moordyn program developed and validated by the National Research Council's Hydraulics Laboratories. The peak tension in the riding chain was estimated for selected combinations of riding chain diameters, mooring chain scopes and water depths. It was found that highest dynamic loads are experienced in shallower waters and for smaller mooring chain scopes.

The estimation of the residual strength of the riding chains required the development of an empirical model to predict the inter-link wastage rate due to wear and/or corrosion and another mechanics-based model to predict the residual strength of chains as a function of the chain steel strength and wastage that might not be circumferentially uniform. The latter was based on a model developed from the wastage rates observed (in a previous CCG sponsored study) for thrash and riding chains in the approaches to Halifax Harbour during a five-year service period.

### Objective

The objective of this project was to produce a buoy mooring chain selection guide in the form of a computer program which identifies riding, thrash and ground chains capable of providing 5 years of unattended service for the following CCG buoys:

- 2.9m Lighted Bell Buoy
- 2.9m Lighted Whistle Buoy
- 1.8m Lighted Buoy
- 1.4m Lighted Buoy
- 3m Lighted Scow Buoy
- 1.5m Lighted Discus Buoy
- 0.6m Spar Buoy
- 0.8m Coastal Buoy (Can and Conical version)
- 1.2m Coastal Buoy (Can and Conical version)
- 1.6m Coastal Buoy (Can and Conical version)

## Scope of Work

The technical work performed in the development of the Mooring Selection Guide (MSG) software outlined in this report include the following:

- development of riding and thrash chain wear models,
- determination of appropriate design environmental conditions,
- determination of buoy mooring dynamic response including ice accumulation, and
- a review of buoy buoyancy/freeboard requirements.

The following report describes the technical investigations and development work performed in order to produce the mooring selection guide. A description of the software and its operation are included in the Mooring Selection Guide User Manual and on-line help menus and are not repeated in this report.

## Further Development Work Recommendations

The Mooring Selection Guide software was developed as a mooring design tool for use by the CCG bases. In order to ensure that the resulting software was useful, the development process included frequent consultation with base operations personnel. During the development project new features and functions were added as needed to satisfy the needs of the end users.

With the delivery of this software some suggestions for further development are given here for consideration:

- The scope of application of the software could be extended to handle the remainder of the CGG buoys. This extension of the software could be handled by either generating more buoy behavior data to enhance the current database or revising existing mooring dynamics models to speed up their operation and improve their computational stability.
- The buoy freeboard calculations and CCG minimum freeboard requirements could be reviewed to improve their performance. The MSG software could be revised to include a buoy additional mass field to enable the user to calibrate the weight of their version of the CCG standard buoys.
- Further information on the degradation of mooring chains could be used to improve the chain wear model. This development requires a concerted effort on the part of the CCG base operations personnel to maintain mooring service and wear data.
- The effectiveness of case hardening the thrash sections of mooring chains to reduce chain wear could be performed. The results of this investigation could be incorporated into the MSG chain degradation model.
- It is suggested that the performance of this software be monitored to identify any future modifications to the software.
- This software should be demonstrated to IALA members to solicit their opinions on the software and develop joint research and development work.

## Sommaire

La Division des aides à la navigation maritime de la Garde côtière canadienne (GCC) est responsable de la conception, du mouillage et de l'entretien des bouées de navigation maritime. Le maintien à poste des bouées est assuré par une chaîne de mouillage qui absorbe le gros des efforts sollicitant la bouée. Dans la pratique courante, cet élément fait l'objet d'inspections fréquentes aboutissant à son remplacement dès que le degré d'usure et/ou de corrosion constaté dépasse les valeurs admises. Cette pratique d'inspection et d'entretien préventif ayant permis d'éviter quasi totalement les ruptures, la Garde côtière considère que son programme est une réussite. Il reste cependant que la rentabilité de l'opération pourrait être améliorée par une réduction des coûts d'inspection et de remplacement des chaînes de mouillage.

La GCC s'est fixé comme objectif à long terme d'obtenir de son parc de bouées, et des chaînes de mouillage, une période de service sans entretien d'au moins cinq ans. Pour y parvenir, elle a confié à Fleet Technology Limited (FTL), de Kanata, Ontario, un marché portant sur l'étude de la faisabilité d'un dispositif de mouillage dont la périodicité d'entretien atteindrait cinq ans.

La démarche a consisté à évaluer et à comparer d'une part les charges statique et dynamique maximales sollicitant les parties pendantes du dispositif de mouillage dans des états de mer variés et d'autre part la résistance résiduelle au bout de cinq ans des chaînes mises en oeuvre, de dimensions et de qualité variées. Les charges dynamiques ont été estimées en fonction de la plus haute vague décennale à l'aide du programme Moordyn réalisé et validé par le Laboratoire d'hydraulique du Conseil national de recherches. La tension maximale sollicitant la partie pendante a été estimée pour diverses combinaisons de diamètre de chaîne, de rapport longueur de chaîne/profondeur d'eau et de profondeur d'eau. La recherche a montré que les charges dynamiques les plus élevées sont associées aux faibles profondeurs d'eau et aux faibles rapports longueur de chaîne/profondeur d'eau.

Le calcul estimatif de la résistance résiduelle a nécessité la mise au point d'un modèle empirique permettant de prévoir le taux d'usure due au frottement des maillons et/ou à la corrosion, et la mise au point d'un second modèle, fondée sur la mécanique des solides, pour le calcul estimatif de la résistance résiduelle en fonction d'une résistance du matériau et un taux d'usure qui ne seraient pas uniformes en tous points de la circonférence des maillons. Ce dernier était fondé sur un modèle exploitant les taux d'usure mesurés, à l'occasion d'une étude antérieure d'une durée de cinq ans commandée par la GCC, sur les parties pendantes et dormantes de chaînes de mouillage établies à différents endroits dans la rade du port d'Halifax.

## Objectif

Cette recherche avait pour objectif la réalisation d’un guide informatisé de sélection des chaînes de mouillage de bouées qui permettrait de déterminer les combinaisons de corps-mort, de chaîne pendante et de chaîne dormante frottant contre le fond qui donneront une périodicité d’entretien de cinq ans dans le cas des bouées ci-dessous de la GCC :

- Bouée lumineuse à cloche, 2,9 m
- Bouée lumineuse à sifflet, 2,9 m
- Bouée lumineuse, 1,8 m
- Bouée lumineuse, 1,4 m
- Bouée chalande lumineuse, 3 m
- Bouée-disque lumineuse, 1,5 m
- Bouée-espar, 0,6 m
- Bouée côtière, 0,8 m (versions cylindrique et conique)
- Bouée côtière, 1,2 m (versions cylindrique et conique)
- Bouée côtière, 1,6 m (versions cylindrique et conique)

## Portée des travaux

Les travaux techniques réalisés en vue du développement du logiciel-guide de sélection des dispositifs de mouillage décrit dans ce rapport comprenaient:

- élaboration des modèles d’usure des chaînes pendantes et dormantes
- détermination des paramètres de conception appropriés du point de vue des conditions environnementales
- détermination de la réponse dynamique des chaînes de mouillage aux charges (ex. : accumulation de glace)
- revue des exigences de flottabilité/franc bord des bouées.

Le rapport décrit les études techniques et les travaux de déveleppoment ayant mené à la réalisation du guide de sélection. La description du logiciel et de son fonctionnement étant fournie dans le Manuel de l’utilisateur et les menus d’aide en ligne, elle n’est pas reprise dans ce rapport.

## Recommandations concernant les travaux de développement complémentaire

Le logiciel-guide de sélection des dispositifs de mouillage a été conçu comme un outil de conception assistée à être utilisé par les bases de la GCC. Pour garantir l'utilité du logiciel, les chercheurs ont abondamment consulté le personnel d'exploitation concerné et intégré au logiciel, en cours de route, de nouvelles caractéristiques et fonctionnalités à la demande de ceux qui seraient appelés à l'utiliser.

Au moment de livrer ce logiciel, il nous semble opportun de suggérer des axes de développement complémentaire à considérer :

- La portée d'application du logiciel pourrait être étendue aux autres types de bouées exploités par la GCC. Cette extension pourrait se faire soit en recueillant davantage de données sur le comportement des bouées, soit en réétudiant les modèles de comportement dynamique des bouées pour accélérer le traitement et améliorer leur robustesse.
- On pourrait revoir les calculs de franc-bord et les exigences minimales correspondantes de la GCC pour améliorer le comportement des bouées. On pourrait également réétudier le logiciel MSG pour y inclure un champ «masse ajoutée» qui permettrait à d'autres utilisateurs de faire intervenir dans les calculs la masse réelle de leurs propres versions des bouées standard de la GCC.
- Des données plus complètes sur la dégradation des chaînes de mouillage permettraient d'améliorer le modèle de prévision de l'usure des chaînes. La réalisation de cet objectif nécessiterait un effort concerté du personnel d'exploitation de la GCC pour la tenue à jour d'une base données sur l'entretien des chaînes de mouillage et l'évolution de leur état.
- Une étude pourrait être faite de l'efficacité de la cémentation comme moyen de ralentir l'usure des chaînes. Les résultats de cette étude pourraient être intégrés au modèle de dégradation des chaînes du MSG.
- Il serait opportun de monitorer la performance du logiciel pour pouvoir cerner les modifications et améliorations nécessaires.
- Il serait bon de présenter ce logiciel à certains membres de l'Association internationale de la signalisation maritime pour connaître leur avis et élaborer avec eux des projets conjoints de recherche-développement.

# Table of Contents

page

1. INTRODUCTION ..........1
    - 1.1 Background ..........1
    - 1.2 Objective ..........2
    - 1.3 Scope of Work ..........3
2. MOORING CHAIN DEGRADATION ..........4
    - 2.1 Effect of Fresh vs. Salt Water on Chain Corrosion/Degradation ..........4
    - 2.2 Chain Wear Models ..........6
    - 2.3 Revised Chain Wear Models ..........7
    - 2.4 MSG Wear Factor ..........13
3. SELECTION OF ENVIRONMENTAL PARAMETERS FOR MOORING DESIGN ..........14
    - 3.1 Review of Canadian Coastal Mooring Site Environmental Conditions ..........14
    - 3.2 MSG Design Environmental Conditions ..........17
    - 3.3 MSG Environmental Factor ..........18
4. MOORING CHAIN DESIGN LOADS ..........19
    - 4.1 Modeling of Peak Tension in the Mooring Chain ..........19
        - 4.1.1 Steady State Mooring Loads ..........19
        - 4.1.2 Steady-State Forces on Buoy Hull ..........20
        - 4.1.3 Buoy Dynamic Response Calculations ..........21
        - 4.1.4 Modeling of Dynamic Loads in Mooring Chains ..........21
    - 4.2 Peak Tensions and Reserve Buoyancy ..........22
    - 4.3 Mooring Line Load Response Surfaces ..........23
5. ICE ACCRETION EFFECTS ..........24
6. SINKER SIZING ..........26
    - 6.1 Minimum and Maximum Sinker Sizes ..........29
7. MOORING DESIGN SAFETY ..........30
8. FURTHER DEVELOPMENT WORK ..........31

REFERENCES ..........32

## List of Tables

page
Table 2.1: Supplementary Chain Wear Data Summary....8
Table 2.2: Influences on Chain Wear Rates....9
Table 2.3: Revised Wear Model Coefficients....10
Table 3.1: Estuary, Coastal and Deep Water Ten-Year Return Period Environmental Conditions16
Table 3.2: Design Environmental Conditions....17
Table 4.1: Mooring System Load Configuration Variables....19
Table 5.1: Buoy Superstructure Ice Accumulation....24
Table 5.2: Sample Ice Accretion Calculations for the 2.9 m Bell Buoy....25
Table 5.3: Calculated Ice Surcharge....25
Table 6.1: Soil Properties for Each Bottom Type....28
Table 6.2: Minimum and Maximum Sinker Sizes....29
Table 7.1: Design Factors of Safety....30

## List of Figures

page
Figure 2.1: Corrosion of Ordinary Steel in the Sea....4
Figure 2.2: Effect of Velocity on Corrosion of Piping by Seawater....5
Figure 2.3: Idealized Worn Chain Cross Section....6
Figure 2.4: Effect of Mooring Depth on Chain Wear....9
Figure 2.5: Revised Thrash Chain Wear Model....11
Figure 2.6: Revised Riding Chain Wear Model - Including Depth Correction....11
Figure 2.7: Riding Chain Wear Model - Including Depth Correction - 1" Dia Chain....11
Figure 2.8: Worn Mooring Chain Link Aspect Ratio Model....12
Figure 2.9: Comparison of Worn Mooring Chain Link Aspect Ratio Data and Model....12
Figure 6.1: Anchor Design Loads....26

# 1. INTRODUCTION

## 1.1 Background

The Marine Aids Division of the Canadian Coast Guard has the responsibility for design, installation and maintenance of navigation buoys. One of the important load carrying components in the buoy system is the mooring chain. In the past, the design requirements and procurement of mooring chain have been based on the use of relatively low strength carbon steel chains. More recently, alloy steel chains have been used; however, the experience with these has been mixed, primarily due to an apparent increase in inter-link wear rate.

