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Ship Collision with the Tokyo Bay Crossing Bridge - Tunnel

Collision avec le pont-tunnel de la baie de Tokyo

Schiffsanstoß gegen den überquerenden Brücken-Tunnel in der Bucht von Tokio

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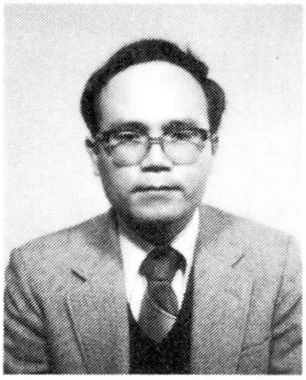
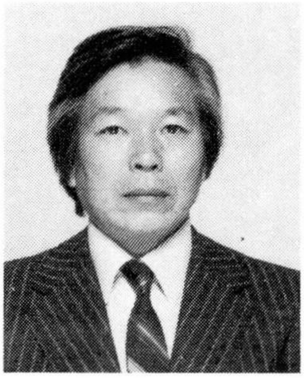


Yujiro Wasa, born 1944, got his master degree at Kobe University, Japan. He joined Nihon Doro Kodan in 1968. Since then he has been in charge of the construction and design of expressways in Japan. He is responsible for the research of the Tokyo Bay Crossing Bridge-Tunnel.



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SUMMARY
The Tokyo Bay Crossing Bridge-Tunnel, 15 km long is planned to cross the Tokyo Bay almost at the middle. A collision probability study was carried out looking into the combined effects of the actual behaviour of vessels entering into and navigating around the Bay, natural environment and the probability of sea accidents and storms. The conclusion obtained so far from studies of the existing situation revealed the need of a protection system for the bridge section of the Crossing against 200,000 devt. vessels in storms and 5,000 devt. vessels in ordinary weather .

RÉSUMÉ
Il est prévu que le Pont-Tunnel de la Baie de Tokyo, de 15 km de long, traverse la baie en son milieu. Une étude de probalitité de collision a été réalisée , en examinant les effets combinés du comportement des navires navigant dans la Baie, de l'environnement naturel, de la probabilité d'accidents en mer et de tempêtes. Les résultats déjà obtenus ont révélé le besoin d'un système de protection de la partie du pont traversant la baie pour les navires de 200.000 t de chargement en cas de tempête et de 5.000 t de chargement en temps normal.

ZUSAMMENFASSUNG
Der die Bucht von Tokio durchquerende Brücken-Tunnel mit einer Länge von 15 km wurde entworfen, um die Bucht von Tokio ungefähr in der Mitte zu durchqueren. Eine Studie über eine Kollisionswahrscheinlichkeit wurde ausgearbeitet, welche kombinierte Einwirkungen des gegenwärtigen Verhaltens von Schiffen, die in die Bucht fahren, natürliche Umgebung sowie Wahrscheinlichkeit eines Unglücks im Meer oder Sturm mit einbezog. Die Folgerung aus nun verfügbaren Daten ist, daß die Brücke mit einem Schutzsystem gegen 200.000-Tonnen Schiffe im Sturm und 5.000-Tonnen Schiffe in anderen Bedingungen versehen werden muß.

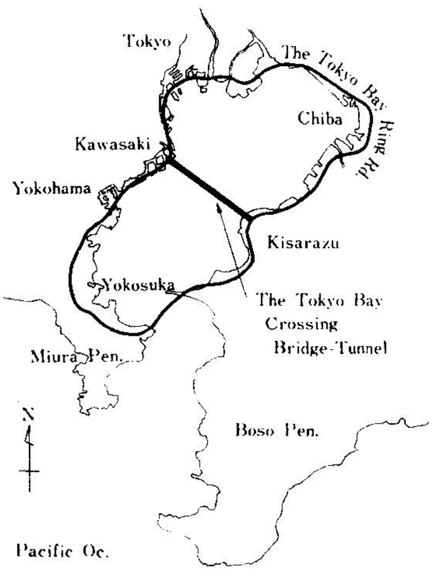
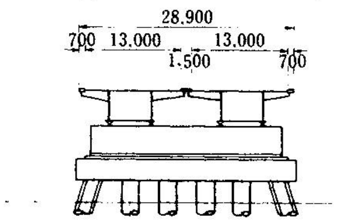
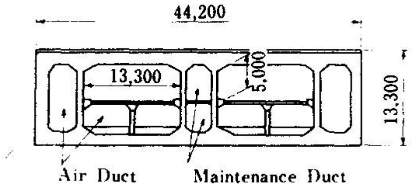


