Ship collisions against bridge piers

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Ship Collisions Against Bridge Piers

Collisions entre navires et piles de ponts

Schiffsstöße gegen Brückenpfeiler

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Chapter 1

Prefatory Notes and General Aspects of the Problem

Prefatory Notes

The conflict of interests arising from demands for unimpeded navigation within our waters and construction of bridges across these waters has been accentuated in recent years by the steady increase in the size of the ships. The large tankers and liners require ample passages, and navigation of these large ships is hampered by the bridge piers.

On the other hand, the bridges — and particularly the large bridges built to establish the only permanent interconnection of comprehensive regions of the country — must be of a design strong enough to take even the most serious collision without any serious damage being inflicted upon the bridge.

Bridge piers of ordinary size and weight cannot, however, take an impact from large ships running at normal speed.

Hence, a problem arises which requires investigation in more detail. (As far as Denmark is concerned, the new Motorway Bridge across Lillebælt, and the forthcoming bridges across Storebælt and Øresund will have to be considered.)

Therefore, the matter is preliminarily and tentatively discussed in this article, including also a theoretical investigation.

Chapter 1 contains, initially, a summary of the practice used in Denmark up to now, and also certain data of more recent origin concerning bridge piers and sizes of ships abroad.

In chapter 2 a number of "case-records" are considered, obtained from Denmark and from other countries, relating to ships' collisions with bridge piers, etc., and reporting also on protecting structures for the piers, which have been built particularly in the U.S.A.

Chapter 3 contains calculations made by A. G. Frandsen, C. E., on the basis of information obtained when a ship had run into the Drogden Lighthouse. This occurrence afforded a number of observations, permitting establishment of an opinion on the matter. Moreover, A. E. Bretting, Professor of Hydraulics, has investigated theoretically the effects on a bridge pier of impact produced by ships; in this connection, and in consultation with the author of this article, the investigation has included a number of different impact forces, acting on the pier, and a series of different velocities of the ship. A summary of the results is given by A. G. Frandsen, in chapter 3.

In chapter 4 some preliminary results of observations from collisions between two ships are briefly reported.

Finally, in chapter 5, the aim has been to arrive at conclusions of a preliminary nature.

We are indebted to the following institutions and others for their favourable response to our inquiries on the subject:

From the U.S.A.:	Department of the Army, Office of the Chief of Engineers, Washington.
	U.S. Bureau of Public Works, Bridge Division, Washington.
	State of California-Department of Public Works.
	Delaware River Port Authority.
	The Port of New York Authority.
Canada:	The St. Lawrence Seaway Authority.
Great Britain:	O. T. Barfod, Chief Engineer, Peter Lind & Co., London.
Germany:	Grün & Bilfinger AG, Mannheim.
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Norway:	The Municipal Engineer of Kristiansund.
Denmark:	Handelsministeriets Søfartskontor (Ministry of Commerce, Shipping Department).
	Fyrdirektoratet (The State Light-House Board).

Vandbygningsdirektoratet (The State Directorate of Marine Works).

De Danske Statsbaner, Baneafdelingen (The Danish Railways).

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C. W. Prohaska, Professor of Shipbuilding at the Techn. University of Denmark, Dr. techn., The Laboratory of Hydro & Aerodynamics.

Burmeister & Wain, Ltd. Shipbuilding Department, Copenhagen.

Lloyds, London, through A. Jessen & Co., Copenhagen.

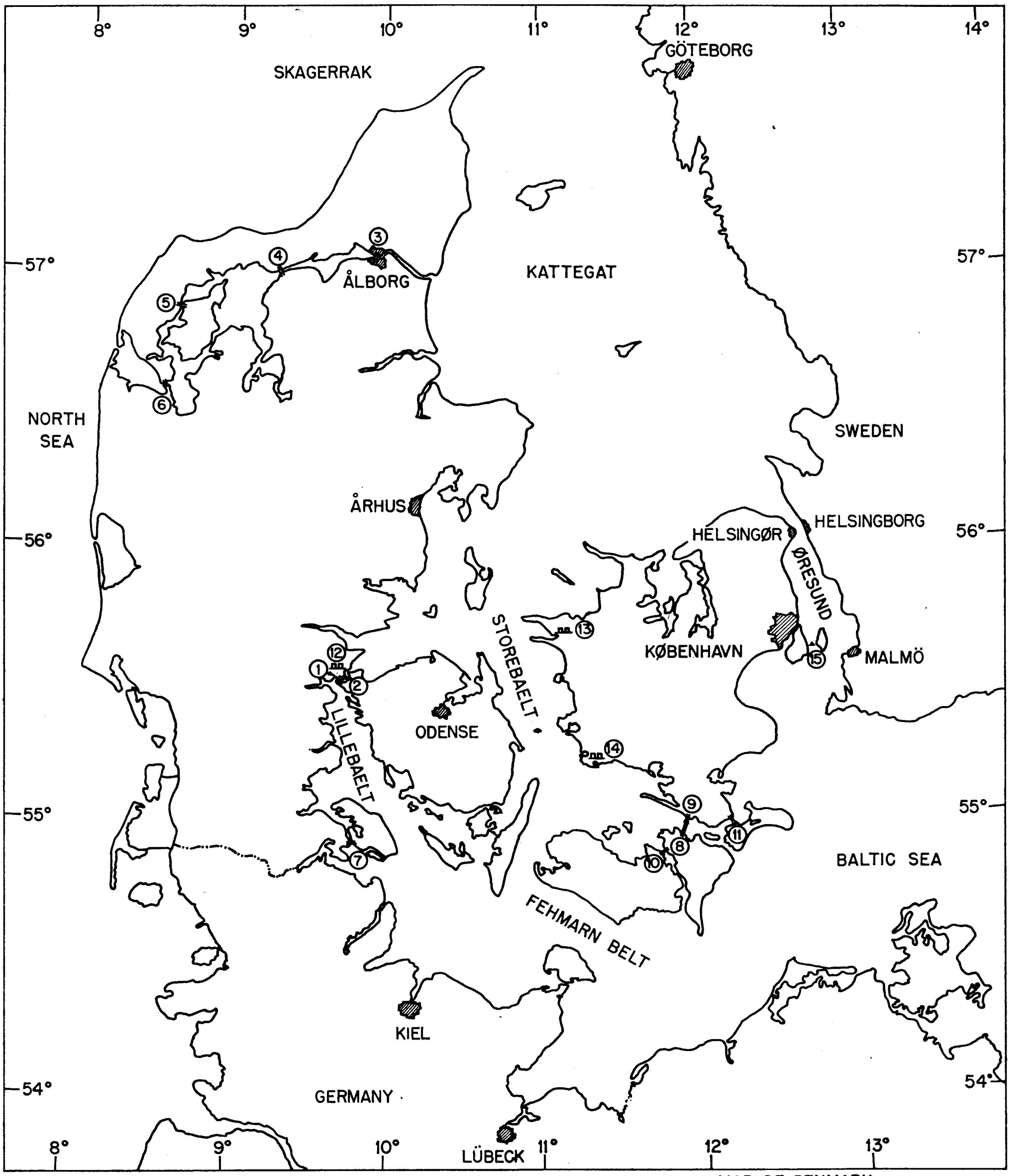
Outlines of Problem

For bridge piers built on land impact from trains or motor cars on the bridge piers is taken into consideration in some cases; for example, a bridge crossing a motorway is designed to resist impact from motor cars, in that the piers next to the roadway are made of a heavier design than the piers further rearward. The reinforcements attained in this way are of very limited economic consequence.

For bridges across waters deep enough to permit navigation by large ships under the bridge spans, a rational practice has been established in Denmark in the course of the last 40—50 years, in respect of the design of the bridge piers. The piers have been designed, in practically all cases, as massive concrete piers, with more or less important cavities, and have been founded directly on firm bottom, or — where soft subsoil was encountered — on a low piling, i. e. on piles driven fully into the ground and not being exposed to free water.

Bridge piers of this design can resist relatively considerable horizontal forces, and the piers and the piles, when required, are designed for horizontal forces from ice of 3—5 t per m of the bridge span, according to the Danish practice. In more exposed places, the ice pressure assumed in calculating bridge piers and pilings may be up to 10 t per m of bridge span, although in such cases the stresses allowed are somewhat higher than normal allowable stresses. Moreover, a force of 20% of the said ice pressure is assumed to act transversely to the longitudinal direction of the piers (which is, as a rule, in the longitudinal direction of the bridge), and at the extreme end of the pier.

For the existing Lillebælt Bridge in Denmark (No. 1 on map), built in 1930—1935, the tender specifications issued by the Danish State Railways stipulated calculation for an ice pressure of 10 t per m of bridge span, and



MAP OF DENMARK

Bridges

1. Lillebælt, existing bridge
2. Lillebælt, new motorway bridge
3. Ålborg
4. Aggersund
5. Vilsund
6. Oddesund
7. Alssund
8. Storstrømmen
9. Masnedsund
10. Guldborgsund
11. Ulvssund

Refineries

12. Fredericia
13. Kalundborg
14. Stigsnæs
15. Drogden Lighthouse

that the ice pressure thus assumed "should include the effect of possible impact of ships". For the Lillebælt Bridge this stipulation resulted in a horizontal force of about 2000 t, acting at water level.

As far as is known to us, these rules have been applied to all Danish bridges of any considerable magnitude, designed by public authorities or by private engineers, such as the bridges across the Limfjord (at Ålborg (No. 3), Aggersund (No. 4), Vilsund (No. 5) and Oddesund (No. 6)) and the bridges across the Alssund (No. 7), Storstrøm (No. 8), Guldborgsund (No. 10) and others.

The results obtained by design in accordance with this practice have been favourable, so far, and the bridge piers have never suffered damage of importance. Superstructures of Danish bridges, on the other hand, have been seriously damaged in a few cases by ships running into them, refer chapter 2.

The piers of Danish bridges (the Lillebælt Bridge not included) have base areas of 150—300 m^2, and the weight of the piers is 4—12,000 t. These figures apply to the bascule piers of these bridges, the other piers have about half the weight of the bascule piers. Where the weight of bridge piers is stated, here and in the following, this weight is to be taken as the actual weight, without any deduction for buoyancy, because the mass of the pier is the factor that is relevant when the effect of impact from ships is considered. The depth of water, which is decisive for the size of ships approaching the bridge, is rather limited, 4—5 m, within the Limfjord and other coastal Danish waters, whereas the depth at the bridge site proper, generally, exceeds these figures considerably (at Aggersund (No. 4) the depth is 10—12 m, at Oddesund (No. 6) more than 20 m, at Vilsund (No. 5) 16 m, at Alssund (No. 7) 14—15 m, at Guldborg (No. 10) 13—15 m, and by the Mønbridge (No. 11) 10—14 m).

By the Storstrøm Bridge (No. 8) the depth is about 10 m near the largest piers (for the navigation spans). The weight of these piers is about 8000 t, and their base area about 300 m^2.

By the existing Lillebælt Bridge (No. 1) conditions are entirely different, the depth of water being about 30 m, the base area of the piers about 950 m^2, and the weight of the piers about 72,000 t, to which comes 5000 t from the dead load of the bridge construction (all figures applying to one pier).

By the two main tower piers for the forthcoming motorway bridge across Lillebælt (No. 2), which are now in the course of construction, the depth of water is about 20 m; the base areas of the piers are about 1100—1200 m^2, and the weight of the piers about 27,000 t, to which comes about 14,000 t from the concrete tower, total 41,000 t, and dead weight of the superstructure of the bridge, about 13,000 t (all figures applying to one pier). In the calculation of these main tower piers an ice pressure of about 4000 t has been assumed, based on 10 t per m bridge span, as mentioned above.

As a supplement to above review of sizes and weights of bridge piers, a few figures from particularly large bridges abroad are given below. The bridge piers referred to are located in waters navigated by large ocean liners:

	Water depth m	Foundation depth layer m		Base area m²	Weight (no deduction for buoyancy) t
1. San Francisco-Oakland Bay, California					
a) Suspension bridge					
Pier W 3	22	68	rock	870	120,000
Pier W 6	32	50	rock	670	100,000
b) Cantilever bridge					
Pier E 3	19	69	rock	1000	125,000
2. Golden Gate, California					
Pier proper	30	30	rock	ca. 1750	ca. 115,000
Concrete fender				ca. 1600	ca. 135,000
3. Carquinez Strait, California (central pier 2 caissons)	25	40	rock	2 × 530	2 × 45,000
4. New Orleans Bridge	22	55	clay	1200	90,000
5. Mackinac Strait, Michigan	43	63	rock	980	145,000
6. Tagus River, Lisbon	25	79	rock	970	150,000

As will be seen, the practice adopted in Denmark and other countries up to now has not given rise to any concern with a view to the possibility of ships colliding with bridge piers, so far; this state of matters can hardly be maintained any longer, however.

This is due to the considerable increase of the size of ships in recent years, and particularly the building of very large tankers of up to 50—100,000 t.d.w., and even 150,000 t.d.w. (Scotch and Japanese shipyards are going to construct berths for ships of 150—200,000 t.d.w.).

The approximate dimensions of large ships are:

Dead-weight tonnage (total weight of the ship fully loaded is about 35 % higher)	50,000 t	100,000 t	150,000 t
Length at water line (total length about 10 m more)	abt. 215 m	abt. 260 m	abt. 290 m
Breadth at water line	abt. 31 m	abt. 39 m	abt. 47 m
Draught (fully loaded)	abt. 12 m	abt. 15 m	abt. 16 m

The latest information (August 1965) on building of large ships is the following:

A. Very Large Ships

A Japanese shipyard is building at the moment two tankers of about 152,000 t.d.w. for Japanese owners.

A Norwegian shipowner has ordered two tankers of a carrying capacity of 160,000 t.d.w.

Shell have ordered, somewhat later, four tankers of still larger carrying capacity, 165,000 t.d.w. each. These ships have a draught of 16.5 m, length 328 m, and breadth 47 m.

