THE MOORING SELECTION GUIDE (MSG) SOFTWARE

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ABSTRACT

Recent Canadian Coast Guard (CCG) buoy mooring maintenance practice includes the retrieval and replacement of mooring chains, on an annual basis, for many coastal buoys. To reduce maintenance costs, a design process was developed at Fleet Technology Limited (FTL) to identify coastal buoy mooring configurations capable of providing up to six years of uninterrupted service. This mooring chain size and configuration selection process has been computerized to form the "Mooring Selection Guide" software. The development of this software, sponsored by the Canadian Coast Guard Marine Navigation Services group and the Transportation Development Centre of Transport Canada, will provide an extended service life mooring design capability to the coast guard bases in a windows compatible software.

The design process, described in this paper, compares the buoy and mooring line hydrodynamic loads with the residual strength of the worn mooring chain and transitional resistance of the mooring sinker. The hydrodynamic load effects are estimated for a set of design environmental conditions using the NRC developed MOORDYN code and used to generate response surfaces for the tension in the mooring chain at the sinker, riding and thrash chain sections.

The corroded/worn geometry of the riding and thrash chain sections of the mooring system are predicted based on a semi-empirical mooring system wear model which considers nominal chain diameter, mooring depth and duration of service. The residual strength of the mooring system at the highest wear location within the riding and thrash chain sections is calculated using an analytical model based on the deformation of curved beams related to a Von Mises failure criteria.

The minimum weight sinker (anchor) required to hold the buoy on station is estimated based on an analytically derived process which considers the mooring tension, including uplift, and the interaction of the sinker and ground chain with the specified bottom type. This process makes use of the active and passive soil pressures and friction forces associated with chain and sinker contact and embedment within the specified bottom material.

The result of the Mooring Selection Guide design calculations is a matrix of acceptable coastal buoy mooring configurations described by minimum required sinker weight and riding and thrash chain diameters. This matrix presentation approach allows the user to select from the acceptable design alternatives to suit the logistic and operational requirements of the situation.

BACKGROUND

The Marine Aids Division of the Canadian Coast Guard has the responsibility for design, installation and maintenance of aids to navigation including buoys. One of the important load carrying components in the buoy system is the mooring chain. In the past, its design requirements and procurement have been based primarily on the use of relatively low strength carbon steel chains.

As a matter of routine practice, mooring chains were inspected annually and if the wastage due to corrosion and/or wear was considered excessive, the chain was replaced. As a consequence of this proactive inspection and maintenance approach, chain failures were infrequent and the overall experience to date with mooring chains was considered to be 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 seven 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 was the use of higher strength and therefore smaller diameter chains. The use of lower strength, large diameter chains has three disadvantages 1) the weight of the large diameter chains reduces the reserve buoyancy of buoys, thus affecting the survivability in extreme sea conditions, 2) the added weight of larger diameter chains adversely affects handling during deployment and recovery and 3) it limits the depth of water in which a given buoy may be moored.

To address both these issues, the Canadian Coast Guard Marine Aids Division initiated a five-year field trial of mooring chains to document the degradation rates of various mooring chain systems (WBL 1994). Based on the results of this study it was shown (FTL 1995) that a five year mooring chain service life was feasible and that higher strength chains would be beneficial for some mooring sites.

With this information it was decided to develop a computer program to aid in the design of long life mooring systems, the Mooring Selection Guide, MSG, (FTL 1996).

INTRODUCTION

Buoys and other floating aids provide markers in the water used by mariners for safe navigation. These aids to navigation are held on station by a mooring system. A typical single leg mooring system, shown in Fig. 1, includes an anchor (sinker) and a chain system. Since the components of the mooring system are essentially arranged in series, the "weakest link" will determine its reliability.

In designing a mooring system, the designer needs to compare the peak loads applied to mooring system components (anchor, riding, thrash and ground chains) with their minimum strength or capacity which is assumed to occur at the end of their service life. Fig. 2 illustrates the roles played by the various mooring system and site characteristics in the design process ensuring reliability of the mooring system components.