Fig.1 Site of the Crossing

Typical Section of Bridge



Typical Section of Immersed Tunnel



1.THE TOKYO BAY CROSSING BRIDGE-TUNNEL

1.1 Profile of The Tokyo Bay

The Tokyo Bay located at about the middle of Japan facing the Pacific Ocean has a long oval shape of roughly 70Km by 20Km(see Fig.1). There are a lot of large port facilities for big cities such as Tokyo which is the center of politics, economics and industries of Japan, as well as Yokohama, Kawasaki, Chiba and others. These ports currently handle about 450,000 vessels of various sizes and 60,000 tons of cargo annually, forming the biggest industrial center in Japan.

1.2 Outline of The Crossing

A new ring road project around the Bay to connect this highly densed and developed living/producing area was planned, carried out and now more than half is opened to the public. The Tokyo Bay Crossing Bridge-Tunnel under planning is to cross the Bay at the middle, cutting short the ring road.
The ring road is 100m wide in most part and consists of a motorway, a national highway and a local trunk road. The Crossing on the otherhand consists of only a motorway. It will cross the narrowest part of the Bay by means of bridges, man-made islands and a tunnel almost straight for about 15Km between the shores.(See Fig.2)Passages will be secured for large vessels, medium ones and small ones separately. A long immersed tunnel will be constructed for securing the passsage of large vessels.

2. INVESTIGATION INTO THE ACTUAL CONDITION

2.1 Navigation of Vessels

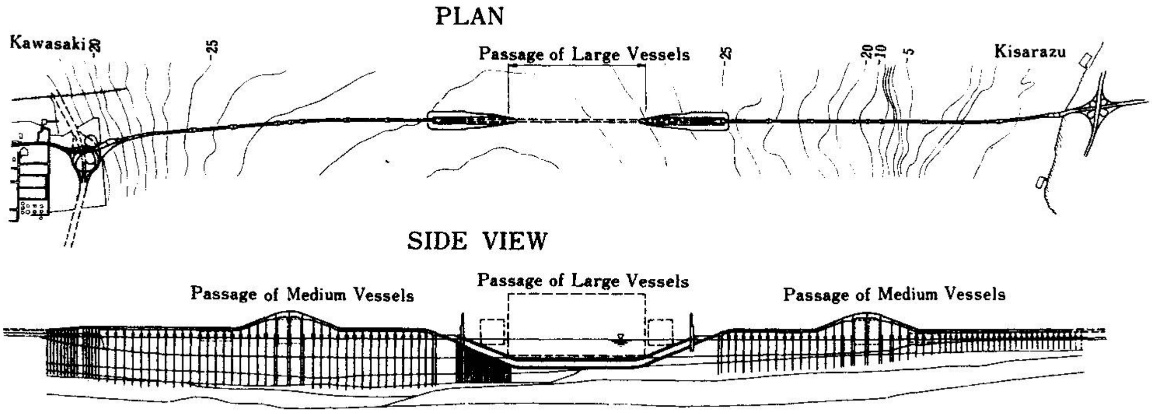


Fig.2 The Tokyo Bay Crossing Bridge-Tunnel

2.1.1 Number of Vessels

The annual number of vessels passing through the Uraga Channel at the mouth of the Bay was 300,000 in 1978 and the number of those entering the principal six ports in the Bay totalled 450,000. Out of these vessels, some 270,000 annually would be going around the proposed site of the Crossing.
The estimation for the year 1985 is 370,000 vessels at the Uraga Channel and 640,000 vessels moving around in the Bay.(See Fig.3)

2.1.2 Size and Type of Vessels

As to the distribution of the size of vessels estimated for the year 1985 shown in Fig.4, more than half is made up of ships of less than 500 gross tonnage. The main passage of the Crossing is planned for 200,000 deadweight size of vessels. The distribution of types shown in Fig.6 is mostly shared by cargo carriers.

