Systems approach to sea waterways

Stanisław Gucma

Maritime University of Szczecin, Marine Traffic Engineering Centre
70-500 Szczecin, ul. Waly Chrobrego 1–2, e-mail: s.gucma@am.szczecin.pl

Key words: marine traffic engineering, sea waterways, conditions of safe operation of ships on sea waterways

Abstract

The system of sea waterways, as defined in this article, consists of three subsystems: waterways, navigational, and traffic control. This author has defined a state vector for conditions of safe operation of ships on a waterway and described interrelations between parameters of sea waterway system and the state vector of safe ship operation conditions.

Introduction

According to the definition, sea waterway must be adjusted to the specific type of navigation undertaken by vessels which have suitable length, breadth, draft and air draft. The basic condition for shipping by sea in its security is understood as the safety of a manoeuvring the ship and its surroundings, as opposed to the possibility of collision (the adverse event brings damages and losses) [1].

The safety of navigation is an overall concept that encompasses all issues related to smooth, accident-free passage of a ship from point A to point B of a sea waterway. By the term “accident” is meant the navigation or manoeuvring accidents, such as:

1. Grounding (broadly understood as an unintended contact of the hull, rudder or propeller with the seabed).
2. Damage to the hull due to ship-shore contact (during ship’s impact on the shore element, where the depth is greater than ship’s draft).
3. Damage to offshore or port structures by direct contact with a ship, or as a consequence of propeller stream impact.
4. Damage to a tug taking part in ship’s manoeuvres.
5. Damage to a seamark.
6. Collision with another vessel moored to a berth or at anchor.
7. Collision with another vessel underway.

Navigational risk, one of the navigation safety criteria, has an increasingly wide use. Navigational risk in i-th section of a waterway can be written as this function [2, 3]:

\[ R_i = f(A_i, S_i, N_i, H_i, M_i, I_i, Z_i) \]  

where:

- \( R_i \) - navigational risk in i-th section of a waterway;
- \( A_i \) - area parameters;
- \( S_i \) - ship’s parameters;
- \( N_i \) - position determination system parameters;
- \( H_i \) - hydrometeorological parameters;
- \( M_i \) - manoeuvre parameters;
- \( I_i \) - traffic intensity parameters;
- \( Z_i \) - traffic control system parameters.

The function of navigation safety (navigational risk) \( R_i \) is a dependent variable, determined by independent variables \( A_i, S_i, N_i, H_i, M_i, I_i, Z_i \) consisting of a factors describing the system: ship – area – positioning system – prevailing hydrometeorological conditions – traffic intensity – traffic control system – manoeuvring tactics.

Each sea waterway has vessel traffic restrictions, which are called the operating conditions of sea waterway operation or operating conditions of the vessel for shipping and relate to:

- parameters of a vessels using a waterway;
- hydrometeorological conditions, under which a specific type of vessels can move;
• parameters of a traffic intensity and waterway capacity;
• conditions of a vessel manoeuvres on a waterway.

Taking into account the above restriction, predicted as conditions of waterway operation, the navigational risk in i-th waterway section for a specific ship performing a specific manoeuvre in preset hydrometeorological conditions can be written in this simplified function form:

$$R'_i = f(A_i, N_i, Z_i) \quad (2)$$

The above relation unequivocally indicates that the determination of safe waterway parameters is strictly related to positioning systems used on an examined waterway, and to vessel traffic control system. This process is presently called as the design of the waterway system [4, 3].

The sea waterway system

In terms of marine traffic engineering the system of the sea waterways consists of a number of separate sections (n). Each waterway section features three basic components [5]:
• waterway subsystem;
• ship position determination system (navigational subsystem);
• traffic control subsystem.

These components are interrelated and have an essential influence on the system properties. The waterway sections are distinguished on the basis of the following comparative criteria:
• manoeuvre performed;
• technical parameters of the waterway;
• technical parameters of navigational systems used;
• prevailing hydrometeorological conditions;
• port regulations and traffic control systems.

Each section is so classified that along its entire length the same comparative criteria should be applied.