As a matter of routine practice, the mooring chains have been inspected frequently and if the wastage due to corrosion and/or wear is considered unacceptable, then the chain is replaced. As a consequence of this proactive inspection and maintenance approach, the chain failures have been infrequent and the overall experience to date with mooring chains is considered a success.

However, the staff at Marine Aids Division felt that this record of success may not have been entirely cost effective due to chain inspection and replacement costs. About six years ago, the Division therefore set a target that the buoy system and the mooring chains should be able to provide at least five years of unattended service.

Another issue of interest to the Division is the use of higher strength and therefore smaller diameter chains. Use of lower strength, large diameter chains has two disadvantages. One is the increased weight resulting in reduced reserve buoyancy of the buoy which may affect survivability in extreme sea conditions, and the second factor is the added weight which affects handling during deployment and recovery.

To address both these issues, the Marine Aids Division initiated a five-year field study in 1989. In this field experiment, thrash chains made from different steels (carbon steel or alloy steel) or of different diameters (1.125’(28.6 mm) to 1.75’ (44.5 mm)) were included in moorings of different lengths for five 2.9 m bell buoys deployed off Halifax harbour (water depth 150 ft. (approximately 46 m)). All five riding chains in this field study were made from alloy steel conforming to specification MA 2020-E and were nominally 1.125’ (28.6 mm) in diameter for the Mooring No. 1 and 1.25’ (32 mm) in diameter for the remaining chains. The focus of this study was the degradation of thrash chains, since the greatest inter-link movement and therefore maximum wastage is encountered in the knee region of the thrash chain.

Following the five-year study, Fleet Technology Limited (FTL) of Kanata, Ontario, was contracted to undertake a study that would form the basis for recommending riding chain strength and diameter(s) for use in conjunction with 1.5" diameter thrash and ground chain for mooring 2.9 m bell buoys in water depths ranging from 30 m to 150 m. The longer term objective of this study is to meet the Marine Aids Division's goal of achieving a minimum of five years of unattended service from year-round navigation buoy mooring chains.

The study involved estimation and comparison of the peak steady state and dynamic loads on the riding chain under severe sea conditions and of residual strength of the riding chains of different sizes and qualities after five years of service. The dynamic load estimation was performed for a 10-year wave using the Moordyn program developed and validated by the National Research Council's Hydraulics Laboratories. The peak tension in the riding chain was estimated for selected combinations of riding chain diameters, mooring chain scopes and water depths. It was found that highest dynamic loads are experienced in shallower waters and for smaller mooring chain scopes.

The estimation of the residual strength of the riding chains required the development of an empirical model to predict the inter-link wastage rate due to wear and/or corrosion and another mechanics-based model to predict the residual strength of chains as a function of the chain steel strength and wastage that might not be circumferentially uniform. The latter was based on a model developed from the wastage rates observed (in a previous CCG sponsored study) for thrash and riding chains in the approaches to Halifax Harbour during a five-year service period.

Based on the above analyses and comparisons, it was concluded that Quality 2 chain, of appropriate size, would be suitable for riding chain applications in water depths ranging from 30 to 150 m. The mooring chain break load and material specification requirements in the current CCG chain specification were reviewed and amendments were recommended to reflect the findings of this study. Recommendations were also made concerning the section of chain diameters and mooring scopes for 2.9 m bell buoys in water depths from 30 to 150 m for various factors of safety (ratio of residual strength of the chain after five years of service and the peak riding chain tension).

## 1.2 Objective

The objective of this project was to produce a buoy mooring chain selection guide in the form of a computer program which identifies riding, thrash and ground chains capable of providing five years of unattended service for the following CCG buoys:

- 2.9 m Lighted Bell Buoy
- 2.9 m Lighted Whistle Buoy
- 1.8 m Lighted Buoy
- 1.4 m Lighted Buoy
- 3 m Lighted Scow Buoy
- 1.5 m Lighted Discus Buoy
- 0.6 m Spar Buoy
- 0.8 m Coastal Buoy (Can and Conical version)
- 1.2 m Coastal Buoy (Can and Conical version)
- 1.6 m Coastal Buoy (Can and Conical version)

### 1.3 Scope of Work

The technical work performed in the development of the Mooring Selection Guide (MSG) software included the following:

- development of riding and thrash chain wear models,
- determination of appropriate design environmental conditions,
- determination of buoy mooring dynamic response including the effects of ice accumulation, and
- a review of buoy buoyancy/freeboard requirements.

This report describes the technical investigations and development work performed in order to produce the mooring selection guide. A description of the software and its operation are included in the Mooring Selection Guide Program Manual, TP 13049E, and on-line help menus and are not repeated in this report.

## 2. MOORING CHAIN DEGRADATION

The mooring chain degradation process involves both corrosion and mechanical wear. The mooring selection guide software was developed to incorporate an estimate of the residual strength of a degraded mooring chain based on its duration of service. To this end, corrosion rates and the factors affecting chain wear were investigated to develop a chain wear model. The following sections describe the results of these investigations.

### 2.1 Effect of Fresh vs. Salt Water on Chain Corrosion/Degradation

Corrosion of structural steels in seawater has been studied extensively, and the results of these investigations are summarized in Figures 2.1 and 2.2. These figures illustrate observed corrosion rates for various seawater operational environments and materials in “mil’s per year” (mpy), [thousandths of an inch per year].

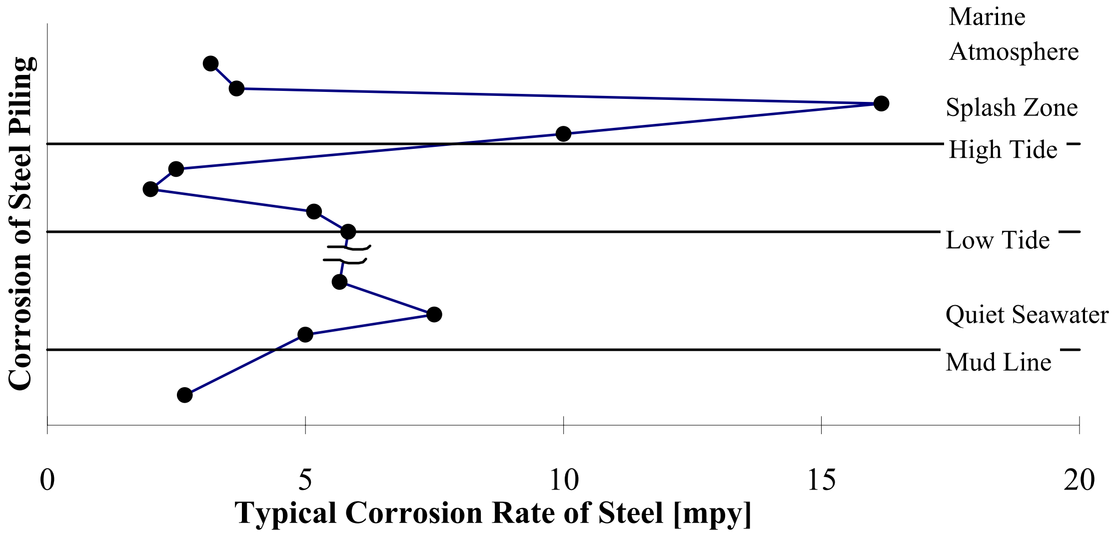
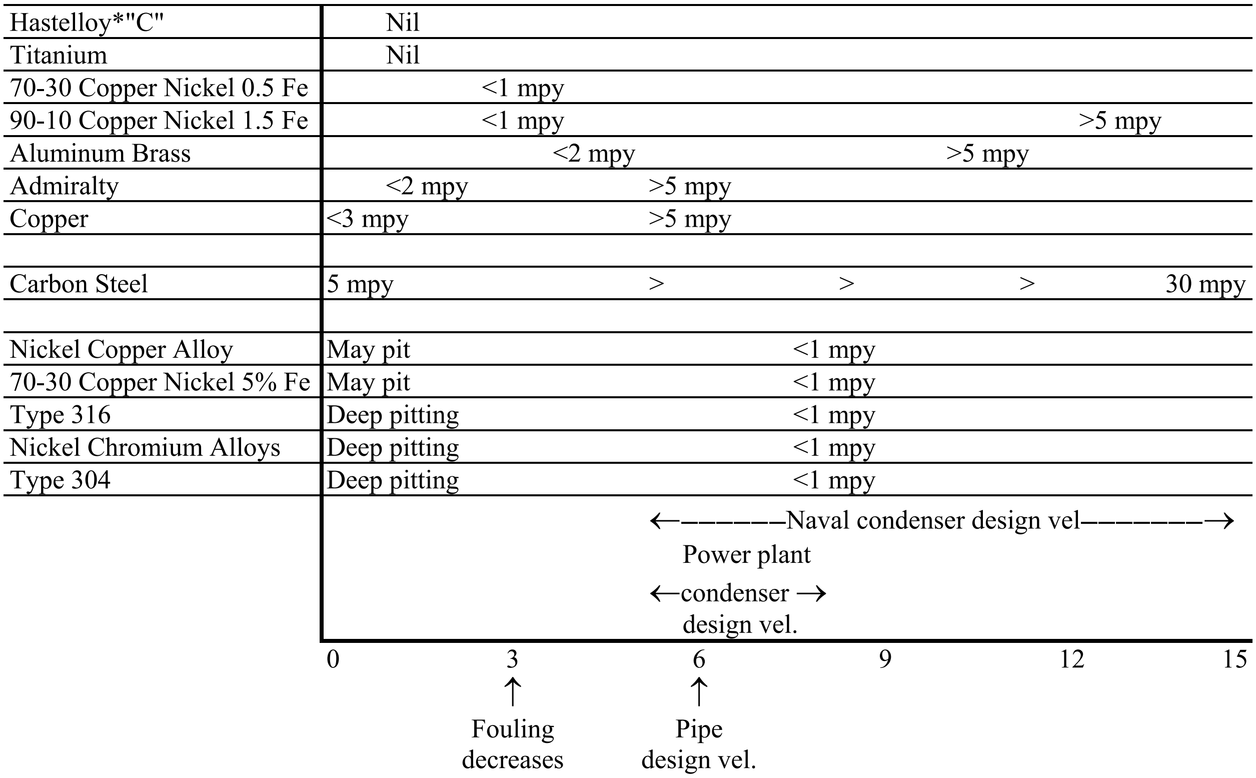


Figure 2.1: Corrosion of Ordinary Steel in the Sea

Figure 2.1 shows that in a seawater environment, the highest corrosion rate is observed in the region of the splash zone (up to about 17 mpy (0.43 mm/year)). However, the mooring chains are always below the waterline; therefore, based on Figure 2.1, the corrosion rate is expected to vary from about 3 to 8 mpy (0.076 to 0.2 mm/year) as a function of depth and/or current.