2.1.3 Speed of Vessels

The actual average speed of vessels at the site of the Crossing, although the maximum speed recorded was 20 knots (37Km/hour), was 10 knots and less than 14

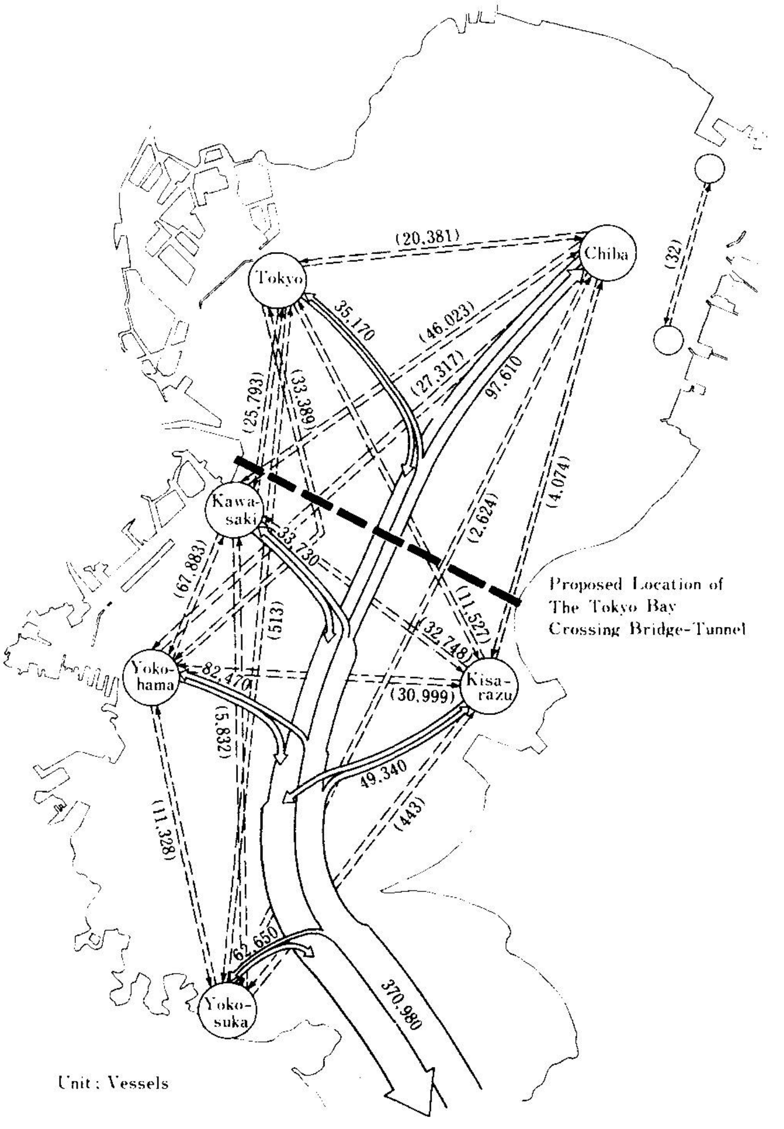


Fig.3 Number of Vessels in the Year 1985

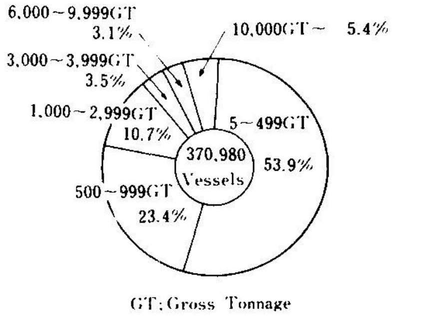


Fig.4 Size of Entering Vessels

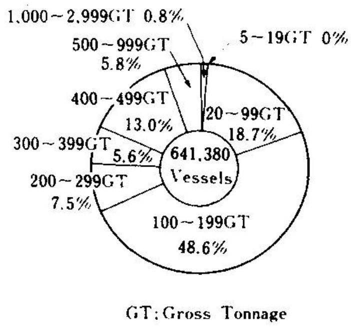


Fig.5 Size of In-Bay Vessels

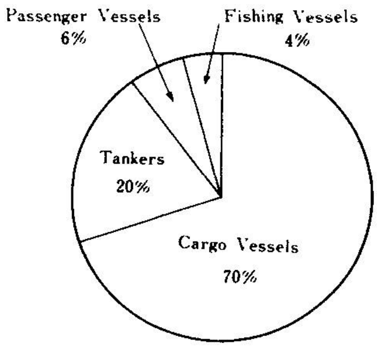


Fig.6 Type of Vessels

knots for more than 95% of the vessels.

The behaviour of navigation is controlled by several regulations. Actual observation revealed that most of the vessels navigated according