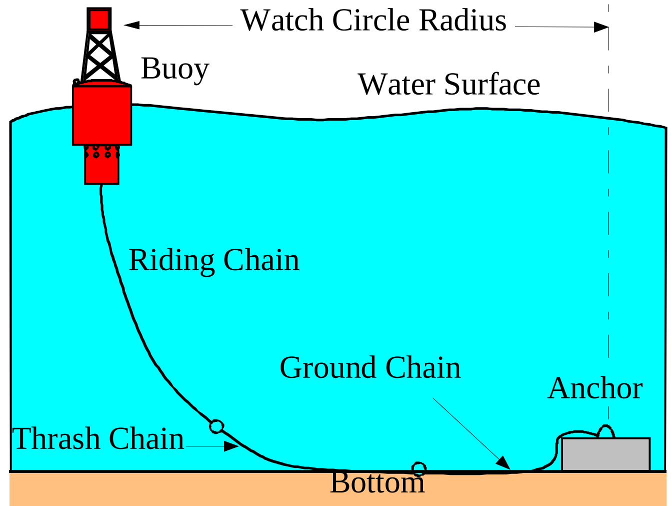


Fig. 1: Typical Mooring System

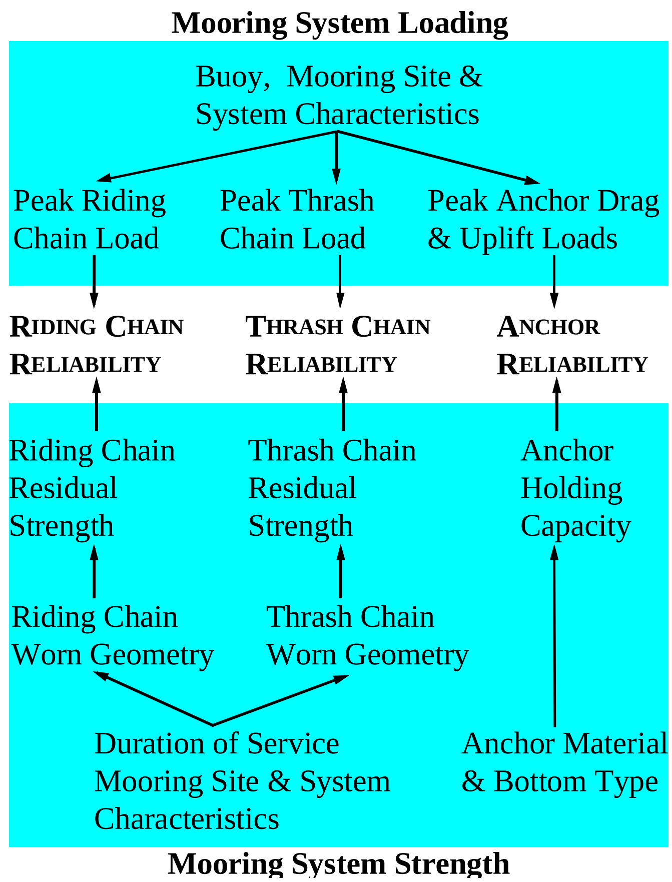


Fig. 2: Mooring System Design Process

In addition to the strength checks outlined in the design process, the designer will ensure the serviceability of the buoy by checking that the buoy can adequately support the mooring system (i.e. adequate freeboard) and that the sinker is retrievable.

MOORING SYSTEM LOADING

The loading on the mooring system is a function of the buoy geometry, its own characteristics (chain weight, diameter and length) and the mooring site environmental conditions (wind speed, current, wave height, water salinity and buoy icing). All of these effects are considered by the MSG software system.

Design Environmental Conditions

Each buoy considered by the MSG software is categorized as an estuary, coastal or deep water buoy. This categorization allows the selection of suitable design wind, wave (height and period) and current magnitudes as a function of water depth for each buoy type. The design wind, wave and current data were established based on a review of the most severe environmental conditions with a ten year return period for severe CCG estuary, coastal and deep water buoys. Based on this information, the depth based descriptions of the design environmental conditions similar to that shown in Fig. 3 for deep water buoys are developed.