Figure 2.2 illustrates the relative susceptibility of various materials to corrosion in a seawater environment at a range of water velocities or currents. All of the chains tested to date in the development of the mooring selection guide (carbon and alloyed steels) would exhibit similar corrosion rates, due to the relatively low alloy content, to that represented by the carbon steel in Figure 2.2.



**Velocities [fps]**

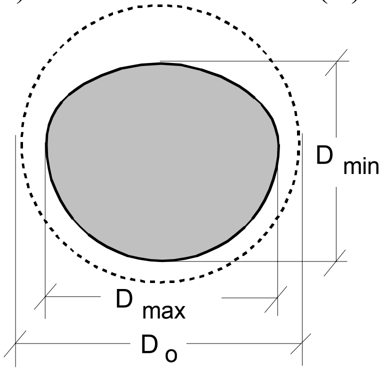
**Figure 2.2: Effect of Velocity on Corrosion of Piping by Seawater**

In fresh water, one would expect the corrosion rate to be lower due to the reduced chloride content. However, no generalizations can be made regarding corrosion rates in fresh water since varying amounts of other corroding species may be present. The corrosivity of "fresh" water depends on its oxygen, sulfur and chloride contents as well as the minerals it contains (water hardness). The amount of these species present can vary over a wide range and this is reflected in the longevity of steel hot water tanks in homes varying from one or two years to as much as 20. For example, fresh water in some localities in Ohio have high sulphur content leading to rapid corrosion of steel.

Due to the difficulty in precisely defining the corrosivity of a “fresh” water mooring environment and the potential for corrosion rates comparable to that of seawater, it is suggested that the chain wear model developed for seawater mooring environments continue to be used for fresh water as well. This assumption is a conservative one but is considered sensible as long as the water impurities at “fresh” water at mooring sites are unknown.

## 2.2 Chain Wear Models

Chain wear is described in the mooring selection guide in terms of the chain diameter ratio (Dr) and the uniform wear (U) as follows:



where:

$D_0$ is the link original nominal diameter
$D_{min}$ is the minimum chain link diameter
$D_{max}$ is the maximum chain link diameter

$$Dr = \frac{D_{min}}{D_0}$$

$$U = \frac{D_0 - D_{max}}{D_0 - D_{min}}$$

**Figure 2.3: Idealized Worn Chain Cross Section**

The CCG five-year Halifax mooring trial data was used to develop empirical thrash and riding chain wear models relating the chain diameter ratios to the duration of service and nominal link diameter. The models which were developed were of the following form:

$$D_r = \frac{C_1 D_o t}{\sqrt{1+t}} + C_2 t^2 + C_3 t + 1$$

where: $C_1$, $C_2$ and $C_3$ are regression coefficients and t is the duration of service in months

While this model adequately described the wear/corrosion of the mooring chains deployed in the Halifax trials it did not provide insight into a variety of factors which influence the wear rate of mooring chains. It is expected that the rate of a mooring chain’s riding and thrash section degradation would be influenced by:

- Nominal chain diameter - It is expected that the rate of change of the diameter ratio (Dr) would be a function of link diameter (higher for smaller diameter chains). The chain wear data collected in the Halifax trials only represents the wear associated with larger diameter chains (i.e. $D_0 > 1$ 1/8’), therefore this effect could not be fully investigated.
- Duration of service - The Halifax data set describes the rate of chain degradation with time and is used to develop the general trends in mooring chain degradation.
- Water depth - The highest wear location in the riding section of a mooring is likely to be at the top of the mooring chain (below the buoy) as these links carry all of the weight of the suspended chain. As water depth increases the inter link load increases, due to the increase in chain weight, therefore the friction and thus wear also increase.

In addition, it has been observed that increasing water depth, for a constant mooring scope, acts as a thrash chain displacement moderator. This indicates that thrash chain wear would reduce with increasing water depth.

Neither of these two effects could be investigated based on the Halifax trial mooring chain wear data since all of the mooring sites had similar water depths.

- Mooring scope - As the mooring scope decreases the mooring becomes taut more frequently and the chain activity increases resulting in a higher chain loads and movement. This would suggest that decreasing mooring scopes would result in higher mooring chain wear rates. Since the mooring scopes of the Halifax test sites were all similar this influence could not be included in the initial chain wear model.
- Bottom type - Thrash chain degradation is predominantly due to wear resulting from the friction between the chain and the bottom. The chain wear caused by each chain movement is a function of the coefficient of friction between the bottom and the chain. This indicates that the rate of thrash chain wear is a function of the bottom type, but for many mooring sites the soil conditions or bottom type cannot be determined.
- Chain hardness - The hardness of the chain steel will determine the rate at which it wears in a given environment. For this reason chain hardness will affect the rate at which the thrash or riding chains will wear. The hardness of typical chain steels does not vary significantly for a given grade of steel so this influence on chain wear rate could not be included in the wear model at this point.

## 2.3 Revised Chain Wear Models

In order to update the chain wear model used by the MSG software, additional worn mooring chain diameter data were collected. The emphasis of this data collection effort was to collect data outlining the wear rates of smaller diameter chain links. The mooring chain measurement data for the 22 mooring chains which were examined are summarized in Table 2.1.

While the supplementary data summarized in Table 2.1 provide a great deal of information on the thrash and riding chain diameter / service life relationship, the detailed description of the mooring system (bottom type, chain length, etc.) were not available for all moorings. In some cases an approximate water depth was estimated and is reported in the summary table.

This supplementary data were used along with the five year Halifax Harbour trial data to revise the chain wear model. It was initially proposed that the revised thrash and riding chain wear models would incorporate the factors outlined in Section 2.1. Table 2.2 outlines the results of the efforts to include all of these factors in the updated wear model and the following sections describe the model revision results.

Table 2.1: Supplementary Chain Wear Data Summary

| LL No or Buoy No | Buoy Name | Buoy Type | Location | Bottom Type | Water Depth [m] | Chain Length [m] | Duration of Service [y] | Nom. Riding Chain Dia. [in] | Nom. Thrash Chain Dia. [in] | Nom. Ground Chain Dia. [in] | Min. Riding Chain Dia. [mm] | Assoc. Max. Riding Dia. [mm] | Min. Thrash Chain Dia. [mm] | Assoc. Max. Thrash Dia. [mm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 523 | Mars Rock | 2.9m Whistle | Halifax H. D2-170 | Rock | 20 | 54.86 | 2 | 1 1/2 | 1 1/8 | 1 1/8 | 35.04 | 37.84 | 24.66 | 29.28 |
| 529 | Pleasant Shoal | 2.9m Bell | Halifax H. D2-182 | Mud | 16.6 | 27.40 | 2 | 1 1/4 | 1 1/4 | 1 1/4 | 27.57 | 28.70 | 24.56 | 27.92 |
| 515 | Navey W. Cautionary | 2.9m Whistle | Halifax H. D2-159 | Rock | 39.4 | 82.30 | 2 | 1 1/4 | 1 1/4 | 1 1/4 | 26.74 | 28.99 | 23.49 | 27.42 |
| 535 | Ives Knoll | 2.9m Bell | Halifax H. D2-183 | Mud | 18.4 | 27.40 | 2 | 1 1/8 | 1 1/8 | 1 1/8 | 29.12 | 31.64 | 28.14 | 30.74 |
| 521 | Herring Cove | 2.9m Bell | Halifax H. D2-169 | Rock | 33 | 54.86 | 2 | 1 1/2 | 1 1/2 | 1 1/2 | 36.00 | 38.62 | 29.43 | 33.44 |
| 511 | Ketch Harbor | 2.9m Whistle | Halifax H. D2-153 | Rock | 45.8 | 82.30 | 2 | 1 1/2 | 1 1/2 | 1 1/4 | 26.90 | 29.60 | 24.94 | 27.30 |
|  |  |  |  |  | *50* |  | 2 | 1/2 | 1/2 | 1/2 | 9.60 | 12.38 | 7.07 | 8.43 |
|  |  |  |  |  | *45* |  | 2 | 1/2 | 1/2 | 1/2 | 9.48 | 11.95 | 9.68 | 12.13 |
| 519 | Lichfield Shoal | 2.9m Whistle | Halifax H. D2-167 | Rock | 23.9 | 54.80 | 2 | 1 1/2 | 1 1/2 | 1 1/2 | 35.44 | 38.13 | 24.00 | 34.48 |
| 544 | Barrie Beach | 2.9m Bell | Halifax H. D2-204 | Sand | 12.9 | 27.43 | 2 | 1 1/4 | 1 1/4 | 1 1/4 | 29.29 | 32.08 | 26.06 | 28.57 |
|  |  |  |  |  | *55* |  | 2 | 3/4 | 3/4 | 3/4 | 13.11 | 16.00 | 12.99 | 15.07 |
|  |  |  |  |  | *30* |  | 2 | 3/4 | 3/4 | 3/4 | 16.72 | 19.21 | 12.29 | 14.28 |
|  |  |  |  |  | *25* |  | 2 | 3/4 | 3/4 | 3/4 | 14.52 | 17.85 | 13.80 | 16.82 |
|  |  |  |  |  | *30* |  | 2 | 3/4 | 3/4 | 3/4 |  |  | 13.07 | 15.38 |
|  |  |  |  |  | *50* |  | 2 | 1/2 | 1/2 | 1/2 | 10.10 | 12.38 | 9.46 | 11.61 |
|  |  |  |  |  | *30* |  | 2 | 1/2 | 1/2 | 1/2 | 10.50 | 12.66 | 8.63 | 11.55 |
|  |  |  |  |  | *25* |  | 2 | 1/2 | 1/2 | 1/2 | 10.33 | 11.65 | 9.03 | 10.65 |
|  |  |  |  |  | *30* |  | 2 | 1/2 | 1/2 | 1/2 | 10.20 | 10.95 | 9.82 | 10.63 |
|  |  |  |  |  | *25* |  | 2 | 3/4 | 3/4 | 3/4 | 15.77 | 18.77 | 12.69 | 16.01 |
|  |  |  |  |  | *20* |  | 2 | 3/4 | 3/4 | 3/4 | 17.27 | 18.21 | 17.00 | 17.07 |
|  | Pennant | 2.9m Whistle | Sambro, N.S. | Rock | 33 | 96.00 | 1 | 1 1/2 | 1 1/2 | 1 1/2 | 35.09 | 38.73 | 28.45 | 37.76 |
|  | Sisters | 2.9m Bell | Halifax H. | Rock | 56.8 | 137.00 | 1 | 1 1/2 | 1 1/2 | 1 1/2 | 35.55 | 39.64 | 22.60 | 33.91 |

Table 2.2: Influences on Chain Wear Rates

| Factor | Riding Chain | Thrash Chain |
|---|---|---|
| Nominal Diameter | - Successfully Included | - Successfully Included |
| Duration of Service | - Successfully Included | - Successfully Included |
| Water Depth | - Successfully Included | - Poor Correlation |
| Mooring Scope | - Insufficient Data | - Insufficient Data |
| Bottom Type | - Not Applicable | - Insufficient Data |

The first step in the wear model revision process was to recalibrate the existing MSG wear models using the Halifax trial and supplementary chain wear data. In order to investigate the effect of water depth on the thrash and riding chain wear rates, the ratio of the recalibrated MSG wear models to the actual wear rates was plotted against water depth to illustrate any water depth related error trends in the data. Figure 2.4 illustrates this comparison for both the riding and thrash chains and fits a regression line to the resulting trends. Both the riding and the thrash chain wear model errors show a similar trend which increases with water depth (i.e. an increased wear due to greater water depths is not being accounted for). The higher $R^2$ value (correlation coefficients) associated with the riding chain depth/wear rate indicates that depth is a more significant influence on the wear rate for riding chains.