to these rules and in order along the passage. However the exceptions were small fishing boats, traces of which were found to be criss-crossing all over the Bay.

2.2 Natural Environment

2.2.1 Wind

The wind records observed around the Bay revealed the wind blowing mostly toward North or South and rarely to the other direction (see Fig.7).

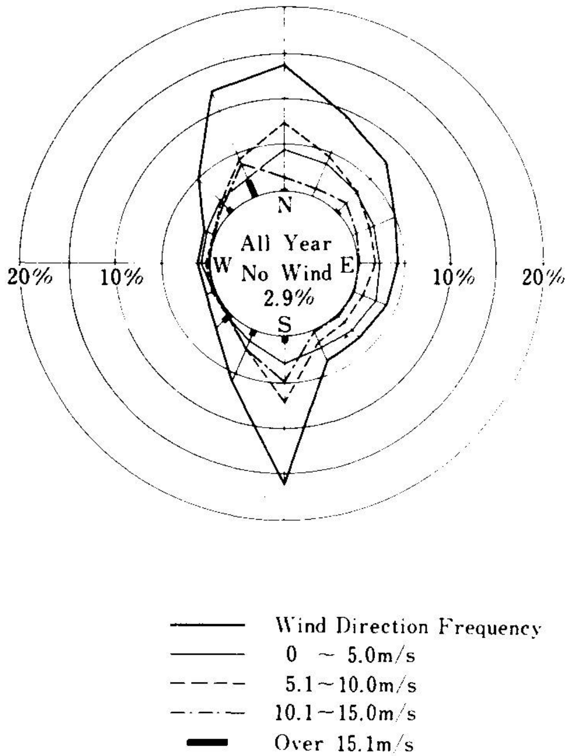


Fig.7 Wind Frequency

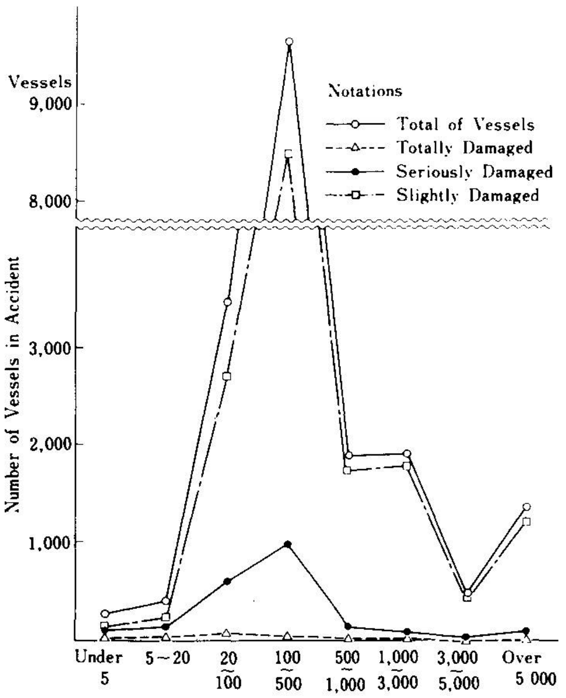


Fig.8 accident Rate

The wind velocity for designing of the Crossing was determined by analyzing those records to be basically 41m/s (as of 1979) which was the expected value for a period of 100 years.

