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Ship Collision against the Sunshine Skyway Bridge

Collision de bateaux contre le pont Sunshine Skyway

Schiffskollisionen mit der Sunshine Skyway Brücke

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SUMMARY
This paper outlines the methods used to perform a threat analysis of ship collisions with the new Sunshine Skyway bridge structure. A rational analysis of pier protection mechanisms and strength requirements of bridge piers was thus facilitated.

RÉSUMÉ
L'article traite de méthodes employées pour l'analyse de risque de collision des bateaux contre le pont Sunshine Skyway à Tampa, Floride. Cette analyse a facilité l'étude rationelle des mécanismes pour la protection des piles, et aussi la résistance requise pour les piles.

ZUSAMMENFASSUNG
Der Artikel berichtet über Methoden der Gefahrenanalyse von Schiffskollisionen mit der neuerbauten Sunshine Skyway Brücke. Die Analyse erleichterte das Verfahren zum Schützen der Brückenpfeiler und der Festigkeitsanforderungen an die Pfeiler.

1. GENERAL

Threat analysis [1] is the technique used to quantify, for any collection of assets, the degree of its vulnerability to damage or destruction by hypothesized threats. As it applies to the bridge problem, threat analysis involves the identification of the vulnerability of the bridge structure to ship collisions. Knowing this vulnerability enables the designer to determine the most appropriate and cost-effective measures to protect against the threats. This paper examines the three essential elements of threat analysis under the headings assets, threats and events, and mechanisms, and explains how the threat analysis findings were used to determine the cost-effectiveness of various pier protection systems for the Sunshine Skyway replacement bridge (Fig. 1). A 396.2 m section of the southbound span of the existing Sunshine Skyway bridge collapsed on May 9, 1980 when one of the anchor piers was struck by an empty 40,000 dwt phosphate carrier (see appendix). Thirty five lives were lost during the accident, as the result of motorists being trapped on, or driving off, the collapsed portion of the bridge.

2. ASSETS

An asset possesses two characteristics. First, it has some value to the organization which owns it; and second, it is capable of being threatened such that, under certain circumstances, its value is lost or damaged. Asset items for bridges are primarily the piers and spans which comprise the structure. While computationally possible to assign each bridge element as a separate asset category, it is generally desirable to group the piers and spans into larger assemblages which represent integrated sections of substructure and superstructure. Table 1 identifies one of the groupings utilized during the Skyway Bridge study. For each grouping of assets, the appropriate event cost parameters were determined.

3. THREATS AND EVENTS

The next phase of the analysis, after the assets have been categorized and evaluated, involves the identification of "threats" and "events".

3.1 Event Costs

Assets are subject to a variety of 'perils' which can cause them to lose value. 'Threats' are ordered pairs of the perils and the asset categories. For purposes of the analysis of the bridge, only one peril was recognized, that being vessel collisions. In the Skyway example, both the number of asset categories and consequently, the number of threats, is six. Each threat may be realized in a variety of different ways; each of these is called an 'event'. The analysis involved separate events in terms of seven classes of ships and barges based on size. Therefore, a potential total of 42 theoretical ship/pier collisions were possible. In fact, fewer were evaluated as it was impossible for certain vessel categories to impact the more distant piers because of reduced bay bottom depth in the area. For each event, it is necessary to determine "event cost" (EC) combining the evaluative parameters of the asset group involved. This EC value is a function of the independent variable, severity. In the analysis of the