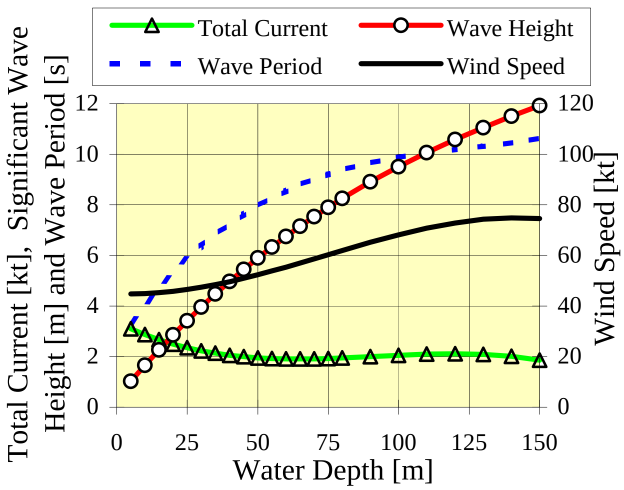


Fig. 3: Deep Water Buoy Design Environmental Conditions

Mooring System Load Estimation

The dynamic behavior of buoy mooring systems were assessed numerically to determined the peak loads applied to its components. The numerical algorithms used to simulate this non-linear dynamic behavior can be time consuming and require a significant amount of computational power which would not be available to the intended users of the MSG software. For this reason it was decided to generate response surfaces to describe the peak loads in each mooring system component for each buoy type. The response surface independent variables are mooring chain diameter, scope (length / water depth) and water depth. These peak load response surfaces were calibrated using the non-linear mooring system load simulation software MOORDYN (NRC 1989) which simulated the behaviour of mooring systems whose scopes, chain diameters and water depths are contained within the range of values shown in Table 1.

Table 1: Mooring Peak Load Response Surface Range of Validity

Variable	Lower Bound	Upper Bound
Mooring Scope	1.5	4
Chain Diameter	3/8 in.	1 3/4 in.
Water Depth*	2 m	150 m

* Minimum and maximum water depths are a function of buoy draft and reserve buoyancy.

Separate response surfaces were calibrated for buoys which are placed in winter service to describe the affects of ice accretion.

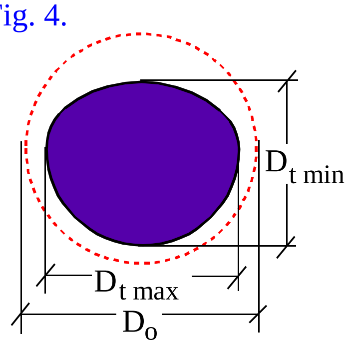
MOORING SYSTEM STRENGTH

In order to ensure that the mooring system components can adequately support the estimated peak loads the minimum expected strength or capacity of the mooring system components are established. It has been observed that due to a combination of mechanical wear and corrosion the breaking strength of the mooring chains will degrade with time. Therefore, the residual strength of the mooring chains at the end of their design service life are compared with their peak loads to assess mooring safety. Whereas, the sinker's holding capacity could increase with time as the sinker settles or becomes silted-in.

Mooring Chain Degradation / Wear

Past experience, data from the CCG five year mooring field trials and other mooring chain wear measurements suggest that the rate and mode of chain wear is different in the riding and thrash sections of the mooring. The peak mooring chain wear is located in the thrash section of the chain (for an active mooring) due to its interaction with the bottom. It is conservatively assumed that the peak thrash chain load coincides with the location of maximum thrash chain wear. The peak wear in the riding chain is expected to be immediately under the buoy where the mooring chain load is a maximum.

Experience indicates that the worn cross-section of a chain link is not circular but may be idealized as shown in Fig. 4.



D_o	link original nominal diameter
$D_{t\ min}$	minimum chain link diameter at time t
$D_{t\ max}$	maximum chain link diameter at time t
D_r	diameter ratio, $D_{t\ min} / D_0$
t	service life in months

Fig. 4: Idealized Worn Chain Cross-Section

Based on these observations and field data several empirical models were developed to describe thrash and riding chain wear in terms of the diameter ratio (D_r):

$$D_r = \frac{\frac{C_1 D_0 t}{\sqrt{1+t}} + C_2 t^2 + C_3 t}{C_4 Depth + C_5} \qquad [1]$$

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 (in inches) and water depth (in meters), respectively. The regressed chain wear coefficients for equation [1] are given below in Table 2 and the form of this relationship is illustrated in Fig. 5 for thrash chains.