2.2.2 Tidal Current

The direction and speed of current in the Bay keep changing every minute accordingly to the tide. However the maximum speed of current was relatively small, 0.8 knots, near the proposed site of the Crossing.

2.2.3 Typhoon

There were statistically about 28 typhoons on average spotted annually and four of them, roughly 14% of all, hit Japan. The probability of strong typhoons with a wind velocity of more than 35 m/s coming around and/or landing near the Bay was about once in ten years.

2.3 Probability of Sea Accident

The accident rate of all the vessels entering the Bay was statistically one in about 1,000 vessels in which one in about 3,800 vessels involved in collision and one in about 5,700 vessels involved in running-on. However most of the accidents occurred inside the port area, so that the previous figures of rate otherwise decrease to about 21,700 and 13,200 vessels respectively. More than half the accidents involved vessels of 100/500 gross tonnage and about 60% of all were fishing boats. The cause of accidents was in most cases related to the manner of navigation. However the damages sustained were usually minor and rarely serious or beyond recovery. (See Fig.8, 9). The collision rate of vessels entering into ports increases as the vessels got larger supposedly due to more difficulty in maneuverability.
The relation between the size of vessels and running on accidents was not clear.

3 PROBABILITY OF COLLISION

3.1 Probability in Case of Storms

The vessels striking the structures of the Crossing in storms were supposed to be the vessels anchoring in the Bay but swept-away by strong winds, the force of which exceeded the capacity of anchor (hereinafter called "Swept-away").
The probability of collision in storms was calculated by a study based on the

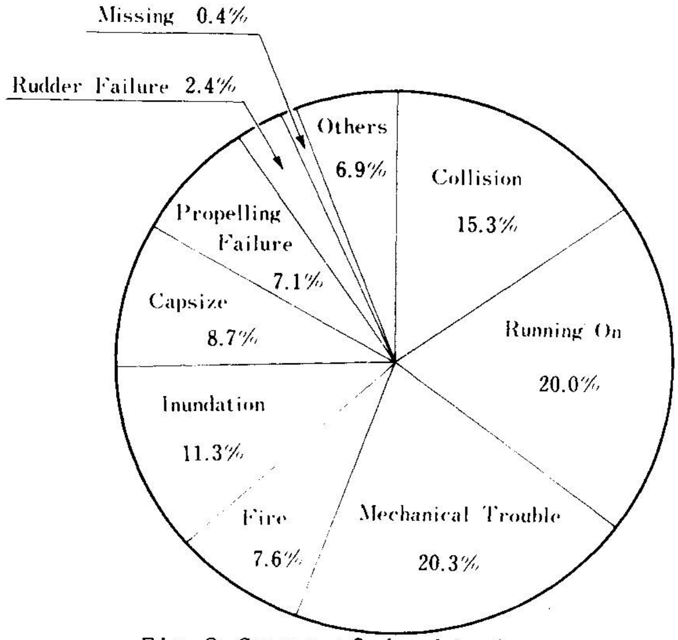


Fig.9 Cause of Accident

investigation of actual samples of vessels evacuating from ports and swept-away vessels, the assumption of conditions, demand and capacity for evacuation of vessels in the Bay, as well as the wind velocity at which vessels start being swept away, record of strong storms and the rate of swept-away of evacuating vessels.

3.1.1 Evacuation Record

The actual evacuation of vessels, mostly cargo carriers of 7,000/ 11,000 gross tonnage, during five typhoons hitting the Osaka Bay between 1965 and 1968 was as follows.
-Distance between vessels and shore-line ;
More than 80% of vessels kept a distance of about 3.7km from shore-line.
-Distance between each vessel;
The average distance between each vessel was about 1,300m but 10,000 gross tonnage class vessels stayed 1,600 ± 300m away from one another.
As an example of counter-measures for evacuation of vessels in the Tokyo Bay during a strong typhoon, many vessels evacuated to the outside of ports following the advice of authority.