A system of the sea waterways is defined by parameters of its elements (subsystems). The three subsystems of sea waterway system inherent in each section are a function of the conditions of safe operation of the vessel. In this connection, the system of i-th waterway section can have the following matrix representation [5]:

$$\begin{bmatrix} A_i \\ N_i \\ Z_i \end{bmatrix} = f(t_{yp}, L_c, B, T, V_i, C_i, H_i) \quad (3)$$

The conditions of safe operation of the vessel on a waterway include:

- type of a “maximum ship”
- length of a “maximum ship”
- breadth of a “maximum ship”
- draft of a “maximum ship”
- allowable speed of a “maximum ship” in i-th waterway section
- tug assistance in i-th waterway section (required number of tugs and their bollard pull)
- vector of allowable hydrometeorological conditions for a “maximum ship” in i-th waterway section.

$$H_i = [d/n, \Delta_i, V_{wi}, KR_{wi}, V_{pi}, h_{fi}, KR_{fi}] \quad (4)$$

where:
- d/n – allowable time of day (day-time or no restrictions);
- \(\Delta_i \) – minimum underkeel (day-time or no restrictions);
- \(V_{wi} \) – allowable wind speed in i-th section;
- \(KR_{wi} \) – restrictions of wind direction (if they occur in i-th section);
- \(V_{pi} \) – allowable current speed in i-th section;
- \(h_{fi} \) – allowable wave height in i-th section;
- \(KR_{fi} \) – allowable wave direction (if waves occur).

To describe the components of the system, I have assumed the following matrix notation for i-th waterway section:

**Waterway subsystem**

$$A_i = \begin{bmatrix} t_i \\ l_i \\ D_i \\ h_i \end{bmatrix} \quad (5)$$

where:
- \(t_i \) – type of i-th waterway section;
- \(l_i \) – length of i-th waterway section;
- \(D_i \) – width of navigable area of i-th waterway section;
- \(h_i \) – minimum depth of i-th waterway section.

Marine traffic engineers distinguish these waterway types:
• fairway:
  – rectilinear section;
  – bend;
• port entrance (rectilinear, or one or more bends;
• anchorage;
• port basin;
• lock.
Fairways, in turn are available in various types, such as:
- dredged fairway (channel) in a water area of less depth;
- fairway with a trapezoid cross-section;
- fairway with a rectangular cross-section;
- fairway with a submarine slope;
- mixed cross-section fairway (with various banks).

Similar cross-sections characterize port entrances.

**Navigational subsystem**

\[ N_{in} = \begin{bmatrix} d_{in} \\ m_{in} \\ n_{in} \end{bmatrix} \]  \hspace{1cm} (6)

where:
- \( d_{in} \) - accuracy of \( n \)-th navigational system in \( i \)-th waterway section (standard deviation);
- \( m_{in} \) - availability of \( n \)-th navigational system in \( i \)-th waterway section (dependent on day/night time and visibility);
- \( n_{in} \) - reliability of \( n \)-th navigational system in \( i \)-th waterway section (technical reliability).

Systems of position determination on waterways can be divided into:
- terrestrial (using methods of optical and radar navigation);
- satellite (using methods of satellite navigation and electronic chart technologies).

Terrestrial systems (optical and radar methods) for position determination make use of shore infrastructure elements (characteristic objects visible from a ship or on a radar screen), and fixed and floating aids to navigation. These non-autonomous systems require the construction of specific navigational infrastructure (system of aids to navigation).

Satellite systems for position determination use various systems and methods of satellite navigation. In these systems, ship positions are displayed on electronic charts that may be based on various technologies. These are autonomous shipboard systems, not related to the infrastructure of a waterway. All they need is a number of devices for ECDIS, PNS, PNDS, etc., installed onboard.

Systems of position determination are designed for three different visibility conditions:
- day-time (good visibility);
- night-time (good visibility);
- poor visibility.

Operational guidelines of the waterway under consideration may limit the number of conditions designed for specific ship size groups, for instance:
- navigation of ships belonging to a specific size group is conducted exclusively at day-time;
- navigation on a given waterway is conducted only in good visibility.

Position determination systems for particular visibility conditions have to be doubled, otherwise a failure of one position determination system creates a risk of navigational accident (a possibility of simultaneous failures of two navigational systems should be considered). Two navigational systems, primary and additional, have to be designed for each of the three visibility conditions.