Table 2: Wear Model Regression Coefficients

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

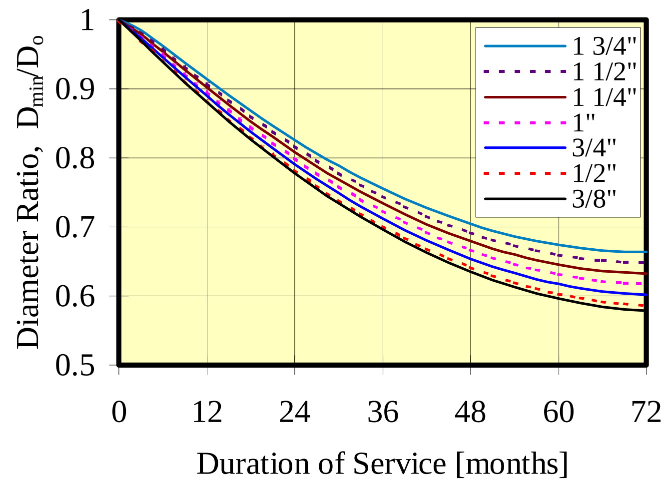


Fig. 5: Thrash Chain Link Wear Model

In order to determine the maximum link diameter the following function describing the ratio of the minimum link diameter to the maximum link diameter (D_{min} / D_{max}) was developed from field data:

$$\frac{D_{min}}{D_{max}} = 0.4202 \frac{D_{min}}{D_{nominal}} + 0.5798 \qquad [2]$$

Mooring Chain Residual Strength

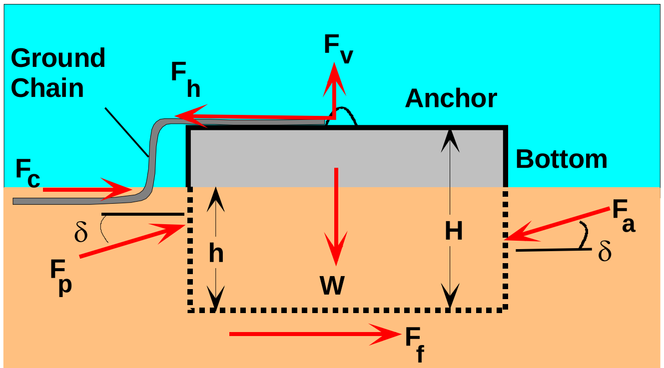
An analytical model was developed based on the theory of curved beams to estimate the breaking load of chain links with non-circular cross-sections. This model calculates the Von Mises-Hencky effective stress at the point of maximum shear stress within the link cross-section for the location of maximum wear. A rigid-perfectly plastic material behavior is used to relate the chain link breaking load with complete link cross-section plasticity. The chain link's minimum specified ultimate tensile material strength is conservatively used in this formulation to predict the design chain, end of service life, residual strength.

Mechanical testing of worn chain links removed from service was used to validate this analytical model. The analytical model was shown to be a good predictor of the actual failure loads since the actual and predicted failure loads differed by less than 10%.

Anchor (Sinker) Holding Capacity

The sinker material and bottom type which indicate the sinker material density and the soil properties of the bottom at the mooring site, respectively, are used to calculate the minimum required sinker size to resist movement caused by the peak 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	chain horizontal load	F_v	chain vertical load
F_c	ground chain friction	F_p	soil passive pressure
F_a	soil active pressure	W	buoyant sinker weight
F_f	sliding friction force	H	anchor height
h	depth of embedment		

Fig. 6: Idealized Sinker 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:

$$F_c = (soil + chain\ weight)\tan\delta \cdot L$$

$$= (((\gamma_c - \gamma_w)A + 2\gamma_s W_s d)\tan\delta)L \qquad [3]$$

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

Z	chain linear unit weight	d	soil cover depth
L	length of ground chain	γ_w	water unit weight
W_c	width of chain link	γ_c	chain unit weight
δ	soil friction angle	γ_s	soil unit weight

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

The soil forces (passive, active and frictional) are calculated according to Coulomb's earth-pressure theories using typical soil properties (δ, ϕ, γ) and a depth of embedment assumed for each bottom type. The soil active and passive forces are calculated as follows:

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

where: [4]

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

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

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

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

where; [5]

$$F_{bottom} = N \tan\delta$$

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

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

$$N = W - F_v - F_p \sin\delta + F_a \sin\delta \qquad [6]$$

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).

$$(F_h - F_c) + F_a\cos\delta - F_p\cos\delta - F_f = 0 \qquad [7]$$

By conservatively assuming that the anchor is a cube, the horizontal force balance is used to determine the minimum required anchor size

The calculated minimum anchor size is compared with CCG minimum and maximum anchor size recommendations, which are dependent on the buoy type and buoy tender lifting capacities.