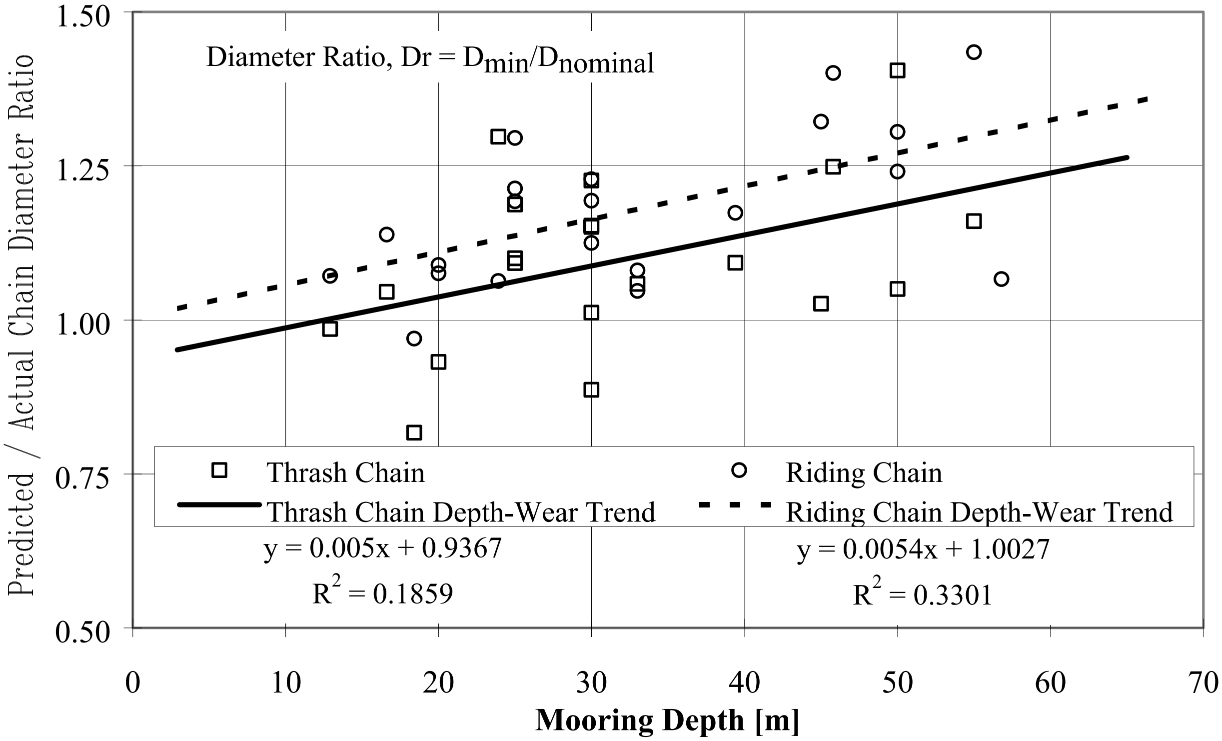


**Figure 2.4: Effect of Mooring Depth on Chain Wear**

The chain wear model was revised to include the influence of water depth as follows:

$$D_r = \frac{\frac{C_1 D_o t}{\sqrt{1+t}} + C_2 t^2 + C_3 t}{C_4 \mathrm{Depth} + C_5} + 1$$

where: $C_1$, $C_2$, $C_3$, $C_4$ and $C_5$ are regression coefficients t, $D_0$ and Depth are the duration of service (in months), new chain nominal diameter and water depth, respectively.

When the revised model (including the depth correction) was calibrated for the thrash chain, it was noted that it did not represent the measured data significantly better than the recalibrated model without the depth correction. For this reason it was decided that the thrash chain wear model coefficients should be:

Table 2.3: Revised Wear Model Coefficients

| | Thrash Chain | Riding Chain |
|---|---|---|
| $C_1$ | $7.332 \times 10^{-3}$ | $2.080 \times 10^{-3}$ |
| $C_2$ | $7.569 \times 10^{-5}$ | $4.962 \times 10^{-5}$ |
| $C_3$ | $-1.162 \times 10^{-2}$ | $-7.336 \times 10^{-3}$ |
| $C_4$ | 0 | $-1.179 \times 10^{-2}$ |
| $C_5$ | 1 | 1.555 |

which effectively eliminates the water depth correction for the thrash chain. The revised thrash chain wear model is plotted against duration of service in Figure 2.5 for a variety of new nominal chain diameters. The figure also plots the old wear model trend for a 1" diameter chain to illustrate the effect of the recalibration.

When recalibrating the riding chain wear model the depth correction improved the fit of the revised wear model to the measured data and the revised model is plotted in Figures 2.6 and 2.7. Figure 2.6 illustrates the effect of water depth on the predicted riding chain wear for the largest and smallest diameter chains (3/8" and 1 3/4") included in the MSG software. The increase in riding chain wear due to water depth increases up to a water depth of 70 m after which it is constant. This discontinuity in behavior is due to a lack of deep water wear data which did not allow the effect of water depth to be investigated.

Figure 2.7 compares the revised riding chain wear model which includes the effect of water depth to the old wear model and a recalibrated model without a water depth correction. The comparison illustrates the difference in predicted wear for a 1-inch diameter chain for all three wear models.

These two chain wear models estimate the minimum chain link diameter based on the nominal new link diameter, duration of service and water depth. The maximum diameter of the chain link cross section (see Figure 2.3) was estimated based on a constant uniform wear (U) and the estimated chain link minimum diameter. The use of a constant uniform wear was investigated by plotting the link cross section aspect ratio ($D_{min}$ / $D_{max}$) as a function of the minimum diameter ratio ($Dr = D_{min} / D_0$) as shown in Figure 2.8.

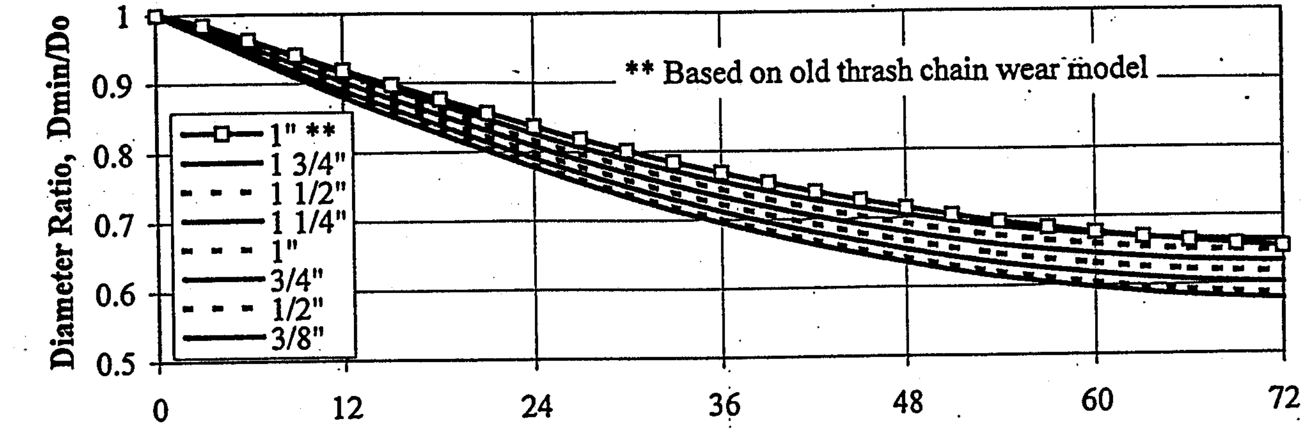


Figure 2.5: Revised Thrash Chain Wear Model

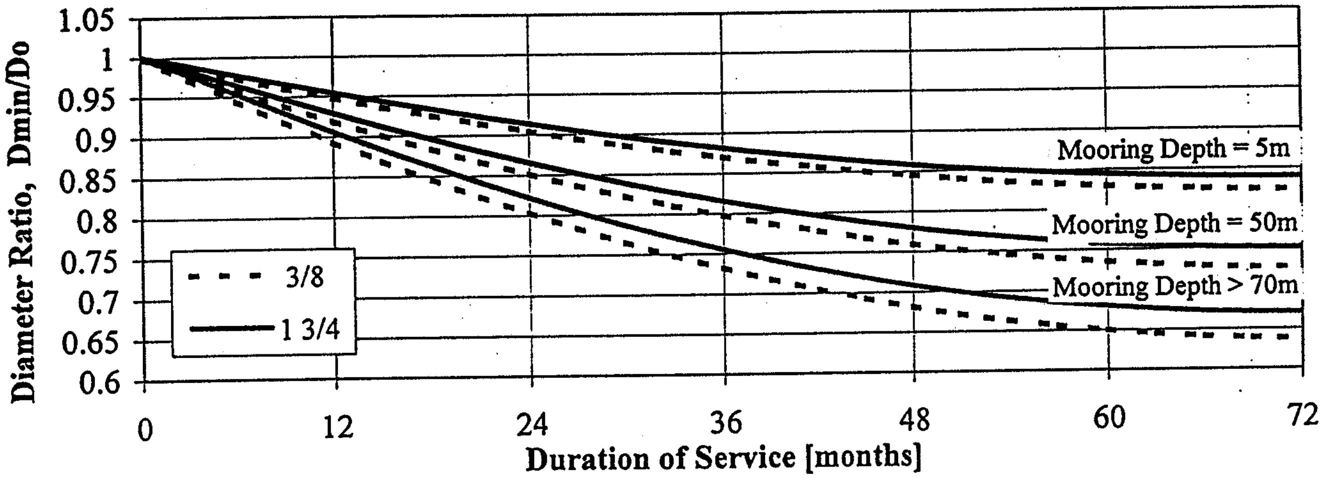


Figure 2.6: Revised Riding Chain Wear Model - Including Depth Correction

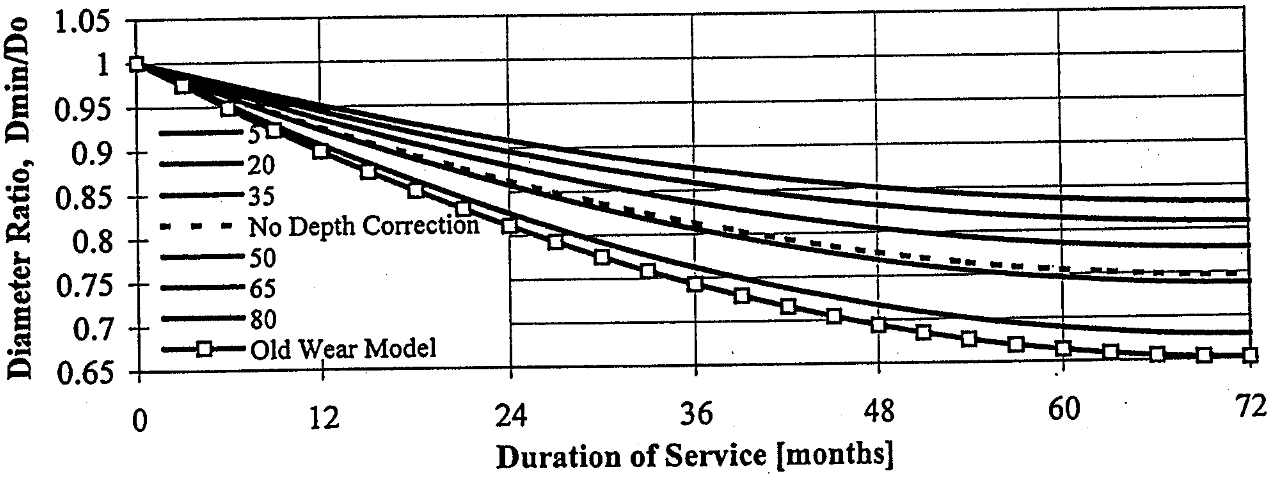


Figure 2.7: Riding Chain Wear Model - Including Depth Correction - 1" Dia Chain

Figure 2.8 indicates that the chain link cross section diameter ratio, for the most severely worn links, is related to the minimum diameter. The data points on the extreme right of Figure 2.8 demonstrate that the maximum chain diameter may be larger than the nominal value. In order to ensure that the chain wear predictions are conservative, a revised regression line which corrects for over sized chains and represents the 80 percent confidence level was developed. Figure 2.9 demonstrates the appropriateness of the link cross section aspect ratio model for all of the observed link cross section data. The model fits the general population of worn chain links (Figure 2.9) as well as it does the severely worn links (Figure 2.8) for which it was developed.