A Japanese oil refinery has ordered a tanker of 191,000 t.d.w., which will be the largest ship in the world, so far.

B. Large Ships of Special Interest to Scandinavia

Shell have ordered 5 tankers of 90,000 t.d.w. each, one of these is being built at the Lindø Shipyard (Odense, Denmark). These tankers can be taken to call at Fredericia, with supplies for the refinery (refer map, No. 12).

Akers, Oslo, have been awarded a contract for three 95,000 t.d.w. tankers for Norwegian owners.

At the Lindø Shipyard two tankers of 80,000 t.d.w. and one of 91,000 t.d.w. are being built for A. P. Møller, and one 91,000 t.d.w. tanker for a Swedish shipowner.

Kockums, Malmö, have built a 74,000 t.d.w. tanker for a Norwegian company.

The Weser Shipyard, at Bremen, has built a 64,000 t.d.w. tanker for German shipowners, and has been awarded a contract by Esso for a 151,800 t.d.w. tanker.

The Howaldt Shipyard at Kiel is to build a 165,000 t.d.w. tanker for Shell and a 171,000 t.d.w. tanker for Esso.

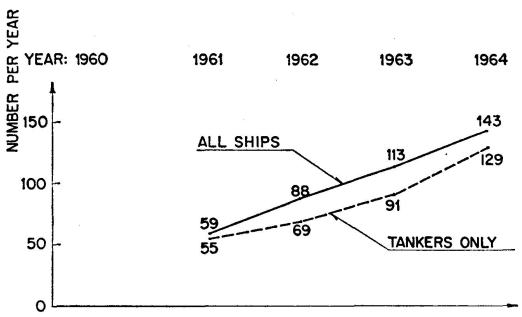
* * *

As will be apparent from the two figures below, a considerable increase in respect of construction of large ships has taken place since 1961. The table shows a classification by sizes of ships of this class, built in 1963 and 1964.

As far as Denmark is concerned (refer map, page 236) it should be mentioned that inner Danish waters are not deep enough to permit navigation by large ships; such ships can, however, pass the Kattegat, the Baltic Sea, Lillebælt (the Little Belt), Storebælt (the Great Belt), Øresund (the Sound), and the Fehmarn Belt, between Rødby and Fehmarn. In Denmark three refineries have been built (refer map, Nos. 12, 13 and 14) which are served by tankers up to 60,000—80,000 t.d.w.

It will be immediately obvious that ships possessing a weight (mass) of the same magnitude as, or exceeding, the mass of the bridge piers will involve a considerable risk to a pier in case of collision, and the pier may be overturned, or it may be displaced on its foundation in the case of a large ship running into it, even at relatively moderate speed.

According to C. W. Prohaska, Professor of Shipbuilding at the Technical University of Denmark, the normal speed of large tankers is 14—17 knots, and these ships have a relatively low engine power, as compared with the



Number of ships launched over 25,000 gross tons ~40,000 T.D.W.

Information obtained from Lloyd's register of shipping.

Tankers over 40,000 T.D.W. put into service in 1963 and 1964 distributed (approx) according to domicile of shipping company

	Registered in						Total	
	Scandinavia		rest of Europe		outside Europe			
1000 T.D.W.	1963	1964	1963	1964	1963	1964	1963	1964
40— 50	11	3	13	7	4	2	28	12
50— 60	11	24	13	8	10	18	34	50
60— 70	2	7	—	12	4	15	6	34
70— 80	—	2	2	1	5	5	7	6
80— 90	2	1	1	3	1	5	4	9
90—100	1	1	4	4	1	7	6	12
	27	38	33	35	25	50	85	123

Information obtained from the periodical "The Motor Ship".

tonnage of the ship. Moreover, such large ships require a considerable distance for retardation, up to 4—5 km, and they can be taken to be less manoevrable than are normal cargo ships of moderate size.

Navigation by ships of considerable dead weight, of a length of 2—300 m, a breadth of 30—40 m, and a draught of 12—15 m involves problems in respect of the bridge piers, particularly in case of poor visibility, and, on the other hand, the passage of a bridge under such weather conditions — or in case of difficulties arising from wind and current — may involve a risk to the ship. In this connection it is of importance, of course, whether the spacing of the piers, depending on the free span of the bridge, is large or small as compared to the dimensions of the ship.

Chapter 2

Reports on Ships' Collisions with Bridge Piers, and Information on Constructions for Protection of the Piers

Ships are no doubt colliding rather frequently with bridge piers, but the reports on such cases are only available to a very limited extent.

In the following are briefly described — in the form of "case records" — a series of documentary cases, some of them from Denmark but the majority from other countries.

A. Denmark

1. The Drogden Lighthouse.
2. Sundry less important collisions.

B. Norway

3. The Sørsund bridge near Kristiansund.

C. Venezuela

4. The Maracaibo Bridge.

D. Canada

5. St. Lawrence Seaway.

E. U.S.A.

6. Outerbridge Crossing, New York.
7. New lift bridge across Arthur Kill, New York.
8. Bridges belonging to the Delaware River Port Authority, Philadelphia.
9. Mooring Dolphin, Philadelphia.
10. The Pontchartrain Bridge north of New Orleans.
11. Carquinez Strait Bridge, California.
12. San Francisco-Oakland Bay Bridge, California.
13. Richmond-San Rafael Bridge, California.
14. San Mateo-Hayward Bridges, California.
15. Golden Gate Bridge, California.

F. England

16. Railway bridge across the Severn, from 1879.

In these case-records are also mentioned protective constructions, existing or planned.

In the past various designs of protective constructions for bridge piers have been conceived, consisting generally of timber fenders attached to the pier, and less frequently of a protecting structure around the pier, or of a dolphin built at some distance from the pier.

Most of these protecting structures have been made to attain a protection of the pier against superficial damage, as might be caused by pack-ice, trunks adrift, debris of various kinds, etc., and against occasional minor impact from ships, which, in passing the navigable channel might touch the pier due to some faulty manoeuvre.

In the great majority of cases no actual protection of the pier has been aimed at, even in waters carrying an intense traffic. This may be due to:

1. the relatively heavy expenses involved in connection with installation of a really effective protection;
2. the navigable channel being wide enough to reduce the probability of a collision to a minimum;
3. the depth of water in the immediate vicinity of the pier being so limited that only small ships can run into the pier; and
4. the pier possessing a so considerable mass, as compared with the ships, that only a very powerful impact will endanger its stability (this last point of view is not applicable to piers on a high piling, however, confer the Maracaibo Bridge, Case Record No. 4).

With the exception of a few of the old turnbridges, as far as is known to us, no protection of any importance, against direct impact from ships, has been provided for any bridge pier in Denmark.

1. The Drogden Lighthouse, Denmark (Just off the Port of Copenhagen See Map, No. 15)

A ship running into the foundation for the lighthouse, whereby a displacement (turning) of the foundation resulted.

1. Collision (Location — Time — Cause)

Location: The Drogden Lighthouse (located in the navigable channel between Amager and Saltholm, SE of Dragør).
Time, etc.: December 2nd, 1946, at 4.18 in the morning.
Cause: Probably faulty manoeuvre.

2. Description of Structure Involved (Refer fig. 1)

The foundation for the lighthouse has an elliptic shape, the axes being 30 and 17 m respectively.

Caisson with heavy concrete walls, transverse walls of concrete, exterior cells with sand filling.

Total weight 13,300 t.

Foundation: direct foundation in 10 m of water, probably on Saltholm lime. Sea-bed horizontal. Bedding of broken stone.

Rubble Protection: about 5 m high, slope 1.5 : 1, consisting of gravel, cobbles, and boulders (up to 500 kg).

No protecting structures.

3. Description of Ship Involved

Type: Cargo boat, s. s. "Blue Island Victory", 10,000 t.d.w., max. displacement about 13,500 t, actual displacement at the moment of collision is not known exactly, but was at least 8500 t.
Speed, etc.: about 16 knots (8.25 m/sec.); the ship struck the lighthouse-structure at an angle of about 30° with the major axis (refer fig. 1).

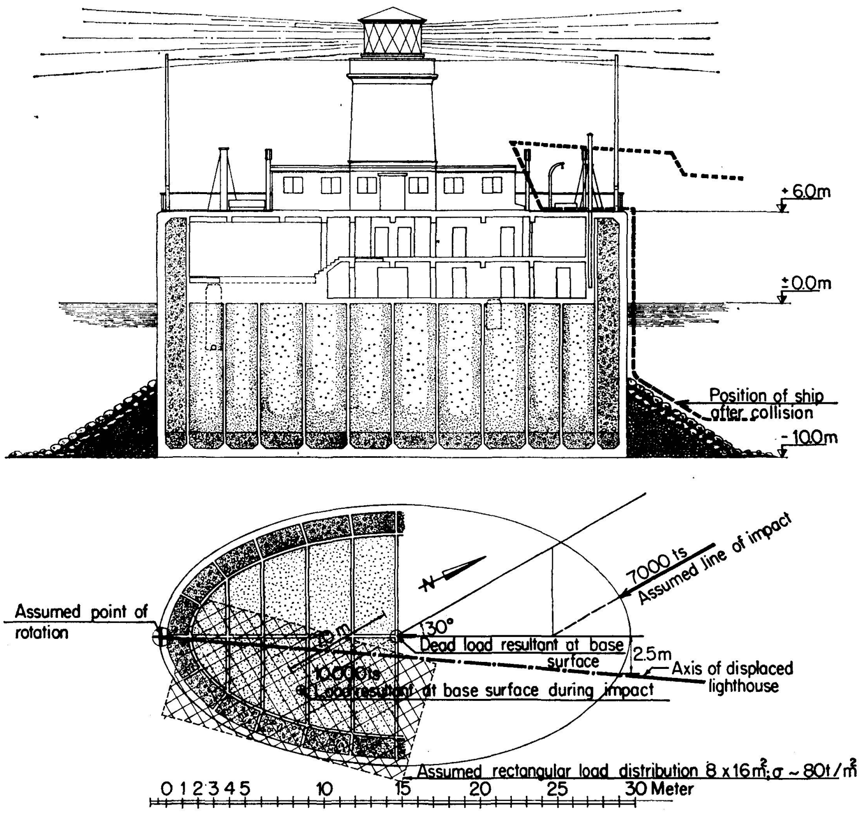


Fig. 1. Drogden Lighthouse, in Øresund, SE of Copenhagen. The plan indicates the ship's line of approach, the displacement of the foundation and the assumed distribution of pressure in the underlying soil at the time of collision.

4. Damage to Structure

Northern end of lighthouse (the end involved in the collision) displaced 2.5 m eastward (refer fig. 1). One metre below water level a hole in the concrete resulted, $2.1 \times 2.5 \times 0.7$ m deep, probably caused by a deck in the ship at this level.

5. Damage to Ship

Stem deformed 5—6 m rearward: "the ship was shortened by 5—6 m".

6. Calculations, refer Chapter *3*

2. Sundry Less Important Collisions in Denmark

In the Port of Copenhagen

Considering the conditions prevailing within the Port of Copenhagen, it is obvious that the Knippelsbro and the Langebro, bridging a navigable channel of a depth of 10 m, will be particularly exposed to impact from ships, and actually ships have run into the piers of these bridges in a number of cases. However, the depth of water at the ends of the piers has been limited to about

6 m and, as a consequence, large ships coming out of control are prevented from reaching the piers. Moreover, tug-assistance is compulsory for all ships of more than 1500 GRT when passing the Langebro and the Knippelsbro.

Therefore, the damage actually caused to the piers of these two bridges has been very limited, being as a rule no more than damage to fenders and ashlar facing.

With Bridges at other Locations

As mentioned in chapter 1, and apart from the ships colliding with bridge piers, ships have in some cases run into superstructures of bridges, whereby considerable damage to these superstructures resulted. As examples should be mentioned: a ship running into the Masnedsund Bridge (see Map, No. 9) in 1935, whereby a steel truss, about 66 m long, fell into the water; ships running into the Ålborg railway bridge (No. 3) in two cases, in 1955 and 1956, whereby considerable damage resulted, particularly in the latter case (4—5 million Kr.); the Aggersund Bridge (No. 4) in 1956, where the bascule was damaged, and the Guldborg Bridge (No. 10) in 1955, where one of the two bascules was damaged.

3. The Sørsund Bridge, near Kristiansund, Norway

Ship colliding with column in side span, resulting in failure of the column.

1. Collision (Location — Time — Cause)

Location: The bridge across the Sørsundet at Kristiansund.
Time, etc.: September 27th, 1963.
Cause: Faulty manoeuvre.

2. Description of Structure Involved (Refer Fig. 2)

The bridge has one main span of 100 m and two side spans of 50 m each, made of prestressed concrete. Navigation is through the main span only. In addition to the two 50-m side spans, there are 7 and 9 spans, on the two sides respectively, of 13 m each, with girders of ordinary reinforced concrete. The supports for the beams are solid single-columns of 140 cm diameter.

The column involved in the collision had a height of about 38 m. The water depth in the vicinity of the column was rather inconsiderable (2—3 m).

Foundations are on rock throughout.

No protective measures had been taken.