Mooring System 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

- the riding chain residual strength must be greater than the peak load applied to it;
- the thrash chain residual strength must be greater than the peak load applied to it;
- the sinker mass is sufficient to hold the buoy on station
- the mooring chain residual strength must be larger than the 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, therefore the minimum buoy freeboard design check is performed only for calm water environmental conditions. In addition, it has become 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 above.

Table 7: Design Factors of Safety

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

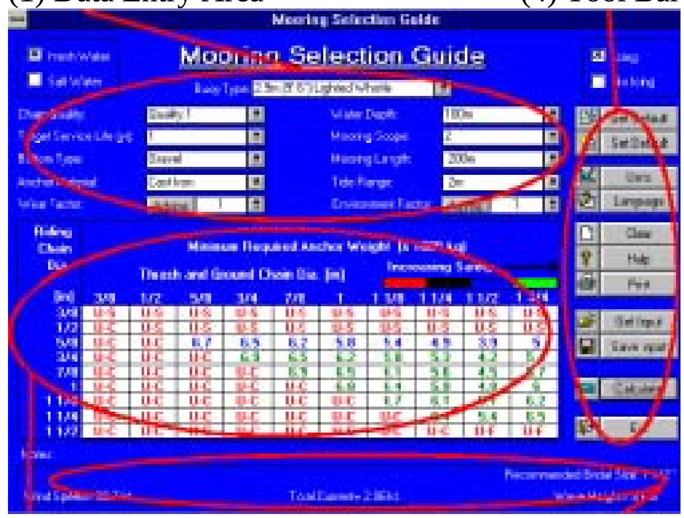
The factor of safety associated with chain strength criteria were selected to match industry standards which specify a chain's maximum working load as 1/4 of the chain's break load. The minimum sinker size factor of safety was selected to calibrate the design process to CCG practice.

MSG SOFTWARE OPERATION

The Mooring Selection Guide provides the user with seamless access to a powerful engineering tool for the design of mooring systems. The MS Windows software interface was developed with input from the end users (CCG Aids to navigation personnel) to ensure that it was user-friendly and a useful design tool. The software incorporates error trapping and a complete Windows style on-line help system to ensure the accuracy and completeness of the design data and provide the user with background information on the design process and assumptions. The bilingual (English and French) software was developed to operate using any of three set of units: metric (m, MPa and kg), imperial (ft, ksi, lb) or nautical imperial (fathoms, ksi, lb) to accommodate the users preferred system of units.

The Mooring Selection Guide (MSG)'s main user interface, shown in Fig. 7, is arranged in four functional areas:

(1) Data Entry Area (4) Tool Bar



(2) Mooring Design Results (3) Design Notes

Fig. 7: Main User Interface Functional Areas

Mooring Design Data

The upper portion of the main user interface provides space for the user to enter all of the required mooring design data. A complete set of mooring design data includes the following information:

- Buoy Type - the 15 most common CCG buoys for which the software can design mooring systems are currently available.
- Water Depth - the low tide water depth at the mooring site.
- Tide Range - the tide range at the mooring site
- Chain Quality - user may select quality 1, 2, or 3 (classification society standard chain strength designations) or enter the chain material's ultimate tensile strength.
- Target Service Life - duration of service for which the mooring system should be designed.

- Mooring Length - length of chain used in the mooring system (the riding chain is assumed to be 0.9 x water depth in length).
- Mooring Scope - ratio of the chain length to water depth. Used as a measure of the relative length of the mooring system.
- Anchor Material - allows the user to select a cast iron, concrete or rock sinker.
- Bottom Type - provides rock, gravel, course soil or fine soil options for the user to select from.
- Icing/No Icing - indicates whether buoy ice accretion should be considered in the design of the mooring system.
- Fresh/Salt Water - indicates if the mooring system is located in fresh or salt water. This parameter affects only the buoyancy calculations as it was noted that this difference in water density had only a minor effect on the mooring peak loads.
- Wear Factor - allows the user to incorporate personal chain wear rate experience in the design process. The ratio of the observed to predicted residual chain strength.
- Environment Factor - allows the user to modify the mooring design to better reflect the mooring site's actual environmental conditions (i.e. wind, wave and current). The environmental factor is specified as the ratio of the peak chain loads generated by the design environmental conditions and those due to the users specified conditions.