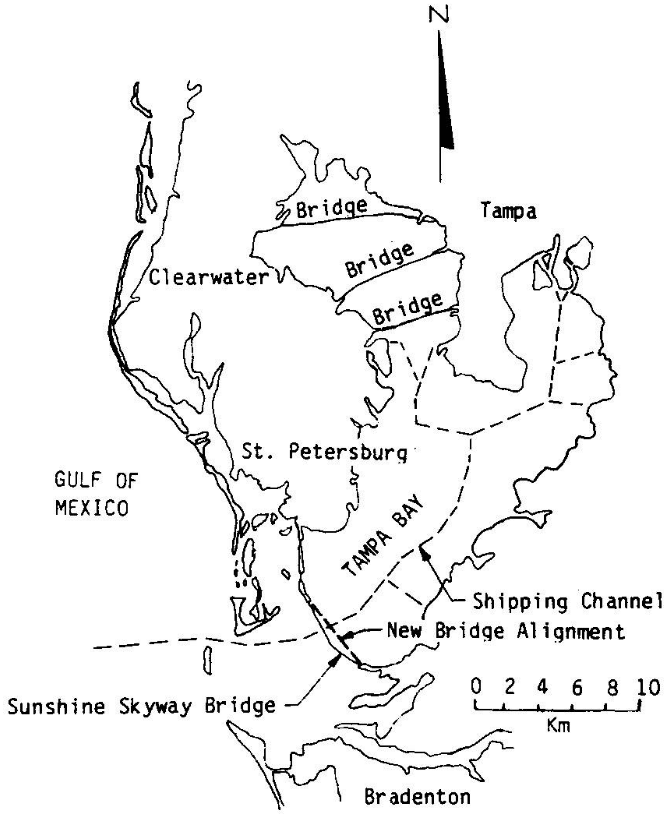

Figure 1. Project Location Map

Asset Categories	Annual Exposure ($1000) for Threat/Event Categories							
	SHIPS (GRT)				BARGES (GRT)			
	0 - 5,000	5 - 15,000	15 - 25,000	25 - 40,000+	0 - 5,000	5 - 15,000	15 - 25,000	TOTALS
Pier 1	47.9	115.9	111.7	42.4	125.4	261.6	38.3	743.2
Pier 2	55.6	127.6	131.8	40.3	44.5	298.6	43.9	742.3
Pier 3	11.7	29.2	31.2	10.6	9.5	70.5	9.9	172.6
Piers 4-6	19.2	45.8	52.2	18.4	15.6	112.7	17.4	281.3
Piers 7-16	17.6	45.6	45.1	14.9	15.3	109.1	16.0	263.6
Piers 17+	4.1	4.8	3.8	0.0	1.8	5.8	2.9	23.2
TOTALS	156.1	368.9	375.8	126.6	212.1	858.3	128.4	2,226.2

TABLE 1. Annual Exposure for Threat/Event Categories

Skyway Bridge, the following function is typical (Fig. 2):

$$EC = s \times PC; \text{ For } s<CR$$

and

$$EC = s \times [(1.4 \times (PC+SC)) + BC + H]; \text{ for } s \geq CR$$

with,

EC: The event cost
s: Severity
PC: Pier cost
SC: Span cost
BC: Business/Commerce Cost
H: Loss of human life cost
CR: Critical severity

The BC costs would include the cost of interruption of motorist access across the bridge due to bridge outage and the inconvenience costs to the port users in the event bridge wreckage were to block the shipping channel. The factor '1.4' is included to account for the fact that the replacement cost will be more expensive than the initial construction costs. An event cost must be developed for each asset category and for the variety of events which would involve that asset category.

3.2 Severity

The severity with which an event impacts an asset can be measured as the proportion of the total asset value affected, the length of time that the asset is denied to the organization, or both. Different events will most likely have different severities. For example, a 100,000 dwt ship will cause significantly more damage than a 10,000 dwt ship, all else being equal. The mathematical model distributes the severity according to a Poisson distribution, P(AS,s). This distribution is completely defined once a parameter termed the average severity (AS) is specified. The value will usually vary with every vessel collision event specified. Once an estimate of the average event severity is made, a distribution over severity is generated. The choice of the average severity unit (i.e., 10%, 20%, 30%, etc.) affects the shape of the distribution. Smaller units of average severity lead to more peaked distributions. Since severity has a limit of 100%, the Poisson distribution must be truncated after the first ten steps and the remaining probabilities proportionately adjusted. The average severity is determined by specifying the value which will generate the required probability of bridge collapse value for that particular event. Critical severity (CR) is defined as the step in the Poisson distribution in which a discontinuity occurs in the event cost formulae (Fig.2). For severity less than CR, the ship impact results in relatively minor damage and the expenditure of funds for repair of the structure. For severities equal to or greater than CR, the ship impact causes a total collapse of the bridge element and requires the expenditure of funds to replace the structure, in addition to the costs associated with loss of life and commerce. The same value of critical severity must be utilized for all events involving a particular asset category; in fact, in the analysis of the Skyway Bridge, a constant value for critical severity was used throughout.