3. Description of Ship Involved

Type, etc.: Russian cargo boat "Privodino", about 5000 t.d.w., displacement unknown.
Speed, etc.: The actual speed at the moment of collision is unknown, it must

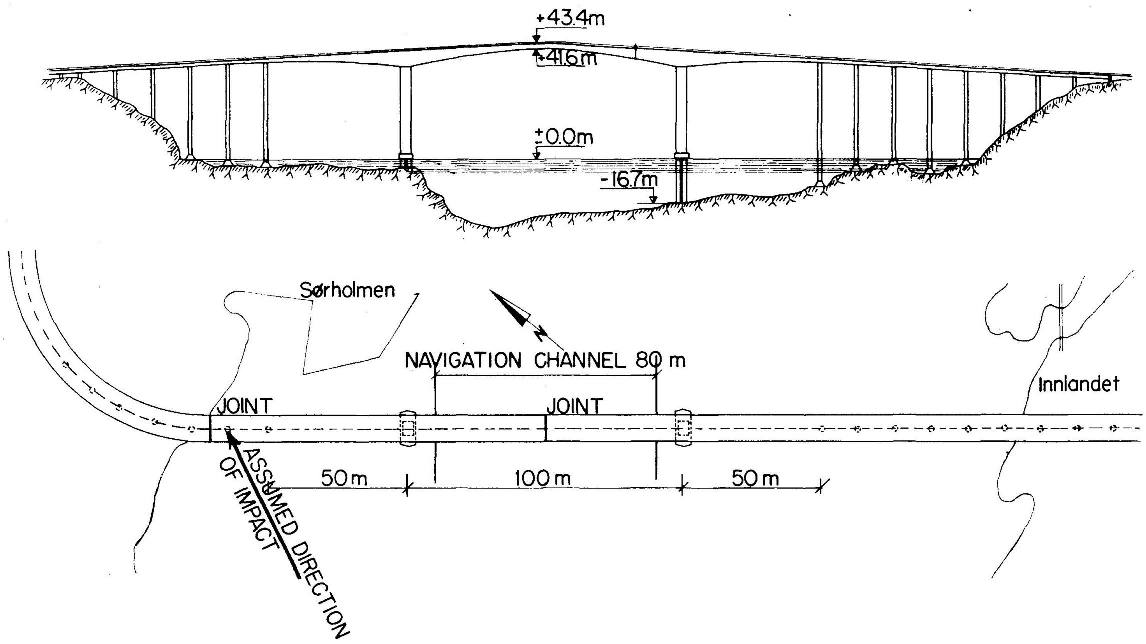


Fig. 2. Sørsund Bridge at Kristiansund, Norway. On the plan is indicated the supposed line of approach of the ship.

have been very low, however, due to the ship taking the ground before the collision with the column. On the basis of an estimated speed of $^1/_2$ knot (0.25 m/sec.) and an estimated displacement of 7000 t, the kinetic energy will be of the magnitude of 20—25 tm. The column was hit directly by the stem of the ship.

4. *Damage to Structure*

The column broke in two places: at the bottom and at the collision-point (the location is not exactly known). The deflection of the column at the collision-point was about 65 cm. The bridge deck was not damaged but was deflected upwards and warped. At a dilatation joint in the deck, located between the column involved and the next landward column, a deformation of 3 cm was observed on one side and 8 cm on the other.

When the column was pressed back into correct position the deck assumed its original shape. The concrete tongue in the joint was broken.

Damages amounted to approx. N. Kr. 200,000.

It is considered that the damage would have been essentially more comprehensive if the speed of the ship had not been materially retarded by the ship taking the ground.

5. *Damage to Ship*

The stem of the ship was crushed (the cylindrical shape of the column was impressed into the stem). Depression about 35 cm.

4. The Maracaibo Bridge, Venezuela

Ship colliding with two piers in side spans whereby collapse of three spans of the bridge resulted.

1. Collision (Location — Time — Cause)

Location: The bridge is crossing the strait constituting the entrance to the Lake Maracaibo in Venezuela.

Time, etc.: April 6, 1964, just before midnight.

Cause: The ship came out of control in approaching the bridge, about 2 km from the bridge (failure of electric system). An anchor was dropped, but too late, the ship swung round and collided broadside on with two of the piers (piers outside the navigation spans).

2. Description of Structure Involved

The bridge has five main spans of 235 m each, which are destined for navigation. Moreover, there is a number of side spans of various lengths. The two piers involved support 85-m side spans, which are not part of the navigation channel.

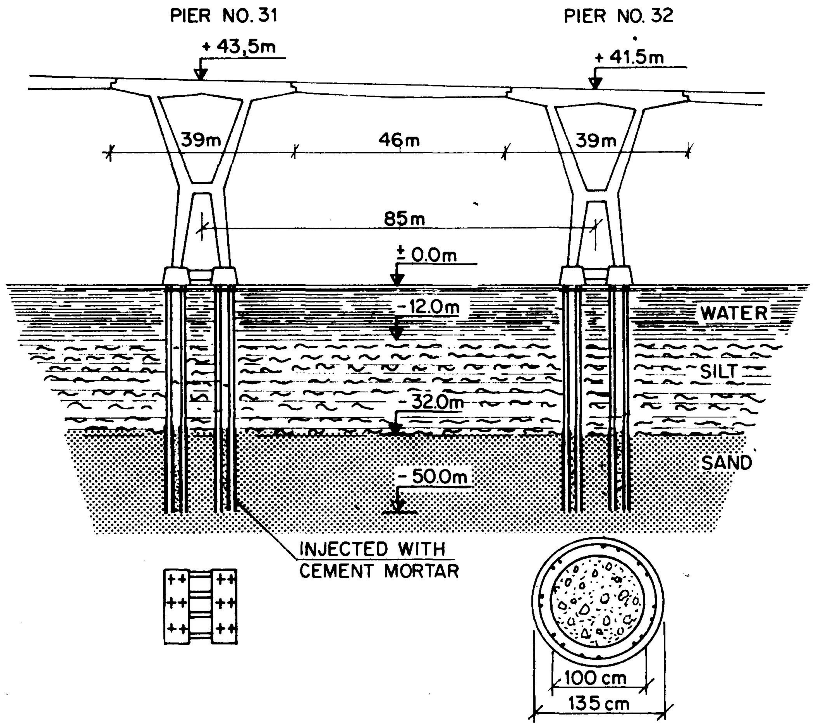


Fig. 3. Maracaibo Bridge, Venezuela. The figure shows the two piers, which were destroyed by the collision.

A pier consists of four reinforced concrete frames, designed as a combined H and V structure. The weight of the pier is about 10,000 t (see fig. 3).

The bridge deck is a cantilever structure with suspended spans.

Each of the piers is founded on 12 vertical piles reaching a depth of about 50 m. The piles are prestressed concrete piles of hollow cylindrical cross section, outside diameter 135 cm and inside diameter 100 cm. The piles were placed in bored holes.

The hollow space inside the piles is filled with concrete, and at the top the piles, in two groups of 6 piles each, are interconnected by reinforced concrete beams, $16.0 \times 4.55 \times 2.70$ m, these beams being, in turn, interconnected by four transversal reinforced concrete beams. The depth of water is about 12 m, and the depth of the soft layers is a little more than 20 m.

No structures for protection of the piers had been provided. The contractors to whom the construction of the bridge, and to a certain extent also the design, had been awarded had suggested to the owners of the bridge that a system of dolphins be provided, to protect the piers for the navigation spans, the suggested design being cellular cofferdams. These structures were not built, however, due to the considerable cost involved.

3. Description of Ship Involved

Type, etc.: Tanker "Esso Maracaibo", 36,000 t.d.w., displacement about 47,000 t.

Speed, etc.: The speed of the ship, when adrift, is estimated at 1 knot (0.5 m/sec.), and the corresponding kinetic energy at about 600 tm. The direction of the ship in relation to the piers at the moment of collision is not exactly known; due to the anchor dropped the ship had swung round, and apparently she hit one pier broadside on and the other with the stem.

4. Damage to Structure

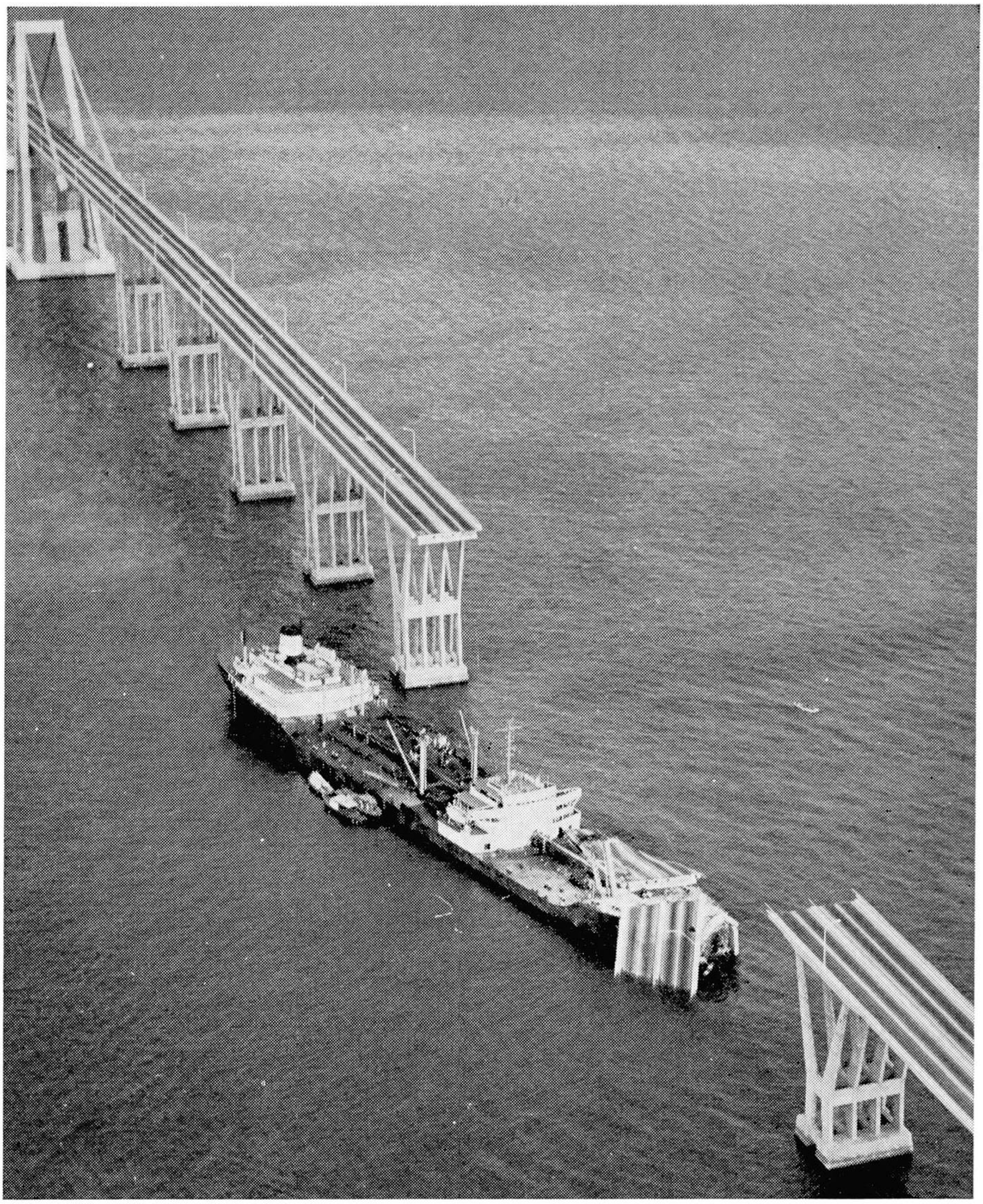
Two piers (Nos. 31 and 32) and their cantilever structures were destroyed (the piles broke). Three suspended spans fell into the water, and several persons perished, driving in motor cars which happened to be on these spans, or during darkness running their cars into the gap. The damage is estimated at about 5 million dollars.

5. Damage to Ship

Suspended spans fell down upon the bow of the ship and considerable damage resulted. The ship sprang a leak, it remained afloat, however (see photos 1 and 2).

5. St. Lawrence Seaway, Canada

In the St. Lawrence Seaway, collisions with the numerous bridges, locks, and quaywalls to be found there are frequent. In most of these accidents movable bridges, lock gates, and safety fender booms are involved. In a number of cases, however, walls for locks or adjacent structures have been damaged by collisions. Some of these structures are provided with fenders, others are not.



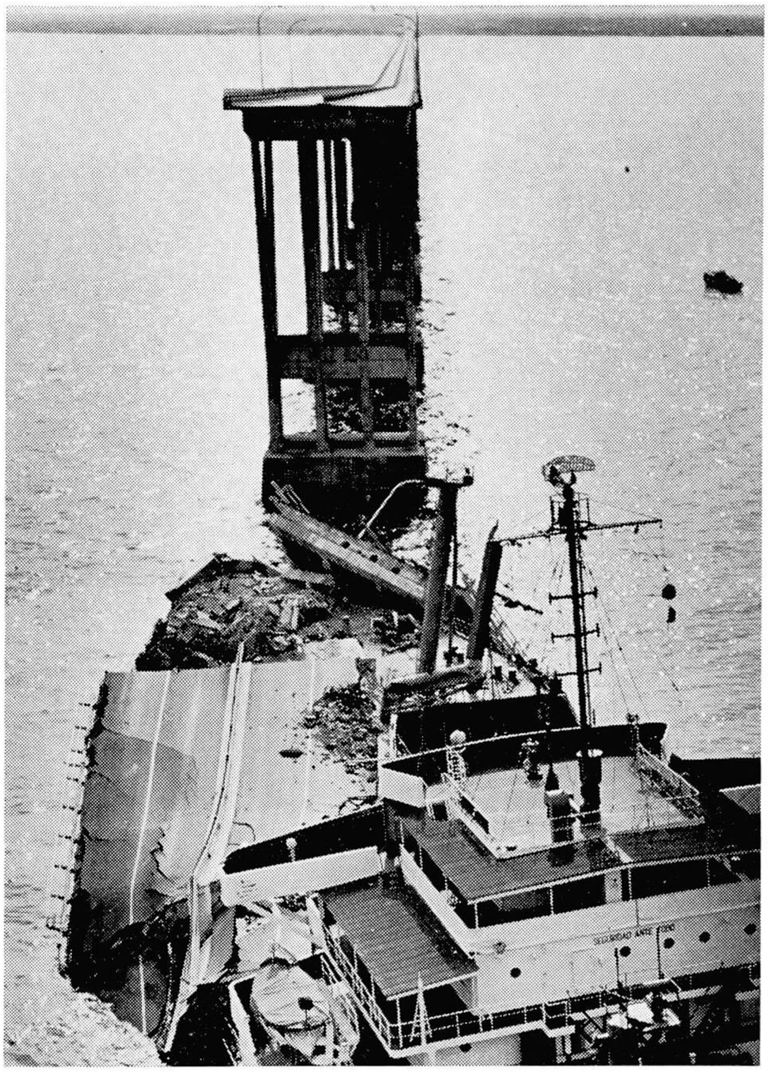
Maracaibo bridge after the collision. Photo 1.