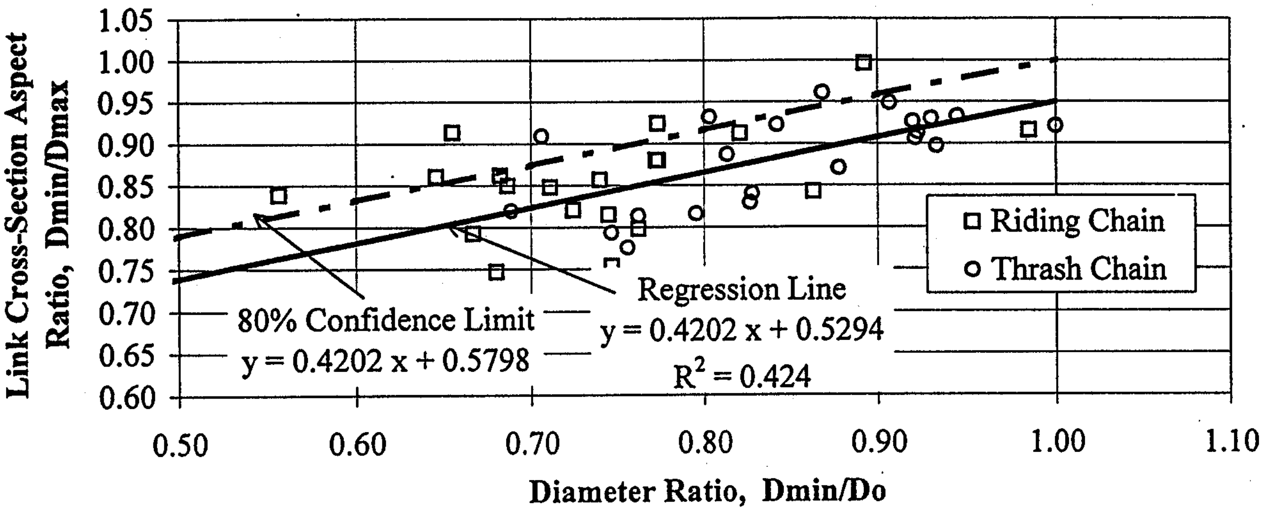


**Figure 2.8: Worn Mooring Chain Link Aspect Ratio Model**

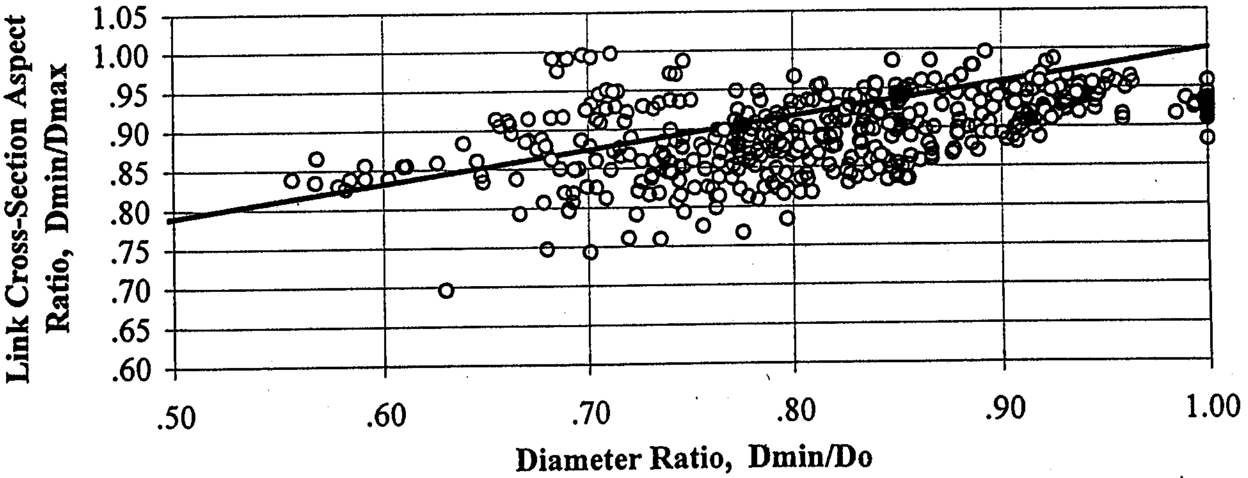


**Figure 2.9: Comparison of Worn Mooring Chain Link Aspect Ratio Data and Model**

## 2.4 MSG Wear Factor

The MSG software provides a chain wear factor to account for the fact that each mooring location has unique site conditions and bottom types which maybe more or less severe in terms of chain wear than those present at the CCG mooring test sites.

The degradation models used in the MSG software were developed based on geometric data collected in a number of CCG field tests of various mooring chains. The most significant set of data was collected during the CCG's five-year mooring study carried out in the Halifax Harbour area at a site with a water depth of approximately 46 m (150 ft) and a rock bottom. However, as noted earlier, the rate of wear in any mooring chain is dependent on the characteristics of the site in question (bottom type, water depth, etc). In order to calibrate the MSG model wear rate to that of a particular site, the software provides a chain wear factor to account for the fact that each mooring location has unique site conditions and bottom types which may be more or less severe in terms of chain wear than those present at the CCG mooring test sites.

The wear factor represents the ratio of the worn chain's residual strength estimated based on the MSG degradation model and the residual chain strength based on user observed degradation:

$$\text{Wear Factor} = \frac{\text{MSG Residual Strength Estimate}}{\text{Observed Chain Strength}}$$

If the mooring site conditions result in higher chain wear than that estimated by the MSG wear model then a wear factor greater than one should be selected. Conversely, values less than 1.0 may be selected for sites with wear rates lower than expected by the MSG wear model. The software will allow the user to input any value for the wear factor ranging from 0.2 to 5.0 (i.e. 1.5 to 5 times the strength).

Advice on the selection of an appropriate wear factor is provided to the user through a chain wear factor advisor within the MSG software. The wear factor advisor calculates the ratio of the mooring chain residual strengths for the predicted and user observed chain conditions. Further information on the wear factor advisor and the chain residual strength calculations is contained in the Mooring Selection Guide Program Manual and on-line help.

It is possible that the wear factors recommended by the wear factor advisor are different for the riding and thrash sections of the mooring chain and the software allows the user to enter separate wear factors for the riding and thrash sections of the mooring chain.

# 3. SELECTION OF ENVIRONMENTAL PARAMETERS FOR MOORING DESIGN

## 3.1 Review of Canadian Coastal Mooring Site Environmental Conditions

A complete review of the operating environments of the CCG navigation buoy fleet was carried out including water depth and degree of shelter. The geographical areas included the following coastal areas under the jurisdiction of CCG's regional offices: Dartmouth, N.S., Saint John, N.B., St. John's, Nfld, and the Vancouver/Victoria region. Records of historical mooring sites where the buoys have been deployed were obtained. These records included, in addition to the chain specifications, the water depths as well as the latitude and longitude. The water depths in all regions varied in the range 1 to 170 m. Speed and direction of currents were obtained from various sources including the Canadian Tide and Current Tables [1], which gave mean and maximum measured currents for selected coastal areas. Other sources of information concerning the magnitudes of coastal currents included more recent measured and predicted databases [2], [3]. The validity and range of application of these data sources were confirmed through personal communication [4]. The above sources provide the tidal current information only and do not provide any clue as to the effects of wind. Therefore, the total surface current is determined as the sum of the nominal tidal component and the wind-driven component. The magnitude of the latter in still water is determined using the wind friction-velocity at the surface. Current velocity variation with depth is taken according to the $1/7^{th}$ power law, which is adequate for two-dimensional mooring response calculations aimed at producing worst-case loading.

The environmental conditions of significance to the performance of moored buoys can be grouped into two categories:

- Survival conditions: scenarios involving the worst combination of environmental parameters that contribute to extreme loads and motions. These conditions are used in the mooring response simulation task.
- verage conditions: the conditions responsible for the normal type of loads and motions the moorings will be subjected to on a daily basis. These conditions are used in the mooring chain wear and or buoyancy calculations.

It is assumed that in the survival condition, the currents, winds and waves are collinear which is the worst case from a loading viewpoint. For each set of conditions, the environmental parameters of interest are:

- tidal range
- total current
- wind speed
- wave spectral parameters (significant wave height, modal (peak) period and shape factor)

In accordance with the above ideas, wind and wave climates for all regions were obtained from the Marine Environmental Data System (MEDS) offices of the Department of Fisheries and Oceans (DFO). The wind and wave data are available in the form of wind and wave atlases produced by the Transportation Development Centre [5]. These covered four main geographical areas: East Coast, Gulf of St. Lawrence, Great Lakes, West Coast. From the above source, the ten-year significant wave heights to be expected at each of the four geographical locations were determined. As the wave heights extracted from the atlases are independent of the water depth, they cannot be directly used for modeling. Within each geographical area, factors influencing the selection of a design wave height are water depth and direction of surface current. As the currents and waves are assumed to be in the same direction, the effect of the surface current is to reduce the wave height and increase the wavelength. The maximum wave height possible is limited by the water depth for which theoretical estimates are available. Using the deep water wave heights obtained from the atlases, the limiting wave heights at various water depths can be derived which are then modified to account for the surface current.

The selection of wave spectra used to determine the peak mooring loads normally depends on the risk criteria adopted by the owner/operator. That is, the owner (in this case, CCG), decides what risk can be economically justified for a particular mooring located at a given site, all other design criteria being satisfied. In this study, for an *in situ* service life of five years, CCG has opted to use a "once in 10-year storm" condition, with associated wind speeds and wave heights. Accordingly, 10-year return wave parameters have been chosen from the MEDS data base. From the selected deep water wave spectra, the modified spectra for any particular water depth can be determined using the method illustrated by Tayfun et al. [6]. In this method, it is assumed that the unidirectional energy spectrum expressed in terms of the wave frequency stays the same during approach to shallow water, since each component harmonic function of the surface elevation retains its energy and conserves its frequency.

The selected environmental parameters - wind speed, total current and significant wave height - are summarized for the water depth ranges of interest in Table 3.1. It can be seen in Table3.1 that the variation of significant wave height over the range of return periods is not high, but there is a lot of overlap in the wave conditions between the regions. Hence, the worst combinations of wave, wind and current conditions were chosen for mooring load and buoy response calculations.