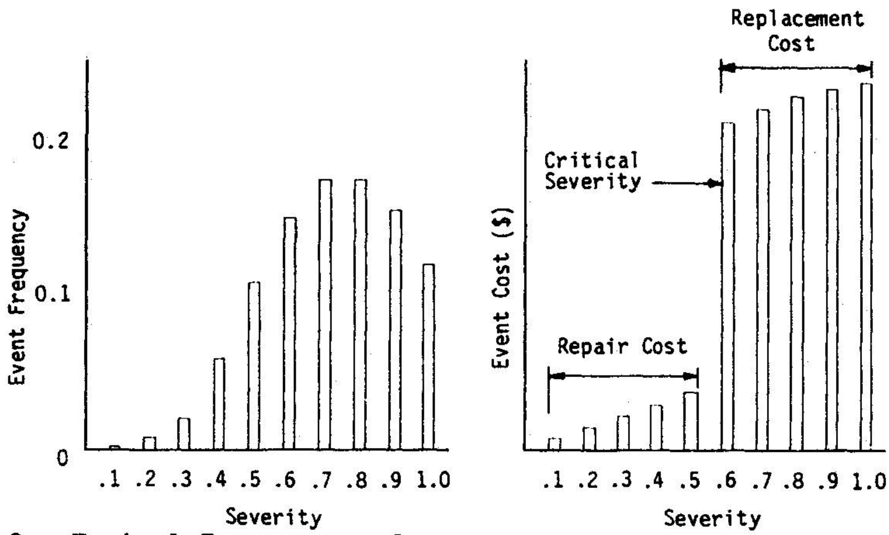

Figure 2. Typical Frequency - Severity - Cost Function Relationship

3.3 Exposure

For each event described, a value known as the exposure (EX) is calculated. Exposure is the expected value of loss to the owner of assets as a result of the event, and is usually expressed in dollars per year. Traditionally, the exposure of an event was derived by multiplying and event cost by its frequency. This is not really satisfactory, particularly because an event might have a wide variety of associated costs depending on a great many external circumstances. These extraneous conditions may be lumped together to yield not an average event cost, but a range of costs distributed against the severity of the event as explicitly defined above as event costs (Fig.2). The event exposure is calculated by multiplying the annual frequency of an event of any severity by the expected cost per event, itself generated using statistical techniques. In fact,

$$EX = AF \times \sum_{s} [EC(s) \times P(AS,s)]$$

Table 1 shows the results of this calculation for the Skyway Bridge.

3.4 Annual Frequency

The annual frequency of vessel collisions was estimated for each event category using the following equations:

$$AF = N \times PA \times PZ \times PG \times PE$$

and,

$$AFC = AF \times PC$$

with,

AF: Annual frequency of a ship collision with a bridge component.

AFC: Annual frequency of bridge component collapse due to ship impact.

N: Number of ships and barges in the various vessel categories which have the potential to strike a particular bridge element.

PA: Probability that a vessel is aberrant (out of the channel).

PZ: Probability that an aberrant vessel is located in a zone in front of a particular pier or pier grouping.

PG: Geometrical probability of a vessel striking a bridge component.

PE: Probability that the vessel master or pilot has not taken successful evasive action to avoid the collision.

PC: Probability of total collapse.

The number of ships and barges transiting under the bridge was estimated based on historical data available from maritime sources, and from making projections of future vessel traffic over the lifetime of the bridge structure. The number of vessels which can strike a pier or span will depend on the vessel gemetry, bridge clearances, and the water depth at the specific zone being analyzed.

The probability of aberrancy was determined for the Sunshine Skyway by analyzing the U.S. Coast Guard accident records for the Tampa Bay area. Knowing the number of accidents and the frequency of vessel traffic, the following probability values were developed:

PA (for ships) = 0.00013
PA (for barges)= 0.00022

As can be seen, the rate of barge accidents is almost twice that of ship accidents. The difference is probably a result of the mandatory pilotage requirements for ships in Tampa Bay, whereas there are limited pilotage requirements for barges. These values correspond closely to the value of PA = 0.0002 which was established by Fuji [2] on studies of ship collisions in Japanese waterways.