6. Outerbridge Crossing, New York, U.S.A.

Ship colliding with pier whereby superficial damage to the pier resulted.

1. Collision (Location — Time — Cause)

Location: The bridge is crossing the southern entrance to the Arthur Kill Strait between New Jersey and Staten Island (State Highway No. 40), New York.



Maracaibo bridge after the collision. Photo 2.

Time, etc.: 1963.
Cause: Unknown.

2. Description of Structure Involved (See Fig. 4)

The bridge was built in 1928. The superstructure is a trussed steel structure with spans of 90—115—230—115—90 m.

The navigation channel is about 185 m wide, and located between piers C and D, the latter being involved in the collision. The pier is 36.5×18.0 m, base area 660 m^2. The depth of water in the vicinity of the pier is 10.5 m and the pier-shaft reaches about 42 m above water level. The weight of the pier proper is about 25,000 t, to which comes the weight of the pier-shaft, about 10,000 t.

The pier is founded on 684 timber piles, and the bottom of the pier proper is about 6 m below ground level. For protection of the pier a detached timber structure, supported on piles, had been provided; this protecting structure was partly destroyed by the collision.

3. Description of Ship Involved

Type, etc.: Tanker "Mill Spring", displacement about 12,200 t.
Speed, etc.: Speed unknown. The ship collided broadside on with the pier.

4. Damage to Structure

The pier was only slightly damaged. Small lumps of concrete were broken off.

The protecting structure was partly destroyed.

5. Damage to Ship

The ship had a number of side plates damaged.

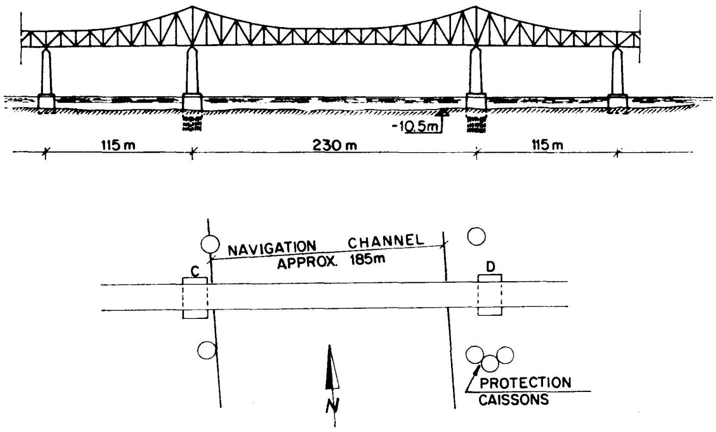


Fig. 4. Outerbridge Crossing, New York. The plan shows the location of the protection caissons in relation to navigation channel and piers.

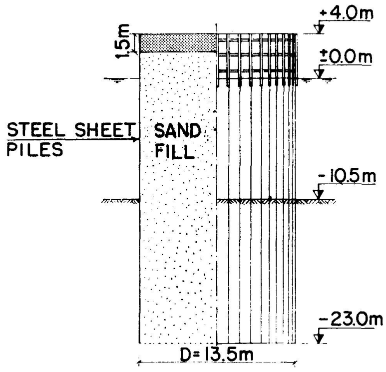


Fig. 5. Outerbridge Crossing, New York. Protection caisson.

6. Protective Measures Planned (Refer Figs. 4 and 5)

As a consequence of this collision, The Port of New York Authority initiated a comprehensive investigation with a view to elucidation of the problem of Ship Collisions against Bridge Piers, which resulted in plans for protection of the piers flanking the navigation channel. The protection contemplated is a number of sand-filled cylindrical sheet pile caissons of 13.5 m diameter. The caissons are furnished with fenders.

The sheet piling is brought down to about −23 m, i. e. about 12.5 m below the sea-bed. The caissons are filled with sand and at the top a 1.5 m reinforced concrete slab is provided. The top 1.5 m of the sheet pile locks is welded throughout. One caisson is placed at each end of a pier; in front of the pier end involved in the collision a group of three caissons is placed. The weight of a caisson is about 6500 t.

The caissons are designed to resist impact from a ship of 40,000 t displacement running at a speed of 3 knots, the corresponding kinetic energy being about 4600 tm. 50% of this energy is assumed to be taken by the caisson, the rest to be absorbed by the ship and through displacement of the caisson.

For the Goethals Bridge, located north of the Outerbridge Crossing and likewise crossing the Arthur Kill Strait, it is intended to build protecting caissons corresponding to the caissons for the Outerbridge Crossing. Rock is to be found at a depth of 5—6 m below the sea-bed, however, and the caisson is anchored to the rock through a number of bolts reaching from the concrete slab down into the rock.

7. New Lift Bridge Across Arthur Kill, New York, U.S.A.

Just north of the Goethals Bridge a lift bridge with a free span of about 160 m has been built recently (refer fig. 6). The piers next to the navigation

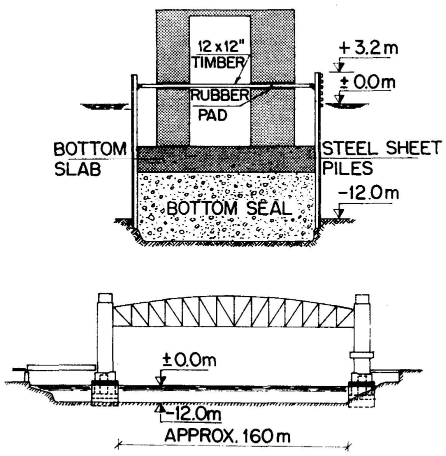


Fig. 6. Lift bridge across Arthur Kill, New York.

channel stand in about 12 m of water. The piers were built within cofferdams of steel sheet piles, which were left in place, constituting permanent protections; they reach about 3 m above water level. Bracing of the sheet piling against the piers is established by timber, and 3″ rubber padding is used. On the outside of the sheet piling normal timber fendering is furnished.

8. Bridges Belonging to the Delaware River Port Authority, Philadelphia, U.S.A.

Owned by this Authority are, for example, two of the more important suspension bridges in the U.S.A., the Walt Whitman and the Benjamin Franklin Bridge, with main spans of 610 and 535 m respectively, both of which are crossing the entrance to the port of Philadelphia. The piers of both of these bridges are located in rather shallow waters (up to 6 m deep) outside the actual navigation channel, the depth of which is about 12 m. Therefore, it was found that the risk of a large ship colliding with the piers could be considered so inconsiderable that protective measures in the proper sense should not be necessary. In addition to the granite ashlar, the piers are furnished with timber fenders, to prevent damage from barges and tugs.

A new bridge across the Delaware River: the Chester-Bridgeport Bridge has now been planned, the spans being 250—500—250 m (see fig. 7).

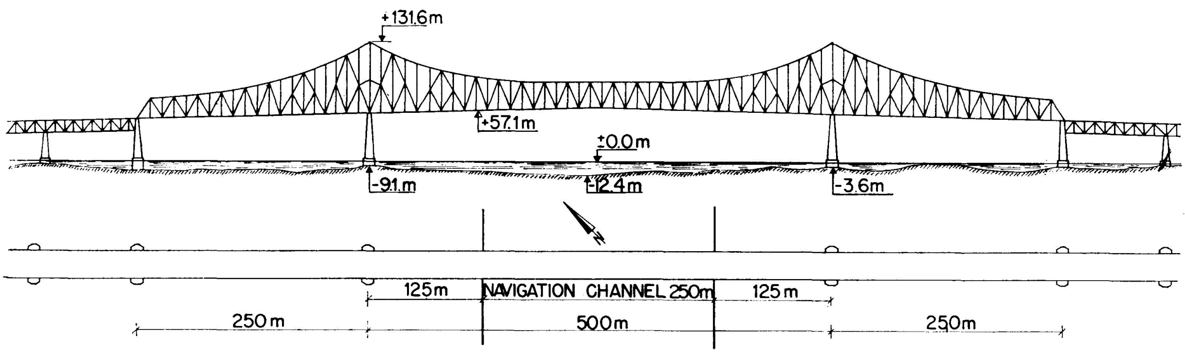


Fig. 7. Chester-Bridgeport Bridge, Philadelphia.

The present navigation channel has a width of 250 m, one half of the navigation span; it is found desirable, however, to have it extended to a width of 300 m. At normal high water the depths of water in the vicinity of the two piers are 5.6 m and 11.4 m on the east side and the west side respectively. As a consequence, the pier on the east side is protected against impact from large ships by shoal water. On the west side rock is to be found both upstream and downstream of the pier, preventing extension of the navigable channel beyond a limit of about 100 m from the pier, so that collision should only be possible in case of faulty manoeuvre. However, as a further precaution, it is proposed to construct a protective fill around the westerly pier to simulate the shoal conditions at the easterly pier. In considering the necessary protective measures, it has been assumed that a large ore-carrier might run into the pier from various directions and at speeds varying within the range of 1.5—6 knots. The weight of the pier (without any deduction for buoyancy) is about 40,000 t. Hence, on the basis of the calculations the stability of the pier should not be endangered. On the other hand, damage to fenders and to the pier might result, the extent thereof depending on circumstances.

The fender, as now planned (refer fig. 8), consists of five layers of timber reaching about 2.5 m above and about 5 m below water level. The fender covers the entire circumference of the pier. The total depth of the five layers of the timber structure is 1.2—1.5 m, so that the fender structure will be in a position to absorb a rather considerable kinetic energy.

9. Mooring Dolphin, Port of Philadelphia, U.S.A.

Ship running into the dolphin whereby overturning of the dolphin resulted.

1. Collision (Location — Time — Cause)

Location: Mooring dolphin belonging to oil pier owned by the Sinclair Oil Company.
Time: 1961.
Cause: Ship off her course due to wind and tidal effects.

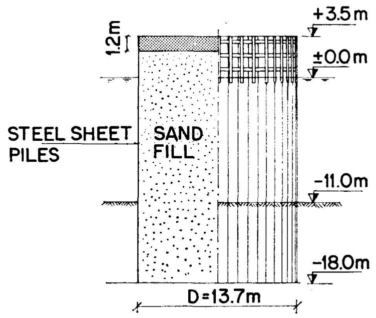


Fig. 9. Mooring Dolphin in the Port of Philadelphia.

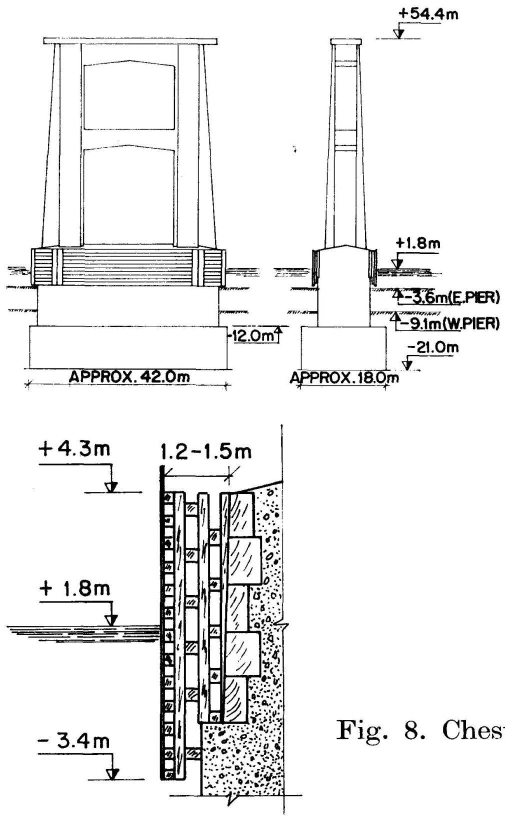


Fig. 8. Chester-Bridgeport Bridge, Philadelphia. Elevation of pier and detail of fender.

2. Description of Structure Involved (Refer Fig. 9)

Circular caisson, of steel sheet piling with filling of sand and gravel. Depth of water about 10—12 m. Total height of caisson about 22 m. Diameter 13.7 m. The top 1.2 m of the sheet pile locks welded throughout the circumference. At the top a reinforced concrete slab, 1.2 m deep, is provided. The reinforcement is welded on to the sheet piles. Weight of caisson about 5000 t.

Timber fender is provided.

3. Description of Ship Involved

Type, etc.: Ore-carrier, 35,000 t.d.w., displacement about 50,000 t.
Speed, etc.: Speed about 8 knots (4 m/sec.), corresponding kinetic energy about 41,000 tm. The ship hit the dolphin with the stem.

4. Damage to Structure

The caisson tilted over, the top moving about 3.5 m, but without being overturned. The sheet piles on the outside were lifted, and on the inside the piles buckled. The welded connections of reinforcement and sheet piles broke.

5. Damage to Ship

The stem was heavily deformed ("several feet"). The deformation took the shape of the caisson wall.

10. The Pontchartrain Bridge North of New Orleans, U.S.A.

Ship colliding with 3 supporting trestles, whereby collapse of four deck sections resulted.

1. Collision (Location — Time — Cause)

Location: Bridge across Lake Pontchartrain, just north of New Orleans. The bridge is about 38 km long.

Time, etc.: June 16, 1964, at 1.30 a. m. Weather clear, water calm, the bridge well lighted.

Cause: Lack of attention on the part of the helmsman.
This is the fifth time a ship has run into the bridge since it was opened in 1956.