Table 3.1: Estuary, Coastal and Deep Water Ten-Year Return Period Environmental Conditions

| Estuary Environment | | | | Coastal Environment | | | | Deep Water Environment | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Water Depth [m] | Wind Speed [Kn] | Total Current [Kn] | Sig Wave Height [m] | Water Depth [m] | Wind Speed [Kn] | Total Current [Kn] | Sig Wave Height [m] | Water Depth [m] | Wind Speed [Kn] | Total Current [Kn] | Sig Wave Height [m] |
| 1 | 45 | 3.2 | 0.3 | 3 | 45 | 3 | 0.8 | 5 | 45 | 3 | 0.8 |
| 2 | 45 | 3.2 | 0.4 | 5 | 45 | 3 | 1.6 | 10 | 45 | 3 | 1.6 |
| 3 | 45 | 3.1 | 0.85 | 8 | 45 | 2.8 | 2.4 | 15 | 45 | 2.8 | 2.4 |
| 4 | 45 | 3 | 1.3 | 11 | 45 | 2.5 | 3 | 20 | 45 | 2.5 | 3 |
| 5 | 48 | 3 | 1.5 | 14 | 48 | 2.3 | 3.8 | 25 | 48 | 2.3 | 3.8 |
| 7 | 48 | 2.8 | 2.1 | 17 | 48 | 2 | 3.9 | 30 | 48 | 2 | 3.9 |
| 9 | 48 | 2.8 | 2.8 | 20 | 48 | 2 | 4.1 | 35 | 48 | 2 | 4.1 |
| 11 | 50 | 2.7 | 3 | 23 | 50 | 2 | 4.3 | 40 | 50 | 2 | 4.3 |
| 13 | 50 | 2.6 | 3.4 | 26 | 50 | 2 | 4.5 | 45 | 50 | 2 | 6 |
| 15 | 50 | 2.5 | 3.9 | 29 | 50 | 2 | 4.7 | 50 | 50 | 2 | 6 |
| 20 | 50 | 2.5 | 3.9 | 32 | 55 | 2 | 5 | 55 | 55 | 2 | 6.5 |
| 25 | 50 | 2.5 | 3.9 | 35 | 55 | 2 | 5.2 | 60 | 55 | 2 | 6.5 |
| 30 | 50 | 2.5 | 3.9 | 38 | 55 | 2 | 5.5 | 65 | 55 | 2 | 7 |
| 32 | 55 | 2.5 | 4 | 41 | 60 | 2 | 5.7 | 70 | 60 | 2 | 7.5 |
| | | | | 44 | 60 | 2 | 5.9 | 75 | 60 | 2 | 8 |
| | | | | 50 | 60 | 2 | 5.9 | 80 | 65 | 2 | 8.5 |
| | | | | 60 | 60 | 2 | 5.9 | 90 | 65 | 2 | 9 |
| | | | | 75 | 60 | 2 | 5.9 | 100 | 70 | 2 | 9.5 |
| | | | | | | | | 110 | 70 | 2 | 10 |
| | | | | | | | | 120 | 70 | 2 | 10.5 |
| | | | | | | | | 130 | 75 | 2 | 11 |
| | | | | | | | | 140 | 75 | 2 | 11.5 |
| | | | | | | | | 150 | 75 | 2 | 12 |

The data presented in Table 3.1 is intended to be used with the following assumptions and definitions in mind:

- Wind, wave and current are assumed to be collinear.
- Wind speed represents one-hour mean wind at 19.5 m above MWL from AES data base.
- Current is the sum of tidal component and wind-induced surface drift, constant over the water depth.
- Significant wave heights are determined from estimated maximum wave heights assuming fully-developed sea conditions.
- Wave heights asymptotically approach the deep-water, ten-year-return significant heights provided in MEDS data base.

## 3.2 MSG Design Environmental Conditions

Based on these observations, continuous polynomial functions of the mooring site water depth for the design environmental conditions (wind speed, current, wave height and wave period) were generated in the following form:

$$\text{Environment Parameter} = a \times \text{Depth}^3 + b \times \text{Depth}^2 + c \times \text{Depth} + d$$

Each buoy was defined as an estuary, coastal or deep water buoy in order to define its design environmental conditions. Table 3.2 provides the design environmental parameters and a listing of the CCG buoys to which they apply. Plots of these functions are provided in the Mooring Selection Guide Program Manual and on-line help.

Table 3.2: Design Environmental Conditions

| | **Estuary Design Environmental Conditions** | | | | **Estuary Buoys** |
|---|---|---|---|---|---|
| | Wind Speed | Current | Wave Height | Wave Period | |
| a | $2.86\times10^{-6}$ | $1.48\times10^{-5}$ | $3.82\times10^{-6}$ | $3.08\times10^{-6}$ | 3.0m Lighted Scow |
| b | $-1.29\times10^{-3}$ | $1.259\times10^{-3}$ | $-1.36\times10^{-3}$ | $-1.15\times10^{-3}$ | 1.5m Lighted Discus |
| c | 0.3364 | -0.07241 | 0.1660 | 0.1574 | |
| d | 44.85 | 3.299 | 0.3006 | 2.603 | |
| | **Coastal Design Environmental Conditions** | | | | **Coastal Buoys** |
| | Wind Speed | Current | Wave Height | Wave Period | |
| a | $6.02\times10^{-6}$ | $3.00\times10^{-4}$ | $5.54\times10^{-6}$ | $3.08\times10^{-6}$ | 0.6m Spar (long and short) |
| b | $-2.29\times10^{-3}$ | $-1.067\times10^{-2}$ | $-1.55\times10^{-3}$ | $-1.15\times10^{-3}$ | 0.8m Cone and Can |
| c | 0.4351 | $4.260\times10^{-2}$ | 0.1797 | 0.1574 | 1.2m Cone and Can |
| d | 41.93 | 2.961 | 0.71896 | 2.603 | 1.6m Cone and Can |
| | **Deep Water Design Environmental Conditions** | | | | **Deep Water Buoys** |
| | Wind Speed | Current | Wave Height | Wave Period | |
| a | $-2.39\times10^{-5}$ | $-2.40\times10^{-6}$ | $9.93\times10^{-7}$ | $3.08\times10^{-6}$ | 1.4m Lighted Buoy |
| b | $5.287\times10^{-3}$ | $6.61\times10^{-4}$ | $-5.40\times10^{-4}$ | $-1.15\times10^{-3}$ | 1.8m Lighted Buoy |
| c | $-5.719\times10^{-2}$ | -0.0550 | 0.1353 | 0.1574 | 2.9m Bell Buoy |
| d | 44.98 | 3.351 | 0.3569 | 2.603 | 2.9m Whistle Buoy |

### 3.3 MSG Environmental Factor

The design environmental parameters were developed to provide a conservative basis for the design of buoy mooring systems. In some cases, the user may have detailed information concerning site specific environmental parameters, some of which may be more or less severe than the design values. In order to remedy this potential problem, the Mooring Selection Guide software offers the user an environment factor which relates the mooring loads generated by the design environmental conditions to those generated by the environmental conditions provided by the user as follows:

$$\text{Environment Factor} = \frac{\text{Observed Mooring Chain Load}}{\text{MSG Mooring Chain Load Estimate}}$$

If the environmental conditions of the mooring site being considered are more severe, i.e. generate higher mooring chain loads, than those assumed as the design environmental conditions then an environment factor greater than 1.0 can be used. Conversely, values less than 1.0 may be used for sites with less severe environmental conditions than those used as the design environmental conditions. The software will allow the user to input any value for the environment factor ranging from 0.2 to 5.0 (i.e. 1/5 to 5 times the load).

Advice on the selection of an appropriate environmental factor is provided to the user through an environment factor advisor within the MSG software. The environment factor advisor calculates the ratio of the mooring chain loads generated for the design environmental conditions to those generated by the environmental conditions provided by the user. Further information on the environmental factor advisor is contained in the Mooring Selection Guide Program Manual and on-line help.

# 4. MOORING CHAIN DESIGN LOADS

It was decided, for the sake of software execution speed, that the MSG software would not include a built-in hydrodynamic buoy simulation code. Instead, the buoy mooring chain hydrodynamic loads were pre-processed to generate a data base of mooring chain design loads as a function of the design environmental conditions and the mooring system configuration. The variables describing the mooring system configuration and their range of interest for the MSG software are listed in Table 4.1.

Table 4.1: Mooring System Load Configuration Variables

| Parameter | Range of Values | Parameter | Range of Values |
|---|---|---|---|
| Buoy Type | 14 buoy configurations | Chain Diameter | 3/8" to 1 1/2" |
| Water Depth | 2 to 150 m | Superstructure Ice Accumulation | on 2.9 m, 1.8 m and 1.4 m lighted buoys |
| Mooring Scope | 1.5 to 4:1 | | |

The effect of water density when considering salt versus fresh water on mooring chain loads was investigated and found to be minor. The following sections outline the process involved in estimating mooring chain loads.

## 4.1 Modeling of Peak Tension in the Mooring Chain

### 4.1.1 Steady State Mooring Loads

The mooring selection process necessarily requires the definition of steady *in situ* loads that will govern the size and strength of the chain. The magnitudes of these loads can be estimated using established engineering principles. The method requires the use of a numerical model that enables a mooring system to be selected to meet the following conditions:

Assuming the buoy to be moored at a site having known water depth, the length and diameter of the mooring chain and the location of the chain attachment point on the buoy hull are determined in order to meet the following requirements:

- The chain is tangential to the sea bottom under most conditions of current, wind and waves at the site (hangs in catenary shape),
- The buoy axis remains nearly vertical under most common conditions of current, wind and waves,
- The reserve buoyancy of the fully equipped buoy is sufficient, under the most unfavorable conditions of current, wind and waves, to react out the mooring tension.

### 4.1.2 Steady-State Forces on Buoy Hull

The steady forces acting on the buoy hull consist of hydrodynamic as well as aerodynamic forces which need to be independently determined on the assumption that the factors contributing to these forces are independent so that no interaction effects need be considered.

Hydrodynamic drag forces on the underwater portion of the buoy hull are taken as proportional to the square of the relative flow velocity. These can be divided into the following:

- Separation (eddy-making) drag or form drag. These arise out of the complete disruption of flow around the submerged portion of the main hull as well as the flow around protrusions and attachments to the hull. The magnitude of the force is proportional to the projected total underwater area and the drag coefficient. The drag coefficient associated with this type of separated flow is independent of the Reynolds number so that constant coefficients can be used. Form drag coefficients for various short axisymmetric shapes have been listed by Hoerner [7] and for semi-submerged cylinders of finite length by Hay [8].
- Wave-making drag: This results from the free-surface effects wherein the water is forced to move vertically against the earth's gravitational forces. The magnitude of the force is proportional to the submerged volume of the buoy and the velocity and the force coefficient is dependent on the Froude number of the flow. The wave-making drag coefficient for the bare hull can be determined from potential flow calculations for a given draft and trim. Wave-making resistance of streamlined shapes can also be derived from scale model tests.
- Friction drag or viscous shear resistance: This may vary as the velocity V, V2 or as any combination of the two. Friction resistance may be estimated quite readily assuming a level of surface roughness. Scale model test data will have to be modified for hull fouling allowance prior to application to full-scale drag calculations. However, the component of total drag attributable to skin friction is very small.

It is frequently not easy to estimate the above coefficients independently for each buoy hull. It is more expedient to determine an overall coefficient for each hull form. A complete survey of drag coefficients for most common buoy hulls is given in [9], which also provides approximate values of overall hydrodynamic drag coefficients applicable to navigation buoy hulls in the Froude and Reynolds number range of interest in this development.

- Aerodynamic drag due to steady wind is a significant component of the total drag. In this case, the relative wind is taken as the true wind measured at the 10 m sensing level and the velocity profile is taken to follow the $1/7^{th}$ power law. The square-law drag formulation involves the projected area of each member of the superstructure and the velocity at its elevation. Interference effects are taken into account if two members are at the same elevation. In the case of icing on the superstructure, the projected area is increased by the amount of ice estimated to have accumulated on the member.

- Wave Drift Forces: These are time-invariant, mean wave forces on the hull as a result of the interactions between the first order buoy motions and the undisturbed incoming waves over several wave cycles. This is normally calculated using potential flow methods involving diffraction and radiation analysis techniques. For axisymmetric hull forms such as buoys, large body of information is available [10], [11] from which wave drift RAOs have been derived. These are then used in conjunction with the wave spectra chosen earlier.

Calculation of the above steady forces have been incorporated in a computer program SBL1 developed and verified in the 70s. The estimation of the additional quasi-steady hydrodynamic drag due to breaking waves was subsequently incorporated in evaluating the worst case of loading on the moorings. Drag characteristics of several buoy hulls obtained through model experiments [9] have been made use of in these calculations, as full-scale drag measurements of similar-shaped, buoy hulls are not available for comparison. All mooring configurations analysed incorporated the drag on the chain due to steady current, the magnitude of which was taken as exponentially decaying with depth. The above calculations are iterative in practice, as the final draft of the buoy is unknown at the beginning.