Table-1 The Number of Vessels Demanding Evacuation in The Tokyo Bay

Gross Tonnage of Vessels	3,000 / 10,000	10,000 / 20,000	20,000 / 80,000	over 80,000	Total
Number of Vessels Demanding Evacuation	141	59	26	9	235

3.1.2 Evacuation Demand and Capacity of the Tokyo Bay

The demand of vessels evacuating from ports in the Bay was assumed to be as shown in Table-1. On the other hand the capacity was assumed to be slightly more than 70 vessels taking into account conditions of evacuation, depth, nature of seabed soil and size of vessels, etc. and by the manner of drawing circles of required diameter in possible area for evacuation as shown in Fig.-10. The lack of capacity was clear.

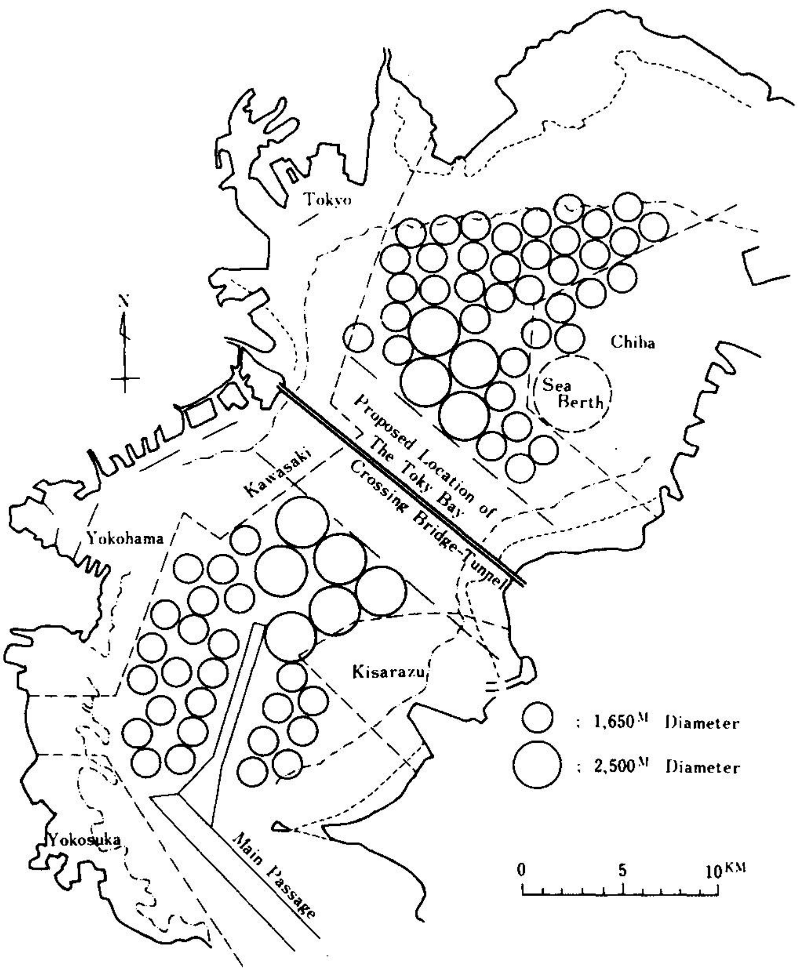


Fig.10 Evacuation Capacity.

3.1.3 Records of Swept-Aways

The investigation into the records of swept-away vessels revealed no relation with the size of vessels or the manner of anchoring. Therefore it was considered that the phenomenon of swept-away was largely affected by the technique of navigation and the state of countermeasures against severe weather according to the weather forecast and sea condition.
The speed of vessels being swept-away was statistically between 0.1 and 3.0m/s with a wind velocity of 30 to 35m/s and for a distance of up to 10km.

3.1.4 Wind Velocity Starting Swept-Away

Vessels tend to start being swept-away, as a result of a study, when the wind velocity of ten minutes on average reaches 25m/s for lightly loaded ones and 30m/s for heavily loaded ones.

3.1.5 Record of Strong Wind apart from Typhoon

A wind of more than 25m/s average velocity, supposedly 30m/s on the sea, never occurred except in case of typhoons according to the Weather Bureau of the Tokyo Area.