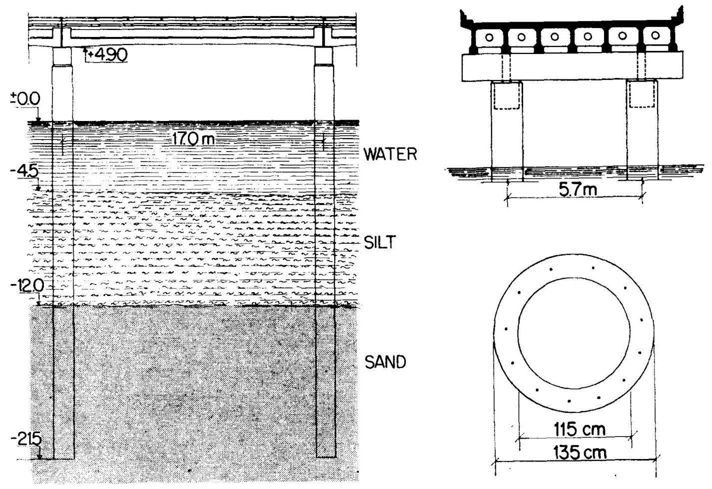


Fig. 10. Pontchartrain Bridge at New Orleans.

2. Description of Structure Involved (Refer Fig. 10)

The bridge is a low level bridge consisting of prefabricated prestressed deck elements, 17 m long and 10 m wide, supported on trestles. The trestles consist of two hollow prestressed concrete piles of type Raymond, outside diam. 135 cm, inside diam. 115 cm, about 27 m long, interconnected at the top by a prefabricated reinforced concrete beam. Clear height to bottom of bridge deck structure 4.9 m. No protective measures.

3. Description of Ship Involved

Type, etc.: Tug towing two barges, the barges probably about 1000 t.d.w. each.

Speed, etc.: The speed at the moment of collision is estimated at about 8 knots (4 m/sec.), kinetic energy of one barge about 1000 tm.

The direction of movement of the individual vessels, in relation to the columns, at the moment of collision is unknown, it is known, however, that tug and barges had altered the course before the collision took place. Therefore, it is possible that the piers were hit at different angles by the individual units.

4. Damage to Structure

3 trestles were hit by the collision, 4 bridge deck elements fell into the water. Two of the trestles were renewed (new piles driven), the third was repaired. Four new bridge deck elements were erected. Total cost of repair about 150,000 dollars.

Due to the frequent collisions (five up to now) the repair service of this bridge is exceptionally well organized. Piles and deck elements are ready in stock. A floating derrick-crane drives the piles and erects the elements. In this particular case the bridge was ready for use within five days.

This was the first of the accidents involving fatal casualties (6 passengers in a bus that happened to be on one of the collapsed deck elements).

5. Damage to Ships

Particulars of such damage are unknown.

11. Carquinez Strait Bridge, California, U.S.A.

The existing bridge connection, leading across a sound with an intense traffic, comprise two parallel bridges, one of them built in 1927, the other in 1958. The superstructures of the two bridges are practically identical, a steel cantilever structure with a central pier and two navigation spans, each having a width of about 335 m (refer fig. 11).

The central pier for the old bridge has a superstructure (tower) of steel, and the substructure consists of four cylindrical reinforced concrete caissons, 12 m diameter. The water depth is about 26 m, and the caissons are founded on rock at a depth of 40 m.

Already at the time of preparing the project it was considered that the central pier, located between two heavily trafficated navigation channels, would be highly exposed to collisions. It appeared to be difficult to arrive at an agreement in regard to the design of a permanent protecting structure, wherefore, after the completion of the bridge, a temporary protection was established, consisting of four ships anchored and moored to the pier. By the end of 1927 plans for construction of a permanent protecting structure were presented, and this structure was built.

This permanent protection, refer fig. 12, consists of a heavily reinforced horizontal concrete slab, supported on vertical piles and rakers, brought down

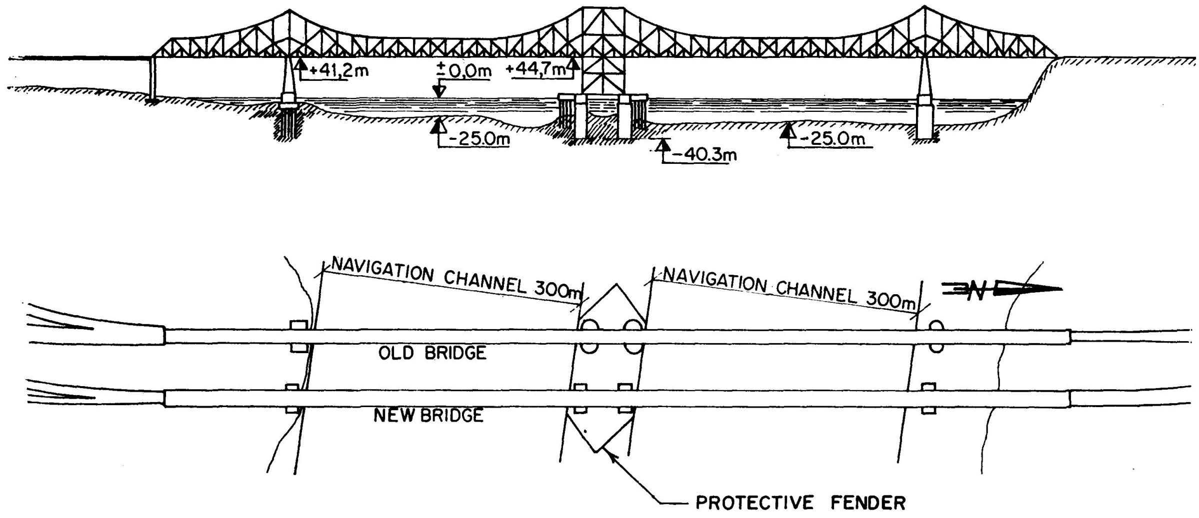


Fig. 11. Carquinez Strait Bridge, California.

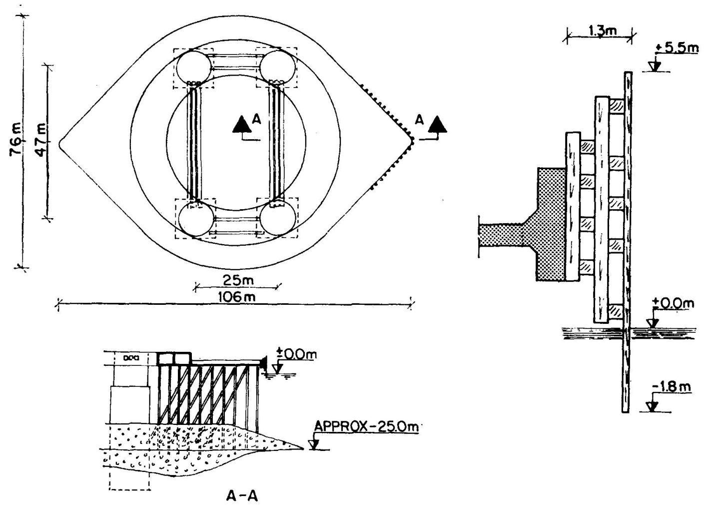


Fig. 12. Carquinez Strait Bridge, California. Pier protection, plan and section, and detail of fender.

into a thick layer of rock debris. The concrete slab is interconnected with the four reinforced concrete caissons, so that the construction in its entirety functions as one unit with a view to absorption of impact. The outer edge of the concrete slab is relatively thin, it is assumed that this part of the slab will be crushed and, partly, be forced into the ship; in this way adequate provision is found to have been made for absorbtion of the greater part of the kinetic energy. Moreover, the concrete slab is provided with a fender, consisting of vertical and horizontal timber with a total depth of about 1.3 m. When the new bridge was built, in 1958, the steel tower of the central pier was founded on two rectangular reinforced concrete caissons, each 33 × 16 m. A protecting structure corresponding to the protecting structure for the old bridge was provided also for the new bridge, and the two protecting structures are now constituting one unit.

As far as is known the fender structures have been involved in two collisions, the first time caused by an unknown ship, and the second time, in 1963, by a barge in tow, in both cases a slight damage to the fender structure resulted.

12. San Francisco-Oakland Bay Bridge, California, U.S.A.

This bridge, crossing the bay between San Francisco and Oakland, has a total length of about 6.5 km and consists of two suspended bridge sections, each having a main span of about 700 m, cantilever spans of maximum about 425 m, and a number of girder spans (refer fig. 13). In the suspended bridge

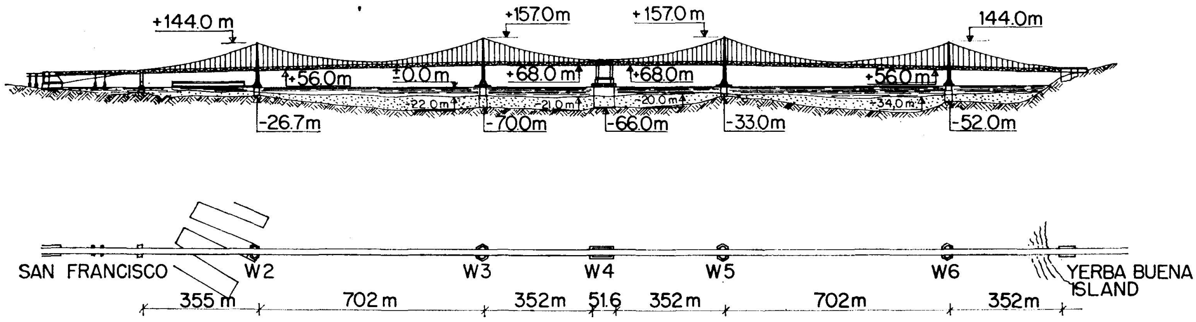


Fig. 13. San Francisco-Oakland Bay Bridge, California.

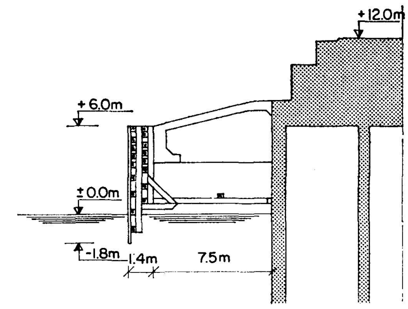


Fig. 14. San Francisco-Oakland Bay Bridge, California. Detail of pier protection.

spans protecting structures have been furnished for piers W 3, W 4, W 5, and W 6 standing in water depths varying from 16 to 32 m. Pier W 2 is located at the end of a harbour pier, and no protection is provided.

The protecting structure (refer fig. 14) is a ribbed concrete slab cantilevered 7.5 m from the ends of the pier and 3.6 m from the sides. To the concrete slab is attached, moreover, a timber fender structure, consisting of several layers of vertical and horizontal timber with a total depth of about 1.4 m, reaching from about 6 m above to about 2 m below water level. Hence, the total distance the ship has to pass before reaching the pier proper will be about 9 and 5 m respectively, whereby a considerable amount of kinetic energy can be absorbed.

In the past, ships have collided with piers W 3 and W 5 in a number of cases. On W 3 part of the fenders has been destroyed on two occasions through impact from an unknown ship. W 5 has been involved in collisions three times, hit at the same place, whereby some damage to the fenders resulted: in 1949 an oiltanker collided with the pier, in 1957 a maintenance ship belonging to the navy, displacement 1700 t, ran into the pier in a dense fog, and in 1963 it was hit by an unknown ship. None of these collisions resulted in damage to the protecting concrete slab.

13. Richmond-San Rafael Bridge, California, U.S.A.

Collision with pier resulting in destruction of protecting structure.

1. Collision (Location — Time — Cause)

Location: The bridge is crossing the San Francisco Bay, California.
Time: August 5, 1961, at 10.25 a. m.
Cause: Failure of steering gear.

2. Description of Structure Involved

The bridge has a total length of about 6.5 km, and provision is made for two navigation channels, each 300 m wide. Each of the navigation channels is bridged by a cantilever structure consisting of a 325 m main span and two 160 m side spans. The rest of the bridge is girder spans with smaller lengths. The majority of the piers for the bridge consist of two columns, carried down to the bottom (depth of water up to 18 m) and founded on steel piles reaching rock. For the cantilever piers flanking the navigation channels, however, the foundation consists of four columns. Concrete cross beams interconnect the columns (refer fig. 15).

These foundations are rather sensitive to the effects of impact from ships, and for this reason a very comprehensive protecting structure has been built,

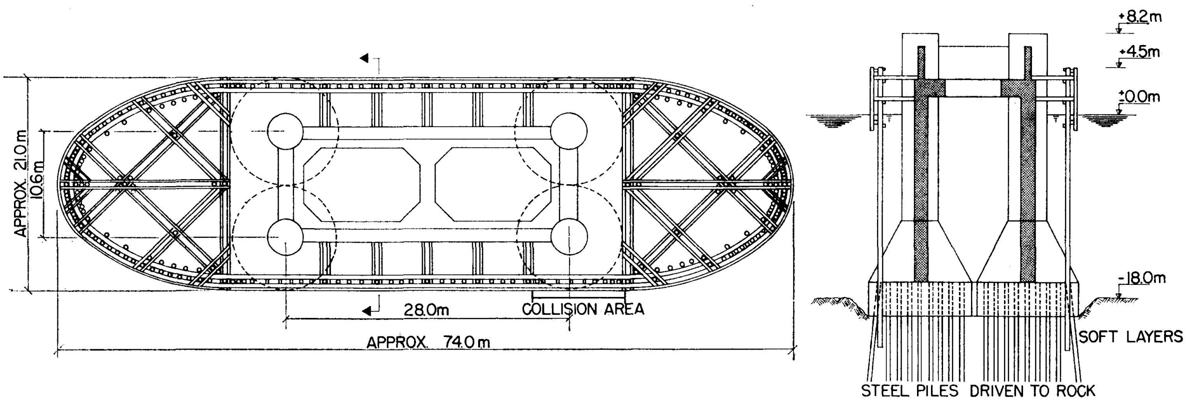


Fig. 15. Richmond-San Rafael Bridge, California. Pier protection, plan and section. Note particularly the extent of the protection in comparison to the four slender bridge piers.

embracing the entire circumference of the pier, refer fig. 15. In principle the protecting structure is detached from the shafts of the columns and consists of horizontal and vertical timber reaching from about 4.5 m above to 1.5 m below water level and attached to vertical piles driven down into the sea-bottom. Upstream and downstream of the pier, where the risk of collision is greater, the protecting structure reaches about 20 m beyond the columns.