Values for PZ were estimated using a normal probability distribution. The median value was established at the centerline of the navigation channel. Based on historical worldwide ship collisions, a standard deviation of 457.2 m was chosen for the distribution. By statistical definition, 68.3 percent of all occurences occur within one standard deviation and 95.5 percent within two standard deviations. The collision zone for each pier or group of piers was defined as the distance between the span centerlines on the adjacent sides of the pier. Once the boundaries are known, a value of PZ can be computed based on the area under the normal distribution for that particular zone.

The geometrical probability that a vessel in the zone will hit a pier is a function of the width of the zone (ZW), the width of the horizontal clearance envelope from the pier(s) in the zone (LC), and the width of the ship (B). The following equation was utilized:

$$PG = \left[1 - \frac{(LC-B)}{ZW}\right]$$

For the same zone and pier widths, a value of PG was calculated for each ship and barge category. A similar equation based on vertical clearance was utilized to compute PG values for an impact between bridge spans and vessel superstructures.

The probability that a ship pilot has not taken evasive action to avoid a collision (such as lowering the anchors, reversing engines, etc.) was modeled using the equation:

$$PE = e^{-(x/\sigma)}$$

with,

x: The distance from the channel centerline to the centerline of the collision zone.

σ: The standard deviation value utilized for the calculation of PZ.

e: The base of the natural logarithm.

The equation models the observed action of piloting, where the closer an abberant vessel is to the channel, the less probable it is that the pilot is aware that he is aberrant; and similarly, the further away from the channel the aberrant vessel becomes, the probability increases that the pilot is aware that he is out of the channel and will take evasive action to avoid the collision.

The probability of bridge collapse varies for each event. It is a function of the vessel size, configuration, speed, direction, mass and the nature of the collision. It is also a function of the stiffness of the bridge pier (or span) to resist lateral loads. The less the lateral design load of a bridge pier, the greater the probability of collapse, and vice versa. The following relationship was developed to compute PC:

$$PC = (A)^{H/PM}$$

with,

H: The ultimate bridge element lateral design force (MN).

PM: The average bow collapse force of a vessel (MN).

A: A constant expressing the estimated probability of collapse when H = PM.

Values for PM were estimated using a modified form of Woison's [3] equation in the form:

$$PM = .333\sqrt{dwt} \quad (MN)$$

with,

dwt: The deadweight tonnage (LT).

The modification revised the constant in front of the radical from the original .440 to .333 and also removed the +50 percent spread estimated by Woison. The revisions were determined by calibrating Woison's equation to generate the forces calculated in the ship collision of the M/V Gerd Maersk with the Newport Bridge in Rhode Island, U.S.A., on February 19, 1981 [4].

A value of A = 0.10 was utilized for the Skyway project, and expresses the estimated number of times a vessel collision would cause the collapse of a pier, given that the vessel impact and pier resistance forces were equal. This represents one out of every 10 collisions causing collapse, with the remainder causing only slight damage to the bridge.

The annual frequencies of all events involving each asset category are indicated in Table 2. Those events involving bridge collapse are separated for all collisions, and the return periods (inverse of annual frequency) are shown. It is interesting to note that whereas Pier 2 (north and south anchor pier) is struck less often than Pier 1, the frequency of Pier 2 collapse is greater. This resulted from the lateral design load of Pier 2 being three times less than that for Pier 1.

Pier No.	Bridge Collision	Bridge Collapse
1, N & S	14	157
2, N & S	31	93
3, N & S	56	162
4-6, N & S	33	96
7-16, N & S	45	88
17+, N & S	500	943
All Piers	6	22

TABLE 2. Bridge Collision and Collapse Return Periods (Years) for the unprotected

The probability of total collapse can also be visualized as the area under the Poisson distribution for all values equal to, or greater than, the critical severity for a particular specified average severity value. This permits the calculation of AS as that which satisfies the equation,

$$\sum_{s=CR}^{\infty} P(AS,s) = PC$$

4. MECHANISMS

Once the events which seem possible have been identified and the quantification of these events has been completed, exposures for each are determined. The exposures of all events within a given threat are added to estimate the threat exposure. Threat exposures are then ranked to determine areas of greatest vulnerability. Once this is done, protection mechanisms are developed to reduce those areas of greatest vulnerability.