3.1.6 Rate of Swept-Away of Evacuating Vessels

It was clear that the vessels evacuating from ports and anchoring in the Bay during a storm would not start to be swept away all at once when the average wind velocity reached the previously mentioned value for starting.
Therefore a study was carried out to confirm the relations between the maximum wind velocity and the rate of swept-away, ratio to the number of evacuating vessels, by looking into the records of typhoons and the inquiries covering the vessels entering the Bay. The following results were obtained.

- Maximum Wind Velocity : 25m/s Rate of Swept-Away : About 1%
- Maximum Wind Velocity : 35m/s Rate of Swept-Away : About 35%
- Maximum Wind Velocity : 42m/s or over Rate of Swept-Away : About 100%

As a conclusion, the swept-away vessels will be about one percent with a maximum wind velocity of roughly 25m/s and all with over 42m/s.

3.1.7 Probability of Collision

- Occurrence Probability of Strong Wind (P_1)

The study revealed the interval of occurrence of wind velocity to start swept-away as 0.73 years to 25m/s for lightly loaded vessels and 6.4 years to 32m/s for heavily loaded ones, by taking into account the statistical interval of strong wind occurrence around the Bay.
The occurrence probability of wind velocity to start swept-away was consequently as follows.

Lightly Loaded Condition (25m/s) $p_{11}=10^{-3.81}$ times/hour
Heavily Loaded Condition (32m/s) $p_{1f}=10^{-4.75}$ times/hour

- Probability of Swept-Away (P_2)

By supposing the swept-away would occur according to the said rate among evacuating vessels, the probability of swept-away, defined as a probability of more than one vessel being swept-away among evacuating ones, was as follows using Poisson Distribution.

Lightly Loaded Condition (Rate of Swept-Away 4%) $p_{21}=10^{-0.06}$
Heavily Loaded Condition (Rate of Swept-Away 21%) $p_{2f}=10^{0.00}$

- Probability of Vessels Approaching The Bridges (P_3)

The product of probability P_1 and P_2 is the probability of more than one vessel being swept-away in the Bay. But in this instance, the probability of swept-away vessels drifting nearer to the bridges was determined as the ratio of the vulnerable part of bridges against collision to the whole length of the Crossing in the susceptible area as follows by assuming the swept-away would occur at random regardless of where the vessels anchored.

$$P_3 = \frac{\text{Length of Bridges}}{\text{Length in Susceptible Area}} = \frac{6.8\text{Km}}{11\ \text{Km}} = 10^{-0.21}$$

- Probability of Vessels Passing Between The Piers (P_4)

The probability of vessels passing between the piers of bridges was determined to be $P_4 = 0$ since most of those navigating around the site of the Crossing were longer than the pitch of the piers.

- Probability of Collision in Storms (P)

The probability of collision in storms was the product of probabilities of each factor, as follows.

- Lightly Loaded $P = P_{11} * P_{21} * P_3 * (1-P_4) = 10^{-4.08}$ times/hour
- Heavily Loaded $P = P_{1f} * P_{2f} * P_3 * (1-P_4) = 10^{-4.96}$ times/hour

Those values showed that there would be one collision every about 1.37 years or so in case the vessels were lightly loaded and every about 10.4 years or so in case the vessels were heavily loaded. But in this study the term "lightly loaded" was defined as empty, a situation which would hardly occur in a storm since the draught of every vessel would be lowered as a precaution to increase steadiness by means of more ballast. Therefore it would be more reasonable to assume the condition of loading to be in between half and heavy which meant the collision rate in storms would be once in about five to ten years.
As a conclusion of this study, the probability of collision, even if all vessels in the Bay were heavily loaded, was once in about ten years which was rather high. Further, it was clear from the investigation into actual conditions that the size of vessels had no relation with their swept-away. Therefore 200,000 deadweight vessels which were the largest ones entering the Bay, had to be considered as object of collision in storms.

3.2 Probability of Collision in Ordinary Time

The collision in ordinary time was statistically caused by navigational errors. Therefore the probability of errors was studied.