The mooring scope, water depth and chain length are by definition related, therefore the user need only enter the water depth and either the mooring scope or chain length. The MSG software provides advisory routines to aid the user in selecting appropriate wear and environment factor values. The advisory routines are accessed by selecting the advise button beside the wear and/or environment factor data fields.

Mooring Design Results

The mooring design results are displayed in the form of a design alternative matrix. Columns in the matrix are associated with ground and thrash chain sizes (diameter) while rows are associated with riding chain sizes. It has been assumed that the ground and thrash chains will be comprised of the same materiel.

A cell which contains a "U- " an unacceptable design based on the design checks performed by the software. Any cell containing a numerical value represents an acceptable design. The numerical values are the minimum sinker weight required for the current input data (i.e. buoy type and bottom type etc..). In general, there are four classes of cells describing the acceptability of the mooring chain combination:

1) **U-C** - Unacceptable based on the design assumption that the thrash chain must be composed of a chain with a diameter larger than or equal to the riding chain.
2) **U-F** - Unacceptable due to a lack of freeboard. The buoy did not have sufficient reserve buoyancy to support the specified chain size combination at high tide.
3) **U-S** - Unacceptable based on the level of safety provided. The residual strength of either the degraded riding or thrash chains does not provide the specified factor of safety with respect to their peak mooring loads.
4) Acceptable solution. The residual strength of the degraded riding and thrash chains both exceed their respective peak mooring loads by at least the specified factor of safety and the freeboard is not less than the pre-determined minimum allowable.

The acceptable mooring chain designs are color coded based on their level of conservatism (factor of safety), as shown in the bar chart of increasing safety above the design matrix:

Detailed results outlining the mooring loads and degradation data used in the design checks to ensure mooring acceptability can be obtained for the latter two classes of design combination cells by selecting the appropriate design matrix cell.

The most economic mooring chain combination would be the acceptable riding and thrash chain combination located nearest to the top left of the design matrix. This combination represents the lightest mooring chain combination.

Design Notes

In order to provide the user with additional information and/or guidance the MSG software incorporates the following mooring system design notes:

- a caution that a non-standard steel strength (other than those specified in the CCG mooring chain material specification - MA 2080) is used in the design process,

- an indicator that some design matrix sinker weights are the minimum or maximum allowable sinker weight (based on CCG experience),
- a maximum watch circle radius (see Fig. 1) used to define the operational effectiveness of the buoy
- a recommended buoy bridle size, and
- an outline of the design environmental conditions used in the design process (wind, current, wave height and period).

Tool Bar

The operation of the mooring selection guide is controlled by the icons contained in the tool bar at the extreme right hand side of the main user interface. These icons allow the user to save or recall mooring design scenarios, change the language or system of units, print the design results, access the on-line help and update the design results matrix after modifying the mooring data.

MSG VALIDATION

The Mooring Selection Guide software employs four individually validated functional components: the mooring load estimation processor, a chain wear model, a worn chain residual strength algorithm and a sinker holding capacity routine. The mooring chain load estimates are developed using a well established mooring simulation software (NRC 1989) which was previously calibrated. The chain wear model is essentially an empirical model which presents the trends observed in the wear of mooring chains in service. The worn chain residual strength algorithm is an analytical mechanics of materials formulations which was experimentally validated. The sinker sizing process is based on Coulomb's earth-pressure theories with standard soil properties and compared with CCG field experiences.

The software was presented to the CCG aids to navigation staff for validation. A variety of mooring design scenarios were tried and the results agreed favorably with the experience of CCG's operations staff.

CONCLUDING REMARKS

The Mooring Selection Guide (MSG) software is an effective, easy to use mooring design tool which considers the time dependence of a mooring system's capacity. This design tool will aid the Canadian Coast Guard to realize their objective of developing mooring systems which can endure up to five years of unattended service. The software will serve all CCG bases since it is adaptable to regional constraints and conditions.

The approach taken in the MSG software allows the user to easily evaluate a variety of mooring configuration alternatives. The matrix of design alternatives indicates the most economical mooring system along with alternative acceptable design solutions from which the user may select based on materiel availability or personal preference.

It is expected that the MSG software will be improved in the future to better serve the Canadian Coast Guard. It is expected that thrash chain wear reduction approaches will be studied and incorporated into this design tool in order to increase the service life of the most demanding mooring sites.

In addition, a simplified sheltered water mooring selection guide software will be assembled which may be applied to the design of mooring systems for virtually any buoy type.

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