There are three different ways by which protection mechanisms impact the analysis: (1) by reducing the overall probability of an event, (2) by altering the severity distribution (more events of a less severe nature), and (3) by reducing the costs of events of whatever severity. The Skyway study investigated the use of physical protection devices such as artificial islands, large diameter dolphins, changes to bouy and range marker locations, electronic navigation systems, and a motorist warning system. The latter would entail a warning system to motorists which would stop all vehicular traffic from driving across the bridge. Table 3 indicates the results of the analysis for the protection mechanisms. Each protection mechanism has associated with it an expected lifetime, an initial cost, maintenance cost and resale value, in addition to its impact on reducing the bridge vulnerability.

Asset Categories	Initial Exposure ($1000)	Revised Annual Exposure ($1000) for Pier Protection System Alternatives								
		Dolphins (4 piers)	Dolphins (6 piers)	Dolphins (12 piers)	Islands (4 piers)	Islands (6 piers)	Islands (12 piers)	Standard Navigation Improvements	Electronic Navigation System	Motorist Warning System
Pier 1	743.2	0	0	0	0	0	0	457.7	616.2	667.5
Pier 2	742.3	0	0	0	0	0	0	460.4	602.2	677.7
Pier 3	172.6	172.6	86.3	86.3	172.6	0	0	107.9	138.6	153.2
Piers 4-6	281.3	281.3	281.3	140.6	281.3	281.3	0	173.7	226.4	252.3
Piers 7-16	263.6	263.6	263.6	263.6	263.6	263.6	263.6	161.2	214.2	241.8
Piers 17+	23.2	23.2	23.2	23.2	23.2	23.2	23.2	17.0	20.4	21.8
TOTALS	2,226.2	740.7	654.4	513.7	740.7	568.1	286.8	1,377.9	1,818.0	2,014.3

TABLE 3. Revised Annual Exposure for Pier Protection System Alternatives

5. COST-EFFECTIVENESS ANALYSIS

In order to provide analytical substantiation of the economic feasibility of bridge protection mechanisms, and to provide a measure for comparing protection alternatives, a cost-effectiveness analysis (CEA) was accomplished. The CEA consists of the computation of yearly costs and benefits associated with a protection mechanism over a fixed term. The costs include construction, maintenance, and operation costs for the mechanisms. Benefits are represented by any reduction in exposure costs (EX) which the mechanism can be shown to provide. The future costs and benefits are converted to present values with standard discounting procedures, based on assumptions for inflation and interest rates. From these present values of costs and benefits, a series of indicators of economic desirability are derived. They include benefit/cost (B/C) ratio, present value of net benefits, internal rate of return, and payback period. Table 4 depicts typical results of the CEA procedures.

Pier Protection Alternative	Initial Cost	Annual Maintenance	Expected Lifetime (Years)	Benefit/Cost Ratio (5% Discount)
Dolphins - 4 Piers	$17,230,000	$23,000	35	3.48
Dolphins - 6 Piers	20,022,000	26,880	35	3.32
Dolphins - 12 Piers	28,603,000	38,400	35	2.26
Islands - 4 Piers	20,440,000	7,000	50	4.59
Islands - 6 Piers	24,080,000	14,000	50	4.33
Islands - 12 Piers	34,240,000	28,000	50	3.54
Standard Navigation Improvements	1,000,000	6,000	20	17.33
Electronic Navigation System	600,000	8,000	10	6.49
Motorist Warning System	220,000	5,000	10	4.26

TABLE 4. Benefit/Cost Ratios for Pier Protection Alternatives

6. CONCLUSIONS

The methodology adopted to analyze the threats and to determine the cost-effectiveness of proposed pier protection devices for the Sunshine Skyway was found to be satisfactory by the Florida Department of Transportation and the Federal Highway Administration, U.S.A. The analysis indicated that a high degree of vulnerability of the bridge would exist if it were left unprotected, so that some form of pier protection would be justified.