### 4.1.3 Buoy Dynamic Response Calculations

The second step in the calculation involved numerical modeling of the dynamic response of the buoy hull for a complete range of wave periods in order to obtain the dynamic response amplitudes and phases. These are required as inputs to the mooring chain dynamic response calculations resulting from the wave-induced motions of the free-floating buoy. The buoy response calculations involve formulation and solution of the equations of motion of the two transitional degrees of freedom: surge and heave. The equations governing the buoy dynamics account for the hydrostatic reactions as well as the hydrodynamic reactions due to the added mass and damping characteristics of the buoy hull. FBMO, the buoy dynamics routine, outputs the heave and surge amplitudes of motion for each wave period.

### 4.1.4 Modeling of Dynamic Loads in Mooring Chains

The shape of the mooring chain in the steady current profile as determined in 4.1.2 is an input to the dynamic calculations. In addition to the steady-state loads due to current and wind, as well as the quasi-steady loading in breaking waves, the periodic wave-induced motion amplitudes of the buoy are also inputs to dynamic time-varying loads in the mooring. The maximum steady-state tension in the mooring chain will be at the buoy end, which is the resultant of the horizontal loads on the buoy hull and the vertical buoyancy forces. The steady-state calculations assume that the wind, current and waves are collinear and acting in the same plane, which provide the scenario for calculating peak magnitudes of the total (dynamic + steady state) loads in the mooring. The magnitudes of the dynamic fluctuations depend on the pre-tension and the inertial, drag as well as elastic characteristics of the chain.

A numerical model of the dynamic response of the mooring chain called "MOORDYN" [12], developed and validated by the National Research Council's Canadian Centre for Hydraulics, has been used to model all the chain mooring configurations. The model uses a two-dimensional lumped parameter representation of the mooring line and involves simple formulations of the forces on the line as well as its longitudinal and lateral elastic deformations due to the external loads. It utilizes a time-domain simulation of the motions of and loads on the mooring line assuming any *in-situ* configuration determined by the chain weight, current drag and pre-tension. The tension and angle are calculated at all nodes (nodal points) of the mooring line. The boundary conditions at the anchor end are specified as having zero motions, while at the top end of the mooring, the buoy surge and heave amplitudes determined in 4.1.3 are specified.

## 4.2 Peak Tensions and Reserve Buoyancy

The instantaneous mooring tension is composed of a steady (time-invariant) component and a dynamic (fluctuating) component. The steady tensions result from the steady drag forces on the mooring chain and the buoy as well as from the mean wave drift forces, as discussed above. The dynamic components result from the excursions of the buoy as well as the reactions of the mooring to the buoy motions. Therefore, the peak tension is the scalar sum of the steady tension and the amplitude of dynamic tension. As the response of the mooring is nonlinear, the dynamic tension can not be calculated separately.

The mooring simulation code calculates the time history of the total tension in the chain.

The simulation of steady-state plus dynamic tensions produces the tension distribution along the length of the mooring. The time histories depict chain tensions at three points: one immediately below the buoy, the second further down the line near the "knee" of the catenary and the third on the ground chain closer to the anchor. With deep-water moorings, there is significant variation in tension along the chain length, while for the shallow water mooring, the tension is nearly uniform along the entire length of the mooring. Another feature of the time history is that the "loading" part of the tension curve is slow indicating that the rate of increase in tension is lower than that for the "unloading" half of the cycle, where the curve is much steeper. In addition, the dynamic steady state is achieved in two cycles of wave motion. "Spikes" in the curves are characteristic of the low-tension parts of the time history and are caused by low damping in the longitudinal (axial) direction. Only actual peak tensions are picked out of the time histories.

The limiting operating conditions for the buoy would be governed by the capacity of the buoy to stay on the wave surface and be visible as well as audible. As the buoy has finite reserve buoyancy, the limiting conditions will be determined by the available reserve buoyancy (i.e. buoyancy in excess of that required to support the mooring chain in calm water). An approximate estimate of the conditions under which the buoy will submerge can be obtained by comparing the available reserve buoyancy with the vertical component of mooring tension. This check was carried out throughout each simulation run in order to monitor periods of buoy submergence.

During rapid wave-induced motions, dynamic line tensions could be several times the steady-state tension built up in steady currents and winds. This increase is generally quantified by the dynamic amplification factor, defined as the ratio of the maximum dynamic tension to the steady-state tension. This parameter is of primary importance in the design of a mooring system, since the mooring safety factors will be based on these.

For shallow water moorings, a quasi-static analysis is adequate as the dynamic effects will be negligible in these cases. In deep waters, the analysis will have to be fully dynamic, while for intermediate depths, the requirements will be mixed depending on the wave parameters.

## 4.3 Mooring Line Load Response Surfaces

Based on the results of the hydrodynamic simulations, a data base of mooring chain load responses to the design environmental conditions was generated. In order to complete the design process the peak loads in the riding chain, thrash chain (including ground chain) and at the anchor must be identified. In order to do this a multiple nonlinear regression was performed to relate the chain loads to the design variables (scope, chain diameter and water depth) through a response surface. The response surface equations which were developed had the following formats:

Riding and Thrash Chain Peak Tension

$$\text{Load} = \frac{f \cdot \text{Depth}^{a}\,\text{Dia}^{d} - b}{\text{Depth} - c \cdot \text{Scope}^{e}}$$

Anchor Horizontal Load (Drag)

$$\text{Load} = \left(f \cdot \text{Depth}^{a}\,\text{Dia}^{d} - \text{Scope}^{b}\right) c \cdot \text{Scope}^{e}$$

Anchor Vertical Load (Uplift)

$$\text{Load} = a \cdot \text{Depth} + b \cdot \text{Depth}^{2} + c \cdot \text{Dia}^{2} + d \cdot \text{Dia} + e \cdot \text{Scope} + f$$

where:

a,b,c,d,e,f are regression constants

Dia is the riding chain diameter

Depth is the water depth at the mooring site

Scope is the mooring scope = chain length / water depth

In order to calibrate the mooring system load response surfaces four sets of regression constants in the equation above were identified for each buoy type. The Mooring Selection Guide makes use of these regression constants and the response surface equations to estimate the mooring system loads.

## 5. ICE ACCRETION EFFECTS

During the winter months, the deck and superstructure of the navigation buoy will be subjected to ice accumulation. This is partly from atmospheric icing and partly because of freezing spray and splash due to the relative motions between the buoy hull and the water surface. The effect of this is twofold:

- Reduction in freeboard resulting in loss of stability.
- Increased hydrodynamic forces due to deeper draft in water and increased surface area in air (windage) due to ice accumulation.

The consequences of the first effect is not dealt with in detail here. The severity of the above icing effects will vary from location to location and the type of buoy structure configuration. For the purpose of determining the mooring loads in the iced-up condition, only the larger buoys are considered. It is also assumed that the same icing scenario is applicable to each buoy, independent of the location.

The effect of ice accretion can be calculated knowing expected accumulation (thickness) of ice on the buoy superstructure. Table 5.1 lists typical rates of icing for various surfaces of a marine structure as recommended by CCG's Navigation Buoy Design Manual [13], which are similar to the DnV rules for offshore structure icing. In the table, it can be seen that horizontal surfaces carry more ice than the vertical members. The weight of ice on sloping surfaces is determined through interpolation between vertical and horizontal rates given in the table based on their angle of inclination. Superstructure icing was estimated using block dimensions of the components.

Table 5.1: Buoy Superstructure Ice Accumulation

| Buoy Category | Buoy Type | Surface Ice Mass [kg/m$^2$] Vertical | Horizontal | Superstructure |
|---|---|---|---|---|
| 1 | Coastal Can & Conical Buoys | 25 | 75 | 75 |
| 2 | River Can & Conical Buoys | 15 | 50 | 50 |
| 3 | Ice Buoys | 25 | 150 | - |
| 4 | Spar Buoys | 15 | 50 | 50 |
| 5 | Boat Type Buoys | 25 | 75 | 75 |
| 6 | Lighted Buoys | 25 | 150 | 150 |

A typical example of the icing calculations for the 2.9 m Bell Buoy is given in Table 5.2. Prior to selecting the final ice surcharge parameters for the mooring load calculations, the surcharge was checked to see whether it provided a reasonable estimate of the icing load without seriously affecting the buoy's stability. The sinkage (increase in draft) due to icing load was calculated prior to continuing with steady-state mooring response calculations, as the new draft results in increased hydrodynamic drag.

Table 5.2: Sample Ice Accretion Calculations for the 2.9 m Bell Buoy

| Structural Surface | Surface Area [$m^2$] | Mass of Icing [kg] |
|---|---|---|
| ● Superstructure | | |
| Cross bars, short struts, foot rests | 1.5388 | 154 |
| Horizontal angles | 1.5244 | 213 |
| Horiz. Supp. for bell | 0.2398 | 36 |
| Vertical angles | 1.6374 | 41 |
| Bell surface | 0.6851 | 21 |
| Lifting legs | 0.3431 | 12 |
| ● Battery pocket cover | 0.7264 | 109 |
| ● Hull top surface | 7.1 | 994 |
| | Total | 1 580 |

Based on this approach the following ice surcharge loads were calculated for the four lighted buoys (see Table 5.3). The effects of icing are considered

Table 5.3: Calculated Ice Surcharge

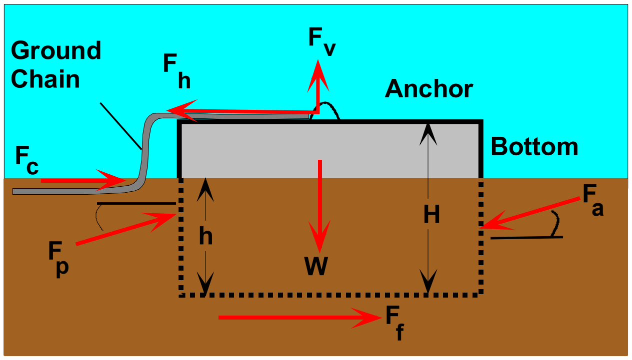
| Buoy | Ice Mass [kg] | Buoy | Ice Mass [kg] |
|---|---|---|---|
| 2.9 m Lighted Whistle | 2 095 | 1.8 m Lighted | 929 |
| 2.9 m Lighted Bell | 1 580 | 1.4 m Lighted | 394 |

With these ice surcharges the dynamic characteristics of the buoys differ significantly from that of the buoys without ice. For this reason the buoys with ice accumulation were treated as individual buoys with respect to all of the mooring design calculations.

## 6. SINKER SIZING

The anchor material, indicating the sinker material density, and the bottom type, indicating the soil properties of the ground at the mooring site, are used to calculate the minimum required sinker size to resist movement caused by the mooring load at the anchor.

The holding power of an anchor against horizontal displacement (being dragged off station) is ensured by balancing the horizontal and vertical anchor and ground chain derived resistive forces with the horizontal and vertical applied mooring chain loads as illustrated below:



| | | | |
|---|---|---|---|
| $F_h$ | mooring chain horizontal load | $F_v$ | mooring chain vertical load |
| $F_c$ | ground chain friction | $F_p$ | soil passive pressure |
| $F_a$ | soil active pressure | $W$ | wetted (buoyant) anchor weight |
| $F_f$ | anchor sliding frictional force | $H$ | anchor height |
| $h$ | depth of anchor embedment | $\alpha$ | embedment depth ratio = $h / H$ |

**Figure 6.1: Anchor Design Loads**

The frictional force generated by movement of the ground chain is estimated based on the buoyant weight of the chain and the weight of the depth of cover assumed for each bottom type. The total chain friction force which is used to reduce the horizontal load applied to the anchor is estimated as follows:

$$F_c = \left(\text{soil and chain weight}\right)\tan\delta \cdot \text{ground chain length}$$

$$= (((\gamma_{\text{chain}} - \gamma_{\text{water}})A + 2\gamma_{\text{soil}} W_s d)\tan\delta)L$$

where: $$L = \frac{\text{Depth} \times \text{Scope} - .9\text{Depth}}{2}$$

$Z$ = chain weight per unit length
$W_c$ = width of chain links
$d$ = depth of chain soil cover
$\delta$ = bottom/soil friction angle
$L_g$ = length of ground chain
$\gamma_w$ = unit weight of water
$\gamma_c$ = unit weight of the chain (steel)
$\gamma_s$ = unit weight of the soil

The depth of soil cover was assumed to be a soil property which is associated with each bottom type.