**Traffic control subsystem**

\[ Z_{im} = \begin{bmatrix} r_{im} \\ o_{im} \end{bmatrix} \]  \hspace{1cm} (7)

where:
- \( r_{im} \) - type of \( m \)-th traffic control system in \( i \)-th waterway section;
- \( o_{im} \) - type of \( m \)-th hydrometeorological information system (hydro-meteorological support) in \( i \)-th waterway section.

Four options of vessel traffic control and hydrometeorological support can be distinguished:
1. Lack of a vessel traffic service (VTS).
2. VTS provides information.
   General information on conditions prevailing on the waterway.
3. VTS deals with vessel traffic organization.
   Information on hydro-meteorological conditions prevailing in each waterway section.
4. VTS includes navigational assistance.
   Information on hydro-meteorological conditions prevailing in each waterway section. A system determining a dynamic underkeel clearance is in operation.

**Conditions of safe operation of ships on a sea waterway**

Interrelations between parameters of the sea waterway system and conditions of the safe ship operation on that waterway impose two reversed problems:

1. Determination of parameters of basic components of waterway system built or modernized (waterway, navigational subsystem, traffic control subsystem). Parameters of a sea waterway system are a function of designed (assumed) conditions of safe ship operation (state vector of safe ship operation):  

\[ \begin{bmatrix} A_i \\ N_{in} \\ Z_{im} \end{bmatrix} = f(W_i) \]  \hspace{1cm} (8)
where:

\[ W_i = \begin{bmatrix} t_{ij}, L_i, B, T, V_i, C_i, H_i \end{bmatrix} \] (9)

2. Determination of the conditions safe operation of ship in the existing sea waterway system whose parameters are known. Then, the state vector of safe ship operation conditions is a function of waterway system parameters:

\[ W_i = F \begin{bmatrix} A_i, N_{in}, Z_{im} \end{bmatrix} \] (10)

The main problem in this case is the identification of the state vector of the conditions safe operation of ship on the waterway (system) under consideration. In the two problems the vector is identified in a different way.

**Conditions of safe ship operation – construction of waterway system**

The conditions safe operation of ship on the designed waterway, under construction or modernization, for one-way or two-way traffic are established at the system design stage, following this algorithm:

1. Identify ports and terminals to which the waterway under consideration is leading.
2. Define “maximum ship” characteristic of a particular port or terminal.
3. Group “maximum ships” characteristic of the ports and terminals by type:
   - oil tankers (dangerous cargo);
   - gas tankers (dangerous cargo);
   - bulk carriers;
   - container ships, reefers, general cargo ships, multi-purpose vessels;
   - ferries, ro-ro vessels;
   - cruise ships, passenger vessels;
   - other ships.
4. In each waterway section traffic intensity is planned for each size group and each type of ships listed above. Generally, three size groups are established, with the length overall \( L_i \) of “maximum ships” as the criterion:
   1) Large ships \( (90\% \div 100\%) L_i \);
   2) Medium ships \( (50\% \div 89\%) L_i \);
   3) Small ships \( (> 50\%) L_i \).
5. Taking into account the parameters of “maximum ships” of each type and traffic intensity for each size group we define the parameters of:
   - “maximum ship” in the one-way traffic;
   - “maximum ship” in the two-way traffic.

6. Using methods of marine traffic engineering we determine:
   - allowable speeds of “maximum ships” of the types under consideration in particular sections of the fairway \( V_i \): ships proceed at various allowable speeds on waterways, depending on the type of navigable area, and ship type and size. On the one hand, these speeds are imposed by operational requirements due to time limits of such vessels as ferries, container ships, ro-ro vessels, gas tankers, on the other hand: the safety of navigation. As a rule, this is a “service speed in restricted area”, at which ships proceed in distant roadsteads and anchorage approaches, or “reduced speed” used on fairways. Service speed for restricted areas is not ship’s maximum speed, but the one developed at “full manoeuvring ahead” setting. Reduced speed, in turn, is used at approach fairways and developed at the main engine set “half ahead” [6];
   - allowable hydrometeorological conditions in each waterway section for the examined ship types \( (H_i) \). An example clearance for a minimum water level is determined depending on the type and size of the vessel, the minimum value of water level and the probability of their occurrence during the period a designed waterway is to be operated.

   WE divide ships into two categories:
   1) ships that cannot wait for a higher water level (ferries, gas tankers, etc.);
   2) ships that can wait for a higher water level.