The top end of the protecting structure is supported on the transverse beams interconnecting the shafts of the columns.

3. Description of Ship Involved

Type, etc.: U.S. Navy "Edmonds" (Destroyer Escort), displacement 1450 t.
Speed, etc.: The actual speed is unknown, but most likely high (the maximum speed of the ship is 28 knots). The ship hit with the stem, probably at a relatively acute angle.

4. Damage to Structure

The part of the protecting structure that was hit (opposite to a pier shaft) was completely destroyed. The damage amounted to about 23,000 dollars. The pier suffered no damage.

5. Damage to Ship.

None, or only slight damage to the ship.

14. San Mateo-Hayward Bridges, California, U.S.A.

A. Old Bridge (Lift Bridge)

1. Collision (Location — Time — Cause)

Location: The bridge is crossing the San Francisco Bay, California.
Time, etc.: November 17, 1960.
Cause: Unknown.

2. Description of Structure Involved (Refer Fig. 16)

The bridge has five main spans, the central span, bridging the 80 m wide navigation channel, being a lift span. The piers flanking the navigation channel have a base area of about 18×8 m. They stand in about 13 m of water and are supported on piles. The weight of a pier, including shaft, is about 5000 t.

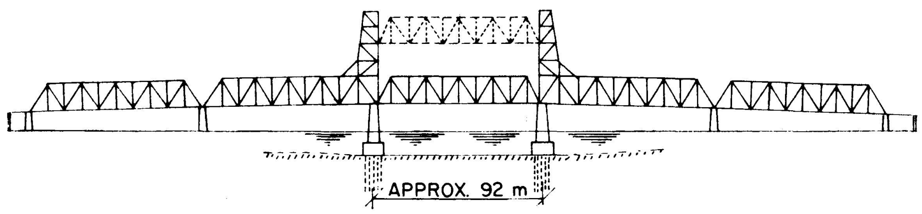


Fig. 16. San Mateo-Hayward Bridge, California (old bridge).

On the channel side of the piers they are provided with a protecting structure (see fig. 17) extended into guiding structures, about 18 m upstream and downstream of the pier. The protecting structure which is detached from the pier, consists of horizontal and vertical timber attached to a T-shaped concrete slab, supported on pile trestles consisting of a vertical pile and a raker of 14″ steel tube, driven down to a depth of about 27 m, i. e., about 14 m into the ground. Moreover, a group of piles is placed at each end of the protecting structure.

3. Description of Ship Involved

Type, etc.: s. s. "Point Reyes", displacement unknown.
Speed, etc.: Speed and direction of movement are not known.

4. Damage to Structure

The part of the protecting structure directly involved in the collision was totally destroyed. The damage amounted to about 75,000 dollars.

No damage was caused to the pier proper.

5. Damage to Ship

Only slight damage was caused to the ship.

6. Subsequent collisions

In April 1964 the protecting structure was again involved in a collision, a barge in tow running into it. Damage to the protecting structure resulted. While the repairs following this collision were in course of execution, a dolphin temporarily installed for protection was run down by a suction dredge in tow.

B. New Bridge (High Level Bridge)

For replacement of the existing bridge (see above) a project for a new high level bridge has been prepared, having three spans over the bay, 115–230–115 m respectively.

The steel towers are about 40 m high. They are rigid frames supported on two cylindrical hollow reinforced concrete columns, 5.5 m diameter, which are carried down to the bottom and are supported on steel piles. The design is analogous to the design used for the Richmond-San Rafael Bridge.

For the two piers flanking the central span with the 150 m navigation channel a protecting structure will be provided, the design corresponding to the design used for the Richmond-San Rafael Bridge (refer fig. 15).

15. Golden Gate Bridge, California, U.S.A.

The bridge is crossing the Golden Gate, the entrance from the Pacific Ocean to the San Francisco Bay. The bridge, completed in 1937, is a suspension bridge, and for many years the main span of about 1280 m was the longest free span in the World; it is now surpassed by the Narrows Bridge.

One of the main tower piers (the southern tower) is located about 350 m from the shore, in 30 m of water, and is founded on rock. Due to tidal changes there is a strong current in the strait, which may reach a velocity of up to 4 m/sec., and as the traffic is considerable there is a great risk of collision in respect of this pier.

The pier construction, refer fig. 18, includes an external concrete cofferdam, with an about 8.5 m thick wall, a sealing layer about 20 m deep, and the pier proper, reaching from level about -10.6 to $+13.4$ m.

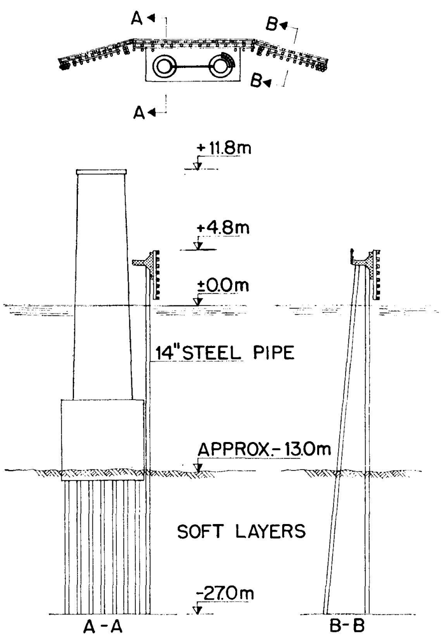


Fig. 17. San Mateo-Hayward Bridge, California (old bridge). Plan and section of pier protection.

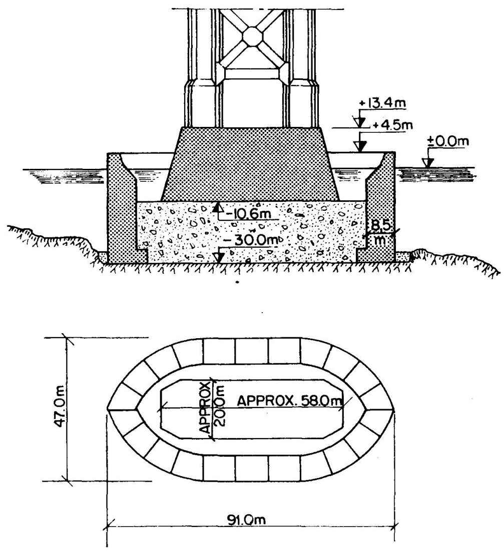


Fig. 18. Golden Gate Bridge, California. Plan of South Tower with concrete wall which was acting as cofferdam during the construction period and which is now acting as permanent protection.

The cofferdam is of approximately elliptic shape, the outer dimensions being about 91×47 m. The concrete was placed under water, in a movable steel shuttering, and carried up to level $+4.5$. Thereafter, the 20 m sealing layer was placed as under-water concrete. The water inside the concrete wall was pumped out, and the pier proper was concreted in the dry. The cofferdam remains in place and constitutes a very effective protecting structure for the pier proper. The weight of the cofferdam is about 135,000 t, whereas the weight of sealing layer + pier amounts to about 115,000 t.

No information is available on ships colliding with this protecting structure.

16. Railway Bridge (From 1879) Across the Severn, England

Ship colliding with a bridge pier, whereby resulted collapse of the pier and two spans of the bridge.

1. Collision (Location — Time — Cause)

Location: Single-track railway bridge across the Severn river, about 20 km upriver from the new suspension bridge, north of Bristol.

Time, etc.: October 25, 1960, at 10.30 p. m. Dense fog.

Cause: Two engine powered barges were accidentally hooked up together, whereby they came out of control. The reason for the hooking up has not been fully elucidated, it may have been due to fog, darkness, current, and negligence.

2. Description of Structure Involved (See Fig. 19)

The bridge is a little more than 1 km long, having a series of spans of about 40—50 m, and two large navigation spans — far away from the place of collision.

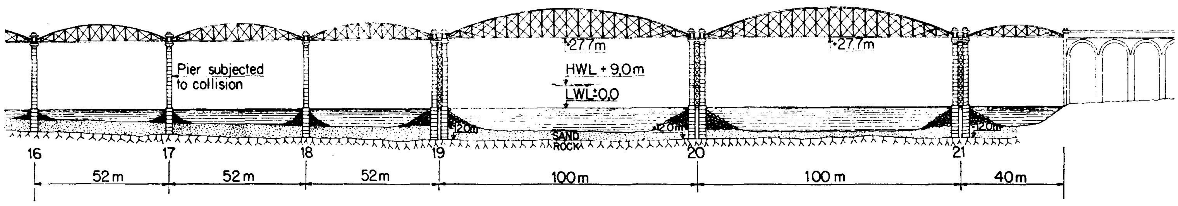


Fig. 19. Severn Railway Bridge, England.

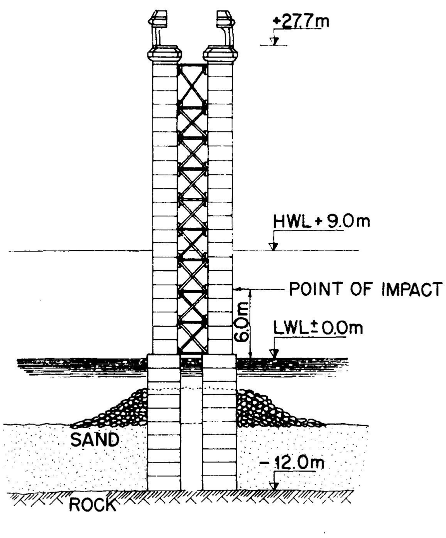


Fig. 20. Severn Railway Bridge, England. Pier 17.

The bridge was built in 1875—1879. The superstructure is of old-fashioned design: Parabolic steel trusses. Clear height under the bridge about 20 m, above high water level (tidal changes amount to about 10 m). Most of the piers, including the pier involved in the collision, consist of two cast iron cylinders, of diameter 2.1 m, filled with "Roman Cement" (see fig. 20). These cylinders stand on two similar cylinders of 2.7 m diameter, carried down to rock, about 12 m below low water level. A stone filling is placed around the lower cylinders. The upper cylinders are mutually braced, interconnected by a cast iron lattice system.

The columns reach a level of about 27 m above low water level.

3. Description of Ships Involved

Two engine powered steel barges carrying oil and with a total weight each of about 400—450 t. They were on the way up-river to the Sharpness dock. Accidentally the two barges were hooked up together, and went adrift, following the current which had a velocity of $3^1/_2$ knot, i.e. relatively moderate, probably making no way through the water. The barges hit bridge pier no. 17 with the side of one barge a little before the beam, and after the collision they drifted on to a mud-shoal at some distance.

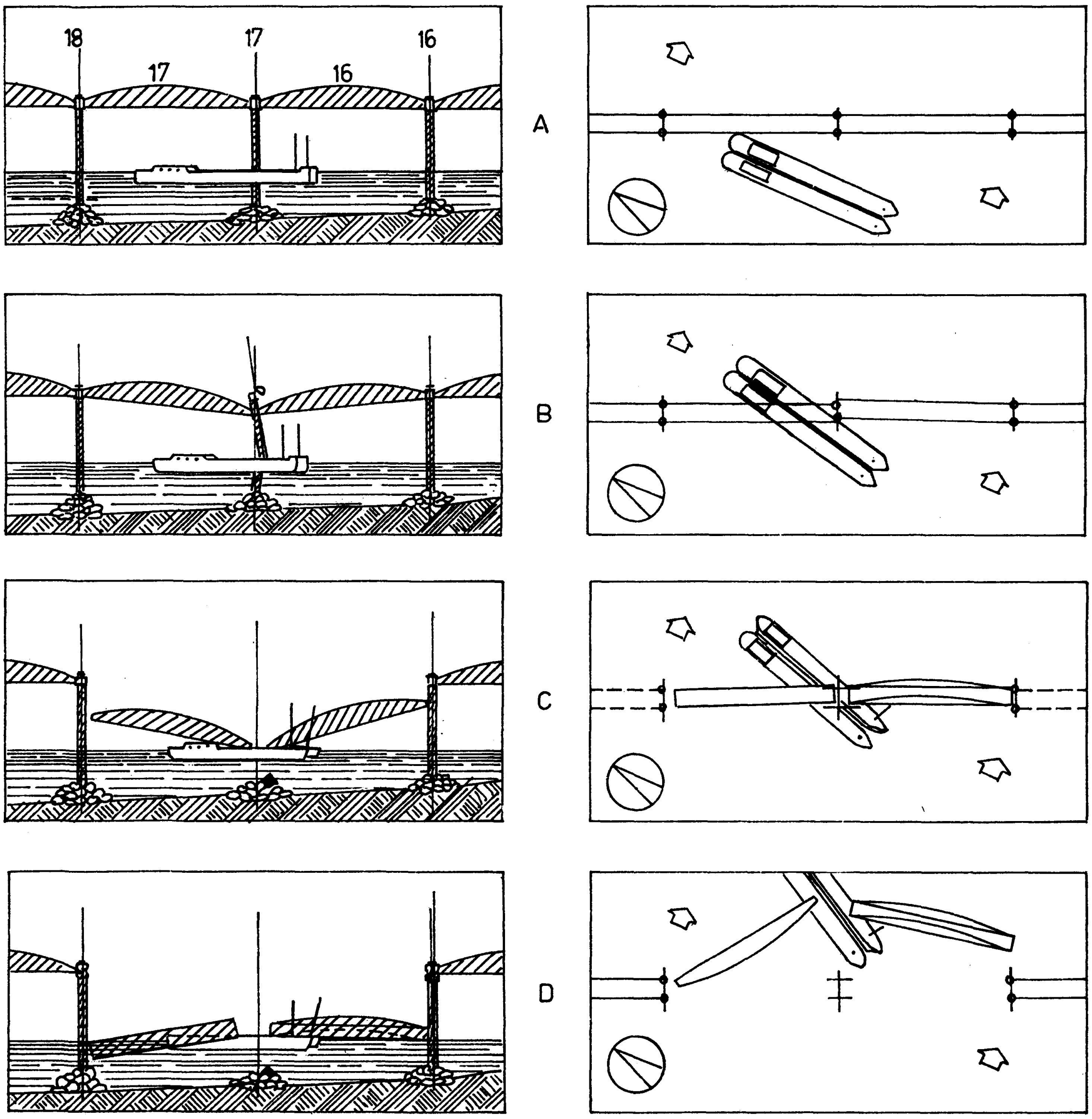


Fig. 21. Severn Railway Bridge, England. Reconstruction of events.