Estimation of the soil forces (passive, active and frictional) are calculated according to Coulomb's earth-pressure theories using the soil properties ($\delta$, $\phi$, $\gamma$) and depth of embedment assumed for each bottom type. The soil active and passive forces are calculated as follows:

$$F_a = \frac{1}{2}\gamma\, h^2 K_a H \qquad\qquad F_p = \left(\frac{1}{2}\gamma\, h^2 K_p + 2c'\sqrt{\frac{K_p}{2}}\right)H$$

where:

$$K_a = \frac{\sin^2(90+\phi)}{\sin(90-\delta)\left[1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi)}{\sin(90-\delta)}}\right]^2} \quad \text{and} \quad K_p = \frac{\sin^2(90-\phi)}{\sin(90+\delta)\left[1-\sqrt{\frac{\sin(\phi+\delta)\sin(\phi)}{\sin(90+\delta)}}\right]^2}$$

and the soil/anchor frictional force resisting sliding is estimated based on contributions from the bottom and sides of the anchor as follows:

$$F_f = F_{bottom} + F_{sides}$$

$$F_{bottom} = N\tan\delta \qquad\qquad F_{sides} = \frac{1}{3}\gamma h^3(1-\sin\phi)\left[\sqrt{\frac{K_p}{2}}+\sqrt{K_a}\right]\tan\phi$$

where N, the effective anchor weight, is the sum of the vertical forces acting on the anchor.

$$N = W - F_v - F_p\sin\delta + F_a\sin\delta$$

The minimum acceptable anchor size is one which ensures that the anchor is not displaced (i.e. the sum of the horizontal forces applied to the anchor is zero).

$$\sum F_x = (F_h - F_c) + F_a\cos\delta - F_p\cos\delta - F_f = 0$$

$$= \left( \frac{1}{2} \gamma h^2 K_p + 2hc' \sqrt{\frac{K_p}{2}} \right) H \cos\delta - \frac{1}{2} \gamma h^2 K_a H \cos\delta$$

$$+ \left[ \left( (\gamma_a - \gamma_w) H^2 + \frac{1}{2} \gamma h^2 K_a \sin\delta - \left( \frac{1}{2} \gamma h^2 K_p + 2hc' \sqrt{\frac{K_p}{2}} \right) \sin\delta - F_v \right) H \tan\delta \right]$$

$$+ \frac{1}{3} \gamma h^3 (1 - \sin\phi) \left( \sqrt{\frac{K_p}{2}} + \sqrt{K_a} \right) \tan\phi - F_h$$

By conservatively assuming that the anchor is a cube, the horizontal force balance is used to determine the minimum required anchor size. It should be noted that the anchor volume and thus its dry weight are a function of the anchor material density.

The soil properties used in the calculation of the minimum anchor size are presented below in Table 6.1. In the MSG software it is assumed that the bottom may be characterized as one of four types (solid rock, gravel, coarse soil or fine soil). The coarse soil bottom type represents soft clay bottoms, while the fine soil bottom type represents silts or fine sand bottom conditions. Since the bottom soil friction angle is a function of the two contact surfaces, Table 6.1 makes reference to both the bottom type and the anchor material.

Table 6.1: Soil Properties for Each Bottom Type

| **Assumed Soil Property** | | **Solid Rock** | **Loose Gravel** | **Coarse* Soil** | **Fine** Soil** |
|---|---|---|---|---|---|
| Internal Friction Angle | $\phi$ | N/A | 35 | 9 | 21 |
| Unit Weight [kN/m$^3$] | $\gamma$ | N/A | 20 | 15 | 18 |
| Cohesion [kN/m$^2$] | c' | N/A | 0 | 10 | 7 |
| Embedment Ratio | $\alpha$ | 0.0 | 0.25 | 0.5 | 1.0 |
| Chain Soil Cover [m] | d | 0.0 | 0.1 | 0.25 | 0.25 |
| **Bottom Soil Friction Angle** | | | | | |
| Concrete Anchor | $\delta_c$ | 29 | 22 | 12 | 6 |
| Cast Iron Anchor | $\delta_s$ | 27 | 20 | 10 | 5 |
| Rock Anchor | $\delta_r$ | 29 | 24 | 14 | 8 |

## 6.1 Minimum and Maximum Sinker Sizes

The calculated minimum anchor size is compared with CCG minimum and maximum anchor size recommendations, which are dependent on the buoy type are shown in Table 6.2. The largest of either the minimum recommended or calculated anchor size is reported in the acceptable design matrix. Past practice and operational limitations (e.g. lifting/handling capacity of the cranes on buoy tenders) dictate the maximum anchor size which may be used to secure a buoy. For this reason a maximum anchor size has been associated with each buoy type.

Table 6.2: Minimum and Maximum Sinker Sizes

| **Buoy Type** | **CCG Drawing Number** | **Minimum Anchor Size [kg (lb)]** | **Maximum Anchor Size [kg (lb)]** |
|---|---|---|---|
| **Deep Water Buoys** | | | |
| 2.9 m (9'6') Lighted Whistle | FA-1010 | 2 700 (6 000) | 4 500 (10 000) |
| 2.9 m (9'6') Lighted Bell | FA-1007 | 1 800 (4 000) | 3 600 (8 000) |
| 1.8 m (6'0') Lighted | FA-1004 | 1 150 (2 500) | 3 600 (8 000) |
| 1.4 m (4'6') Lighted | FA-1001 | 500 (1 100) | 2 300 (5 000) |
| **Coastal Buoys** | | | |
| 0.6 m (2'0') Spar Short | FA-3005 | 450 (1 000) | 2 700 (6 000) |
| 0.6 m (2'0') Spar Long | FA-3005 | 450 (1 000) | 3 600 (8 000) |
| 0.8 m (2'6') Coastal Conical ver. | FA-2002 | 225 (500) | 2 300 (5 000) |
| 0.8 m (2'6') Coastal Can ver. | FA-2001 | 225 (500) | 2 300 (5 000) |
| 1.2 m (4'0') Coastal Conical ver. | FA-2004 | 450 (1 000) | 900 (2 000) |
| 1.2 m (4'0') Coastal Can ver. | FA-2003 | 450 (1 000) | 900 (2 000) |
| 1.6 m (5'6') Coastal Conical ver. | FA-2006 | 450 (1 000) | 900 (2 000) |
| 1.6 m (5'6') Coastal Can ver. | FA-2005 | 450 (1 000) | 900 (2 000) |
| **Estuary Buoys** | | | |
| 3.0 m (10'0') Lighted Scow | FA-1015 | 450 (1 000) | 1 200 (2 500) |
| 1.5 m (5'0') Lighted Discus | FA-1019 | 225 (500) | 680 (1 500) |

## 7. MOORING DESIGN SAFETY

The acceptability of a mooring system configuration is based on the following design checks:

- ensuring that the buoy can maintain the minimum required freeboard
- a riding chain residual strength to peak load comparison
- a thrash chain residual strength to peak load comparison
- the minimum required sinker mass to hold the buoy on station
- a comparison of the thrash chain residual strength to anchor weight for retrieval.

While it is critical that the residual strength of the chain be higher than the peak mooring load to ensure that the buoy is not lost during a storm event, it is not reasonable to require that the buoy retain its minimum freeboard during the ten-year storm event. In addition, it has become an expected maintenance practice to reset mooring sinkers after a severe storm (i.e. ten year storm) which indicates that sinkers were not necessarily sized to withstand the ten-year storm as is done by the MSG software. For these reasons, the following different minimum levels of safety were applied to the five design checks outlined in Table 7.1.

Table 7.1: Design Factors of Safety

| Design Check | Minimum Factor of Safety |
|---|---|
| Buoy Freeboard | 1 |
| Riding Chain Strength in Service | 4 |
| Thrash Chain Strength in Service | 4 |
| Minimum Sinker Size | 1.2 |
| Thrash Chain Strength at Recovery | 2 |

The factor of safety associated with chain strength criteria were selected to match industry standards which specify a chain's maximum working load as 1/4 of the chain's break load. The minimum sinker size factor of safety was selected to calibrate the design process to CCG practice.

## 8. FURTHER DEVELOPMENT WORK

The Mooring Selection Guide software was developed as a mooring design tool for use by the CCG bases. In order to ensure that the resulting software was useful, the development process included frequent consultation with base operations personnel. During the development project new features and functions were added as needed to satisfy the needs of the end users.

With the delivery of this software some suggestions for further development are outlined here for consideration:

- The scope of application of the software could be extended to handle the remainder of the CGG buoys. This extension of the software could be handled by either generating more buoy behavior data to enhance the current data base or revising existing mooring dynamics models to speed up their operation and improve their computational stability. If the latter approach is employed the current data base of mooring loads would be used as a basis for checking and calibrating the revised model.
- The buoy freeboard calculations and CCG minimum freeboard requirements could be reviewed to improve their performance. The MSG software could be revised to include a buoy additional mass field to enable the user to calibrate the weight of their version of the CCG standard buoys.
- Further information on the degradation of mooring chains could be used to improve the chain wear model. This development requires a concerted effort on the part of the CCG base operations personnel to maintain mooring service and wear data.
- The effectiveness of case hardening the thrash sections of mooring chains to reduce chain wear could be performed. The results of this investigation could be incorporated into the MSG chain degradation model.
- It is suggested that the performance of this software be monitored to identify any future modifications to the software.
- This software should be demonstrated to International Association of Lighthouse Authorities (IALA) members to solicit their opinions on the software and develop joint research and development work.
- The Sheltered Water Mooring Selection Guide, a companion software developed to design moorings for wind and current effects, should be distributed with the MSG for review.

In addition, the following comments are given to indicate related areas which deserve further attention.

- The CCG buoy design manual should be reviewed and updated to include the lessons learned in this and other design projects.
- Standardization of buoys and mooring materiel (e.g. swivels and shackles) could serve to reduce operating costs.

## REFERENCES

1. Canadian Tide and Current Tables, published by Dept. of Fisheries and Oceans, Ottawa, 1981.
2. Numerical Models of Currents on the Canadian East Coast, Dept. of Coastal Oceanography, Bedford Institute of Oceanography, Dartmouth, N.S.
3. Semi-empirical models of coastal currents on the West Coast, Channel Consulting Services, Victoria, B.C., 1996.
4. Communications with Dr. Mike Woodward, Institute of Oceanographic Sciences, Sidney, B.C.
5. Wind and Wave Atlas, Volumes I, II, III, IV, available from the Transportation Development Centre, Montreal.
6. Tayfun, M.A., et al., “Design Considerations on Wave Spectrum Estimation”, Proc. of International Symp. on Wave Measurement and Analysis, ASCE, Vol. 1, 1974.
7. Hoerner, S.F., **Fluid Dynamic Drag**, published by the author, Brick Town, N.J., 1958.
8. Hay, A.D., “Flow About Semi-Submerged Cylinders of Finite Length”, report from School of Engineering, Princeton Univ., N.J., 1947.
9. Menon, B., “Drag Coefficients of Navigation Buoys”, Arctec Canada Ltd. report to CCG Marine Aids Division, #1949FR, April 1986.
10. Bertaux, H., **Buoy Engineering**, Published by John Wiley and Sons, 1978.
11. Newman, J.N., **Marine Hydrodynamics**, MIT Press, 1977.
12. Faure, T.D., “Experimental and Numerical Investigations of Mooring Line Dynamics”, National Research Council Technical Report, 1989/09, TR-HY-029.
13. “Navigational Buoy Design Manual”, Canadian Coast Guard Internal Report.