The application of the threat analysis techniques summarized in this paper must be approached with some caution. As with any form of statistical analysis, accuracy of results is dependent on the extent of knowledge and research utilized in the formulation of the important input assumptions for the model, and the extent of the experience of the organization using it.

The use of the approach as a design tool to determine optimum span length, vertical clearances, and pier strengths to minimize the vulnerability of the bridge to ship collisions has not been fully explored; however, it appears that this can be a valuable aspect of the methodology.

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APPENDIX

Photograph of the M/V Summit Venture accident with the existing Sunshine Skyway Bridge on May 9, 1982.

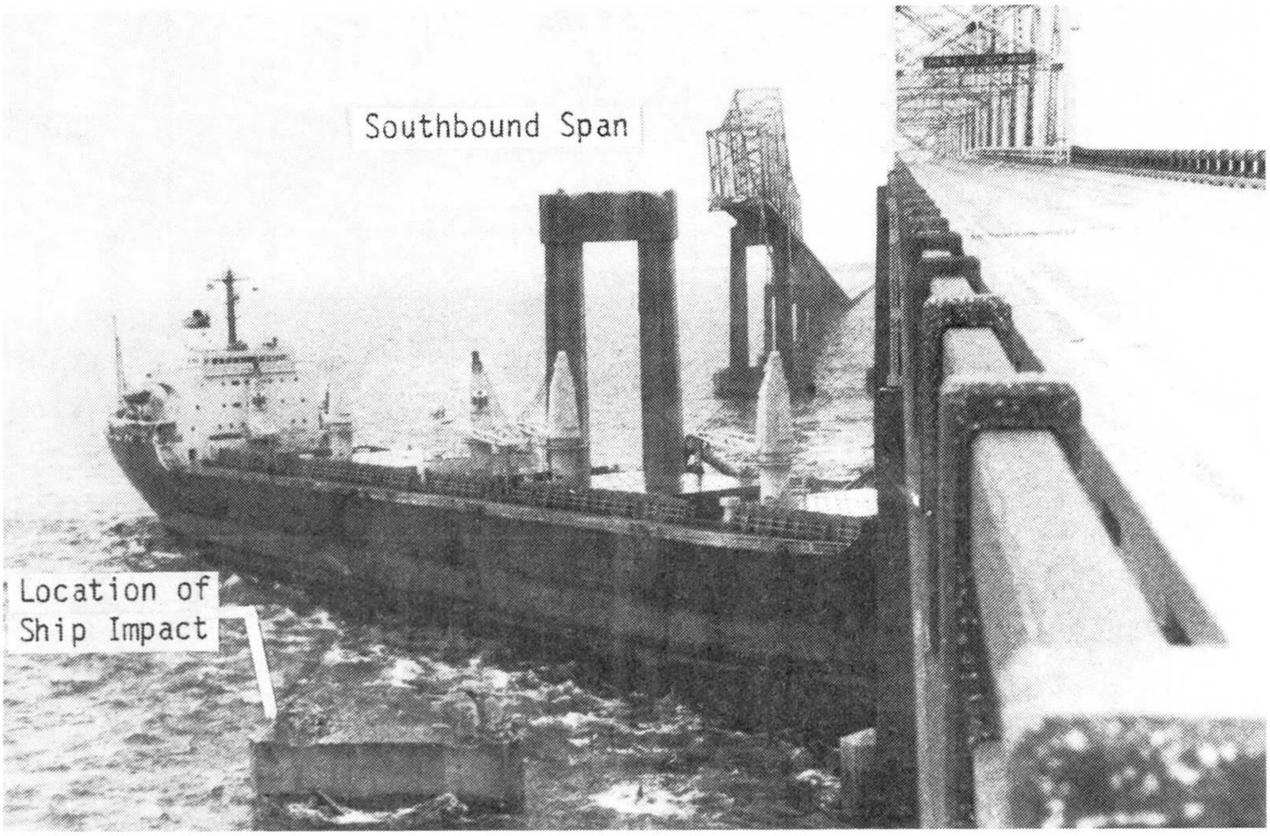

Photo: T. P. O'Neill, Courtesy Shackleford, Farrior, Stallings & Evans, P.A.