4. Damage to Structure

When the barges collided with bridge pier no. 17, the pier collapsed entirely and broke into many pieces. The two bridge spans supported on pier no. 17 fell down upon the barges, drifting with the barges over a certain distance.

Fig. 21 illustrates the results of a thorough investigation undertaken by Peter Mason, Consulting Engineer. As a matter of course, Peter Mason undertook, among other investigations, a calculative analysis of the impact, and found — quite naturally — that the pier could not take any impact of importance.

5. Damage to Ships

Both of the barges were heavily damaged: depressions over a length of several metres originating from the collision with the bridge pier, the deck destroyed, probably by a bridge span coming down, and damage from fire following an explosion in the oil. Out of the crew of 8, 5 members were killed, probably by bridge spans coming down.

* * *

Finally, it should be mentioned that the bridge pier concerned was of old-fashioned design and not suitable to resist impact from ships, likewise as the bridge in its entirety is out of date, and now is likely to be demolished, because restoration probably will be expensive beyond reasonable limits.

In respect of the history of the bridge it should be mentioned that ships have had serious collisions with the bridge in 7 cases (presumably small ships), resulting in material damage to the piers and ships involved. Thus the pier now collapsed, no. 17, was hit by a 400 t barge which had gone adrift. The pier did not collapse but serious longitudinal cracks developed in both steel cylinders, within almost the lower half of the cylinders, likewise as the lattice bracing interconnecting the cylinders was splintered, and was replaced by bracings of modern steel. Also other piers have been damaged by collisions. These waters are not carrying very much traffic, and the traffic is now rapidly decreasing.

A statement of interest is that the large number of piers across the whole waterway has given rise to erosion of large quantities of sand at the foot of the numerous short spans. This has resulted in development of increased velocity of the current through these short spans and, in turn, an increased risk of barges drifting away from the actual navigation spans with larger span.

Finally, it should be mentioned that the bridge on a certain occasion was hit by an aeroplane! The consequences of this accident are unknown, however.

In the discussion of the accident in the "Institution of Structural Engineers", London, refer "The Structural Engineer", February and October, 1963, it is mentioned, among other things, that the bridge is "practically an exact scale model of the suggested bridge across the Channel between England and France".

Chapter 3

Approximative Calculations Relating to Impact from Ships on Bridge Piers

1. *Ship Colliding with the Drogden Lighthouse, December 2, 1946*

The results of the calculations given in the following should be taken as no more than an indication of orders of magnitude. This because such calculations necessarily must be based on estimated values of many of the decisive parametres. E.g. the weight and the velocity of the ship at the moment of collision are not known accurately. Nevertheless, it has been deemed useful to get an idea of the energy transfer and the forces acting during the impact by a simple straightforward calculation. In general the assumptions have been chosen so that the resulting forces should be on the safe side (too big). It has not been considered justified to apply more refined calculation principles (e.g. variable force during impact, etc.) in the present case.

* * *

In respect of data relating to lighthouse and ship, refer to Chapter 2, No. 1.

In order to arrive at an idea of the amount of energy transferred to the lighthouse through the collision, and of the forces that must have developed, the following estimative considerations are made (compare fig. 1):

As mentioned earlier the displacement of the ship at the moment of collision is not known exactly, but it could not be more than 13,500 t and probably not less than 8500 t. The calculation is carried through under the assumption that the total weight was $S = 13{,}500$ t. If, alternatively, the lower limit is used, the forces, etc. will be reduced correspondingly.

The approximate velocity of the ship was $v = 16$ knots $= 8.25$ m/sec. On this basis the kinetic energy is estimated at:

$$E = \frac{S}{G}\frac{v^2}{2} = \frac{13{,}500}{9.81}\frac{8.25^2}{2} = 47{,}000 \text{ tm}.$$

G being the acceleration due to gravity.

Considering that the ship is fully stopped by the collision, the kinetic energy E will be absorbed by

a) deformation of the ship;
b) displacement of the lighthouse structure as a whole, whereby the absorbtion of energy is effected by frictional resistance developed between lighthouse structure and supporting medium;

c) (local) deformation of lighthouse structure;
d) kinetic energy of, among other things, the water masses agitated by the movement of the lighthouse structure.

To establish estimatively the part of the energy, E, absorbed by the displacement of the lighthouse structure, two ways of reasoning can be applied, classified A and B in the following. In the following calculations the contributions from c) and d) have been left out of consideration.

A. Work from Friction between Lighthouse and Supporting Medium

The pressure acting on the base area is weight 13,300 t less buoyancy 4000 t, equal to 9300 t. With an estimated allowance for the rock filling, it is assumed that the vertical load has been approximately 10,000 t within the area where the actual forces have exceeded the frictional resistance. Under the assumption of central distribution of the load (which can hardly be correct due to the overturning effect of the forces from the impact, see under B below) a frictional force of $F = \mu \cdot 10{,}000$ t has been "working" over a length of $a = 1.25$ m during the displacement. Hence, the friction work is

$$A_F = \mu \cdot 10{,}000 \cdot 1.25 = \mu \cdot 12{,}500 \text{ tm},$$

and the fractional part of the kinetic energy absorbed by the displacement will be

$$\varphi = \frac{A_F}{E} = \frac{\mu \cdot 12{,}500}{47{,}000} = \mu \cdot 0.265.$$

Assuming μ to correspond to frictional angles of 30° and 45° respectively, is found

$$\varphi = \begin{cases} 0.15 & (\mu = 0.58), \\ 0.27 & (\mu = 1.00), \end{cases}$$

which indicates, in turn, that the part of the energy transferred to the lighthouse structure is within the range of 15 to 30%. If the lower limit of the weight of the ship is used, these fractions are found to be 25—40%.

B. Work Absorbed by Displacement, Compared to the Work Absorbed by Deformation of the Stem of the Ship

As a matter of course, the forces acting during the impact did not remain constant during the impact-period. Assuming, however, that an average impact force K can be reasonably accepted, this average impact force has produced the following work:

$$A_F = K \cdot 2.5 \sin 30° = K \cdot 1.25 \text{ tm},$$

the displacement at the contact point, about 2.5 m, having a component of about 1.25 m in the direction of the movement of the ship (refer fig. 1).

The depression of the stem of the ship amounted to 5—6 m, and the magnitude of the work absorbed thereby will thus be

$$A_D = K \cdot 5.5 \text{ tm}.$$

Assuming $E = A_F + A_D (= K \cdot 6.75)$, i.e. all energy is assumed to have been absorbed by these two classes of work, is found

$$\varphi = \frac{A_F}{E} = \frac{1.25}{6.75} = 0.19,$$

which fraction is of the same magnitude as found under A above.

The order of magnitude of the average impact-force has been

$$K = \frac{47{,}000}{6.75} \sim 7{,}000 \text{ t}^{1)}.$$

This force would be in a position to overcome a friction corresponding to $\mu = 0.7$, and would have developed a translational movement if it had been directed towards the axis of the lighthouse. Seeing that a rotation occurred, the force must have acted eccentrically in relation to the lighthouse axis. Through a rotating movement an essentially higher friction can be overcome.

However, it will now be possible to arrive at an opinion on the inaccuracy of the assumption made under A, of central distribution of the load on the ground:

If the force is acting at water level the displacement of the point of action of the resultant at the base surface will be

$$x \cong \frac{7{,}000 \cdot 10}{10{,}000} = 7 \text{ m},$$

and it is seen that it would not be in a position to overturn the lighthouse (the resultant falls actually within the base area). The friction-work is too roughly estimated, however, the displacement of the resultant reducing the work involved in the displacement (= friction-work) to perhaps half the value estimated under A; and the agreement between fractions of transferred energy results poorer (as mentioned above, however, the friction may have been higher, and the kinetic energy of the ship lower; thus again tending to improve the agreement).

In fact, the considerations under B show the following quite obvious aspects which should be realized:

1. The higher the flexibility or resilience of the impact-absorbing structure is, the more impact-energy will it absorb, the more will it be deformed or damaged, and the less the ship will be deformed and damaged.

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[1]) If the displacement of the ship had been estimated at 8500 t this force would be about 4500 t.

2. An "absolutely" rigid pier (which must in fact be the ideal in respect of bridges) will not absorb any energy at all theoretically; it is, on the other hand, naturally exposed to forces which result lower the more the ship is damaged (the result being a long impact period and a long deformation-length).
3. The energy increases in direct proportion to the weight of the ship and to the square of the velocity. It is obvious that the strain on the pier will increase with increasing energy, the forces developed during the impact will, however, depend on a number of circumstances, such as the design of the ship.

   An evaluation of the effect developed by impact from a ship is, therefore, subject to considerable inaccuracy.

C. Local Effects

The hole below water level has an area of about 5 m², and under the assumption of even distribution of the impact force over this area, the average compressive stress has been of the magnitude of:

$$\sim \frac{7{,}000}{5} = 1400 \text{ t/m}^2 = 140 \text{ kg/cm}^2.$$

2. An Attempt at a General and Theoretical Treatment of the Problems

Professor A. E. Bretting's investigation: "Collision with Bridge Pier at Lillebælt" of 25. 11. 1964 contains a theoretical and numerical valuation of the problems in connection with ships' collisions against bridge piers.

The investigation, which has been done on occasion of and in consultation with the author, is based on a number of simplifying assumptions which have been necessary because the actual problems in general are so complicated that a calculation considering all aspects cannot possibly be carried out.

Consequently, it has been considered most important to include the decisive parametres only in the basic assumptions for the treatment. In principle it has been tried to formulate a method of calculation which on the whole would give too favourable results, because beforehand it seemed obvious that the risk of serious damage in case of a collision was in fact very high. So actually the question was not to make a basis of design for the pier calculation, but, on the contrary, to be confirmed in a clear and unequivocal way, in the assumption of the risk. It is obvious, however, that the principles applied in the investigation, perhaps after some adaptation, can also be utilized in designing protective measures for bridge piers.

There will be no detailed statement of the theoretical considerations, but the applied assumptions are the following:

Only a central collision between ship and pier will be treated. A collision affecting the pier in an eccentric way will in general be more dangerous.

In the investigation the total weight resting on the pier is assumed to be concentrated in the pier. This will also give too favourable results because the more or less elastically supported masses of the superstructure will not at once participate in the acceleration of the pier, but on the contrary, according to the circumstances, be subject to heavy oscillations.

During the collision the pier will make a translation in the direction of the impact. The movement is restrained by the displacement resistance developing in the foundation area, and this resistance is assumed to increase linearly following the movement to a certain ultimate limit, above which the resistance is assumed to be constant during the rest of the movement. This form of rupture has been considered decisive in the present case. However, to tall slim piers overturning will often be a greater risk.

The mass of the ship is also assumed concentrated in the centre of gravity. The assumption of a central collision in the longitudinal direction of the ship is not a "favourable" assumption, but obviously the most risky for the pier. On the other hand the assumption must be considered rather realistic and probably the only one which makes possible a rational treatment, and still only with a rough approximation.

Decisive for the whole investigation is the ability of the ship to absorb by crushing a considerable part of the impact energy. It is assumed that the stem of the ship hits the pier and that the stem is crushed. The force, the crushing force, with which the pier is affected by the ship, must in principle depend on the "crushing length" of the ship. The force will restrain the movement of the ship, but at the same time accelerate the bridge pier, which, however, as the movement of the pier increases, will be restrained in its movement by the foundation resistance.

"Crushing" of the ship will continue as long as the velocity of the ship exceeds the velocity of the pier. When the two masses have attained equal velocity, the combined mass of ship and pier will continue the movement, subject only to the restraining effect of the resistance from the foundation, until zero velocity results.

The magnitude and the development of the crushing force of a ship are difficult to estimate, although as regards the magnitude some experience is available from the collision with Drogden Lighthouse and also from the investigations made by Minorsky and Spinelli. For simplification, the crushing force is assumed to remain constant as long as the crushing of the ship is in progress. For the numerical investigation, however, different values of this force have been applied to one and the same type of ship. The assumption of a constant force during the collision can, of course, only be characterized as a rough approximative description of the very complicated development of the rupture of the many different constructions involved. In particular, the assumption that the impact force will attain its full value from the moment of initiation may lead to some less realistic results in case of low collision velocities. In case of higher velocities, where the impact-periods result longer, the idealization in this respect will be of less consequence.

* * *

Formulation of the equations of motion in respect of ship and bridge pier: Assuming the movement of the ship after the initiation of the impact to be y, and the movement of the pier to be x, the crushing length of the ship will be $z = y - x$. The mass of the ship is M_s, and the mass of the pier is M_p. Considering the period from the initiation of the impact until ship and pier have possibly attained equal velocity, the following equations are valid:

$$M_s \ddot{y} = -K(z) \qquad \text{(for the ship)}, \tag{1}$$

$$M_p \ddot{x} = K(z) - R(x) \qquad \text{(for the pier)}. \tag{2}$$

In these equations $K(z)$ means the crushing force of the ship as function of the crushing length, z, and $R(x)$ means the foundation resistance of the pier as function of the movement of the pier, x, while $\ddot{y}$ and $\ddot{x}$ mean the acceleration of the ship and pier, respectively.