   For the former category, we assume a minimum water level occurring in a 20-year period of waterway operation (a period of durability of built waterways). For the latter category other values can be adopted (e.g. minimum water level occurring in a five-year period), and for such ships in particular, we may apply the dynamic method of underkeel clearance determination.

   After the determination of the conditions safe operation of ship on the designed (built or modernized) waterway, we calculate parameters of basic system components (waterway subsystem, navigational subsystem, traffic control subsystem). The parameters of designed waterway subsystems are determined using the above described optimization method, in which the objective function is the cost of construction and operation of the sea waterway.
system. Safe depths and widths of a manoeuvring area are in this method calculated using deterministic, probabilistic or combined models. The most accurate methods for the purpose are computer simulations based on probabilistic models [7].

**Conditions of safe ship operation – existing waterway systems**

In existing waterway systems, that is when the mentioned subsystems’ parameters are known, the conditions of the safe operation of ship are specified in regulations of maritime administration. These regulations often provide for an exceedingly large safety margin, hardly justifiable.

The research problem can be herein formulated as the determination of some new conditions of safe ship operation on the examined waterway, that is a change of some elements of the state vector of safe operation conditions in the existing waterway system. The problem results from changed requirements of the waterway user, and usually comes down to the execution of the following tasks:

- increase in parameters of “maximum ships”;
- increase in allowable ship speeds;
- introduction of other type of ships (e.g. carrying dangerous goods);
- decrease of allowable hydrometeorological conditions.

The execution of each task consists in following the steps of this algorithm:

1. The waterway user defines his needs requiring some changes to be made in condition of the safe operation of ship, after which “new operational conditions” are specified.

2. Required safe depths \(T_{sy}(t)\) and widths \(d_{ij}(1 - \alpha)\) safe manoeuvring areas are calculated for the “new operational conditions”. These calculations are made using deterministic, probabilistic or combined models.

3. Required safe depths and widths of the safe manoeuvring areas for “new operational conditions” are verified using the navigational safety conditions:

\[
\begin{align*}
&d_{ij}(1 - \alpha) \subset D_i(t) \quad \text{or} \\
&h_{sy}(t) \geq T_{sy}(t) + \Delta_{sy}(t) \quad (11)
\end{align*}
\]

or the navigational risk:

\[
R_i \leq R_{a,ke}
\]

where:

- \(D_i(t)\) – navigable area in \(i\)-th waterway section (safe depth condition at instant \(t\) is satisfied);
- \(d_{ij}(1 - \alpha)\) – safe manoeuvring area of \(j\)-th ship performing a manoeuvre in \(i\)-th waterway section in \(k\)-th navigational conditions, determined at a confidence level \(1 - \alpha\);
- \(R_i\) – navigational risk of passing \(i\)-th waterway section;
- \(R_{a,ke}\) – acceptable navigational risk;
- \(h_{sy}\) – area depth at point \(x, y\);
- \(T_{sy}\) – ship’s draft at point \(x, y\);
- \(\Delta_{sy}\) – underkeel clearance at point \(x, y\).

If any of the conditions of navigation is not satisfied, such element of the state vector of the conditions safe operation of ship is determined by the method of successive approximations that satisfies the condition.

4. Verified of the conditions safe operation of ship on the examined waterway are defined (now changes have been made in the verified elements of the state vector of safe ship operation conditions). These verified conditions do not necessarily fully satisfy user’s needs, and these needs may be satisfied only after modernization (reconstruction) of the considered waterway system.

**Conclusions**

The presented definition of a sea waterway system includes three basic elements, or subsystems:

- waterway subsystem;
- ship position determination (navigational) subsystem;
- traffic control subsystem.

Essential parameters of each subsystem have been identified, characterized and presented in the matrix notation.

This author has also determined the state vector of the conditions safe operation of ship on a waterway, and defined relationships between parameters of sea waterway system and conditions of safe ship operation, formulating two reversed problems:

1. Determination of parameters of waterway system built or modernized (subsystem elements).
2. Determination of the conditions safe operation of ship in the existing waterway system.

An algorithm has been developed to determine:

- of the conditions safe operation of ship in a waterway system to be established;
- of the conditions safe operation of ship in an existing waterway system.
References