Table-2 Summary of Probability of Collision in Ordinary Time

Gross tonnage of Vessels: Passage	Damage	5 ~ 100	100 ~ 500	500 ~ 1,000	1,000 ~ 3,000	3,000 ~ 10,000	10,000 ~ 20,000	20,000 ~ 100,000	over ~ 100,000	Total
For Small Vessels	Totally	$10^{-6.94}$ (994)	—	—	—	—	—	—	—	$10^{-6.94}$ (994)
	Seriously	$10^{-5.33}$ (24)	—	—	—	—	—	—	—	$10^{-5.33}$ (24)
	Minor	$10^{-4.54}$ (4.0)	—	—	—	—	—	—	—	$10^{-4.54}$ (4.0)
	Total	$10^{-4.47}$ (3.4)	—	—	—	—	—	—	—	$10^{-4.47}$ (3.4)
For Medium Vessels	Totally	—	$10^{-7.29}$ (2230)	—	—	—	—	—	—	$10^{-7.29}$ (2230)
	Seriously	—	$10^{-5.18}$ (17)	$10^{-6.23}$ (193)	—	—	—	—	—	$10^{-5.14}$ (16)
	Minor	—	$10^{-3.91}$ (0.9)	$10^{-4.73}$ (6.1)	—	—	—	—	—	$10^{-3.85}$ (0.8)
	Total	—	$10^{-3.88}$ (0.9)	$10^{-4.71}$ (5.9)	—	—	—	—	—	$10^{-3.82}$ (0.8)
Sub Passage		—	$10^{-4.21}$ (1.9)	$10^{-4.37}$ (2.7)	—	—	—	—	—	$10^{-3.98}$ (1.1)
For Large Vessels		—	—	—	$10^{-5.05}$ (13)	$10^{-5.41}$ (29)	$10^{-5.70}$ (57)	$10^{-5.90}$ (91)	$10^{-6.90}$ (907)	$10^{-4.79}$ (7.1)

Note ; The probability of collision to be Times/Hour.
Figures in bracket to be the interval year of occurrence.

3.2.1 Probability of Collision in Main Passage of Large Vessels

The probability of collision with man-made islands located at both sides of the tunnel was studied by the following four methods (see Table-2).
- The rate of vessels running on the small islands at the mouth of the Bay to all the passing vessels.
- The study of general statistics on both sea accidents and harburs.
- The investigation of draught and traces of vessels by normal distribution.
- The investigation of draught and traces of vessels by Rayleigh distribution.

3.2.2 Probability of Collision in Sub Passage

The probability as shown in Table-2 was determined as the rate of vessels navigating in water shallower than their draught running on the man-made islands by assuming the traces of passing vessels being normal distribution.

3.2.3 Probability of Collision in Passage of Medium and Small Vessels

Assuming the probability of navigational errors to be 10^{-4}, the product of this value and the probability of collision without correcting the direction were determined as the probability of collision in the passage of medium and small vessels as shown in Table-2.

4 CONCLUSION

The study revealed the possibilities of vessels striking the bridges of Crossing in both entirely different situations which were the swept-away vessels in storms and navigational errors in ordinary time. The conditions of collision in these situations can be concluded as follows.

4.1 In Storms

Since the object of collision was the swept-away vessels, the absolute speed of striking vessels would be the added value of the swept-away vessel's speed against water and the speed of current, and could be considered to be 2.0m/s for heavily loaded vessels and 4.1m/s for lightly loaded ones.
The 200,000 deadweight vessels, which were the largest ones entering the Bay, should be considered as the object.

4.2 In Ordinary Time

Most of the causes for collisions in ordinary time were navigational errors. The correcting efforts of navigation were taken statistically when the approaching vessels were at the latest some distance twice their length before striking. Therefore the striking speed would not be the normal navigating speed but the one reduced after some operation to avoid the collision and to lower the speed by means of stopping the engines etc., and assumed to be about 12 knots (6.2m/s). The object of collision could be determined as the vessels of less than 100,000 gross tonnage which had a collision probability of less than $10^{-7.0}$ (negligible in engineering terms) for the main passage of large vessels, and 1,000 G.T. for the passages of medium vessels which were bridge sections.

4.3 Further Study

The protector would be large if it were designed fully according to the results of this study. Therefore further study including some additional specific investigations and introduction of stricter regulations on navigation and evacuation, would be needed to establish more appropriate and adequate countermeasure against ship collision and protection systems for the Crossing.