In case ship and pier attain a common velocity the crushing of the ship will stop, and we have for the combined mass:

$$(M_s + M_p)\ddot{x} = -R(x). \tag{3}$$

These equations define the development of the impact when the initial velocity of the ship is known. In general the equations can be solved only by numerical integration. With the above-mentioned simplified assumptions in respect of $K(z)$ and $R(x)$, as used in this investigation, an analytic solution is possible. The discussion of the different situations that may occur will, however, be rather complicated and lead too far.

* * *

With a view to a numerical analysis the following assumptions have been applied (refer also to Appendix 1):

— The size of ship considered has a total displacement of about 50,000 t, corresponding to about 37,000 t.d.w.

— The mass of a ship of this size is of the same magnitude as the mass of one of the piers for the Lillebælt Bridge, having a total weight of about 50,000 t, buoyancy not considered. Of this weight, however, only 20,000 t is concentrated in the pier proper, and the remaining about 30,000 t originate from the superstructure. In the investigation the entire weight is taken as being concentrated in the pier, however, as mentioned in the preceding.

— The pier is assumed to be in a position to take an ultimate horizontal force of 6000 t.
Elastic conditions are assumed to be exceeded, when the displacement of the pier is in excess of 0.1 m. For displacements beyond this limit the resistance from the pier is assumed to remain constant.
— The crushing force of the ship is difficult to evaluate, therefore three different crushing-force values have been investigated:

$K =$ 3,000 t, corresponding to a "soft ship";
$K =$ 10,000 t, corresponding to a "medium-hard ship";
$K =$ 30,000 t, corresponding to a "hard ship".

A crushing force of $K = 10{,}000$ t must be considered of probable magnitude in respect of a ship of the size considered; $K = 3000$ t, on the other hand is considered to be close to the lower limit of the range of possibility, and $K = 30{,}000$ t is likely to be at the upper limit.
— In the investigations three different velocities of the ship, prior to impact, have been considered, viz.: 6 m/sec., 3 m/sec., and 1 m/sec., corresponding to about 12, 6, and 2 knots respectively. A velocity of 3 m/sec. corresponds approximately to the maximum velocity of the current in the narrow Danish sounds, like Lillebælt, Limfjorden, etc.
— The results of the calculations relating to the 9 cases investigated (3 velocities have been investigated, combined with 3 different crushing-force values of the ship) are given in a table in Appendix 1. As will be seen from the table, the displacement of the pier increases considerably with the velocity of the ship, except for the case of a crushing force of $K = 3000$ t, which is equal to one half of the ultimate resistance to displacement of the pier and, therefore, under the assumptions adopted, just cannot produce plastic deformations of the pier. It will be seen, moreover, that in respect of a "soft ship" the greater part of the impact energy (here taken equal to the kinetic energy of the ship prior to the impact) is absorbed by the crushing of the ship, and the crushing lengths found for this ship result very considerable in this case, particularly for the high velocities.
For a "medium hard ship" the pier displacement and the crushing length of the ship are of equal magnitude, and the pier absorbs 35—47% of the impact energy.
For a "hard ship" the crushing lengths, as a matter of course, result much shorter, and the pier displacements essentially larger than in the cases considered above, and the part of the energy absorbed by the pier approaches 50%. (This particular result is due to the assumption of equal masses of ship and pier, in the case investigated.)
— In the table is stated, moreover, the duration of the impact. The impact-period increases with the speed, and decreases with increasing hardness of the ship.

— Finally, the table contains the acceleration of the pier that will result, expressed as a fraction of the acceleration due to gravity.

— Under the simplified assumptions adopted, the maximum acceleration of the pier results proportional to the crushing force, and independant of the velocity of the ship, which can hardly be said to be in very good accordance with actual circumstances.

* * *

Irrespective of the fact that the simplified assumptions adopted in some cases may result in somewhat theoretical values, the principal conclusions drawn from the investigation can hardly be disputed:

A ship colliding with a bridge pier, and possessing a mass of the same order of magnitude as the mass of the pier, may in many cases cause serious damage to the pier and force it out of position, to such an extent that the entire structure must be considered as destroyed. Only very optimistic assumptions in respect of the capacity of the ship to absorb impact energy will lead to a relatively moderate effect on the pier.

The size of the ship considered, and the velocities assumed in the investigations must be said to be absolutely realistic, in respect of navigable waters like Lillebælt, and, as already mentioned the assumption relating to the mass of the pier is somewhat on the favourable side. The assumed resistance of the pier to displacement can be taken as realistic in the present case, but this assumption can, of course, be greatly varied, depending on the conditions of foundation.

In conclusion there is good reason to emphasize that bridge piers in waters with extensive navigation should be protected, to avoid the disastrous consequences which may arise from a collision.

Chapter 4

Collision between Two Ships

Although the conditions prevailing in connection with collisions between two ships are not directly comparable with the conditions developing when ships collide with bridge piers, the collisions between ships may, nevertheless afford certain information of interest concerning the deformations of the ships resulting from the collisions.

From statistics it is known that a high percentage of collisions between ships occur in canals, within ports and in territorial waters, i. e. in water leaving only limited space for ships' operations.

Collisions will be of more serious consequence in future than has been the case previously, due to increasing sizes of ships, and due to higher speed.

Shipping experts are in possession of a comprehensive material — photos and written statements — describing the effects of collisions between merchant ships. For example, V. U. MINORSKY, Naval Architect, New York[2]), states that the results of such collisions almost always show a relatively non-elastic impact on which it is difficult to establish a calculative investigation, due to the complex structure of the ship. The forces developed in connection with a collision are, as a rule, acting under circumstances where the steel plating, and other members, are strained beyond the limit of elasticity.

American shipping experts are in possession of data relating to a large number of collisions of ships of relatively recent origin, about 50 case-records, reported by the U.S. Coast Guard. In these cases the speed of the ships, their mutual angle at the time of collision, and other information such as the depth of the effect of the impact and the geometry thereof, are known. About 50% of the said 50 case-records are elucidated to such an extent that they are applicable to a certain approximative calculation of empirical character, allowing in turn a prediction of the penetration of the stem of a ship into a ship's side, provided that displacement, design, and speed of the ships are known. On the other hand, the calculations do not aim at a determination of the forces developed between the two colliding ships, and are, therefore, not directly relevant to ships colliding with bridge piers. Experimental investigations of collisions between ships have been made, through application of scale models, by F. Spinelli, Professor at the Shipbuilding Laboratory of the University of Napoli. The experiments aimed at an elucidation of the results of a ship equipped with nuclear power being exposed to a sideward impact, opposite to the reactor, from a tanker of 45,000 t.d.w. (weight fully loaded about 60,000 t) running at a speed of about 11 knots (about 5.5. m/sec.). Through the tests were determined primarily the depths of penetration of the stem of the tanker into the various protective installations around the reactor room. At the same time it was observed, however, that the ship run down and the ship running into it received almost the same acceleration although in opposite directions, during the collision, viz. 11% and 13.5% respectively of the acceleration due to gravity. This confirms that the impact in connection with such collisions is almost non-elastic. The force acting between the two ships during the collision was measured at about 8000 t (about 13% of the weight of the ship running into the other).

For ships with nuclear power it is considered at the moment that the reactor for the ship should be placed about 6—7 m beyond the ship's side, the

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[2]) Refer V. U. MINORSKY: "An analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants" 1959.

interjacent space being provided with longitudinal and transversal bulkheads. Hence, the space will permit a deformation of the said magnitude without the reactor being hit.

Chapter 5

Conclusion, with Special Reference to Interprovincial Bridges

Considering large bridges interconnecting important provinces, where no supplementary interconnection is to be found, damage to the bridge may amount to a "national catastrophe", in case such disaster would cause an interruption of traffic on the bridge for some time, short or long, like it happened to the Maracaibo Bridge, Venezuela, in April 1964 (refer Chapter 2, No. 4), and also a loss of human lives.

Large present-day ships — large tankers, liners, or cargo ships — running into a pier will, as a rule, involve higher risk than does drift ice. Bridges, as will be known, are designed to resist even the strongest gales, strong enough to prevent road-traffic on the bridge; hence, it is realized, effects of nature are less dangerous to bridges than are the impact forces from ships.

What, than, would be the means to safeguard large bridges standing in deep waters with extensive traffic of large ships?

Piers must be as few as possible, i. e. the spans must be large.

Moreover, the bridge piers must be provided with effective protection against impact from ships. The protecting structure must be resilient and permit bending or displacement over several metres (3—6 m), without any damage being inflicted on the pier proper. Such resilient protection would also cause less damage to the ship than would result from rigid protective structures, due to the elastic impact. A powerful collision will, as a rule result in damage to the ship; a ship running stem on into a bridge pier at some speed may be shortened by several metres by the collision!

However, the owner of the bridge, looking at the matter from his angle, would prefer the ship to be damaged, instead of essential damage being caused to the bridge.

Protecting structures built in 10—30 m depth of water are extremely expensive (compare the figures in Chapter 2: No. 6, Outerbridge Crossing, New York (figs. 4 and 5); No. 11, Carquinez Strait, California (fig. 12); No. 12, San Francisco-Oakland, California (fig. 14); No. 13, Richmond-San Rafael, California (fig. 15); No. 15, Golden Gate, California (fig. 18)).

Shipping people must be entitled to reasonable conditions for navigation by large modern ships under the bridge. In this connection, navigation under poor visibility conditions, in strong current, and in case of a gale must be taken into consideration, ships sailing in ballast being liable to considerable leeway in these cases. Moreover, provision should be made for large ships to pass one another in passing the bridge on opposite courses.

Spans of 300—400 m are likely to be too small[3]), as compared to lengths of 200—300 m of the ships; this means that the bridges must, as a rule, be designed as suspension bridges, which have been built, in certain cases with spans up to about 1300 m.

Hence, the conclusion will be that:

Bridges built in deep waters passed by large ships must have spans greater than 3—400 m, and the bridge piers must be provided with protecting structures, which are expensive.

The conclusion is, of course, to be taken as presenting principal aspects of the matter, this present treatise aiming at a contribution to the elucidation of the problem, to be taken into consideration in connection with the planning of forthcoming major bridges.

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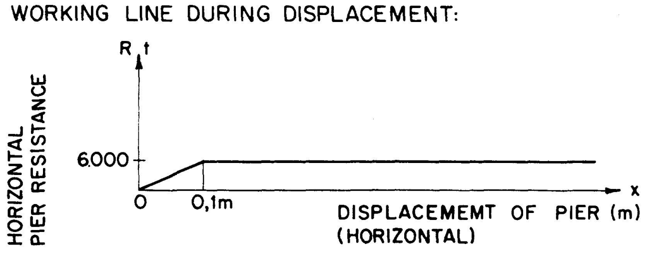
[3]) Largest spans of bridges of designs other than suspension bridges are as follows:

Cantilever bridges	max. span m	Rail/road
Firth of Forth, Edinburgh	521	double-tr.
Quebec, Canada	549	double-tr.
The Greater New Orleans Bridge	473	road
Howrah, Calcutta	456	road
Arch Bridges		
Sidney Harbour	503	4 tracks for urban railw. + road
Bayonne, New York	504	road

Appendix 1
Investigation of Impact from Ships

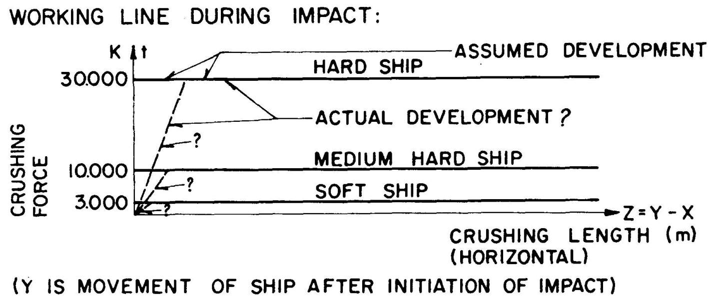
Assumptions

Pier (the same in all cases investigated) weight excl. buoyancy about 50,000 t. Resistance from displacement to ultimate $R_{max} = 6000$ t.



Ship: Displacement about 50,000 t (T.D.W. ~ 37,000 t) (the same in all cases).
Crushing resistance (constant during impact):

$K =$ 3,000 t soft ship
$K =$ 10,000 t medium hard ship
$K =$ 30,000 t hard ship



Velocities of ship (before impact)
6 m/sec. (~12 knot), 3 m/sec. (~6 knot) og 1 m/sec. (~2 knot)

Crushing force K	Soft ship $K = 3{,}000$ t	Medium hard $K = 10{,}000$ t	Hard ship $K = 30{,}000$ t
Velocity of ship	6 m/sec.	6 m/sec.	6 m/sec.
Displacement of pier	0.1 m	5.2 m	7.1 m
Crushing length of ship	30 m	5.9 m	1.6 m
Part of engergy absorbed by pier	0.3 %	35 %	47 %
Impact period	10 sec.	5.3 sec.	5.1 sec.
Acceleration of pier (as a fraction of the acceleration due to gravity G)	0.06 G	0.20 G	0.60 G
Velocity of ship	3 m/sec.	3 m/sec.	3 m/sec.
Displacement of pier	0.1 m	1.5 m	1.9 m
Crushing length of ship	7.5 m	1.4 m	0.4 m
Part of energy absorbed by pier	1.3 %	38 %	48 %
Impact period	5 sec.	2.7 sec.	2.6 sec.
Acceleration of pier	0.06 G	0.20 G	0.60 G
Velocity of ship	1 m/sec.	1 m/sec.	1 m/sec.
Displacement of pier	0.1 m	0.25 m	0.26 m
Crushing length of ship	0.7 m	0.13 m	0.04 m
Part of energy absorbed by pier	12 %	47 %	49 %
Impact period	1.7 sec.	1.1 sec.	1.0 sec.
Acceleration of pier	0.06 G	0.20 G	0.60 G

Summary

In recent years characteristic features of shipping have been steadily increasing traffic and a very conspicuous increase of the tonnage of the ships. As a consequence, the risk of ships colliding with bridge piers has increased, and, considering that only a very small number of the existing bridge piers possess masses exceeding the mass of the very large ships built in present days, it is obvious that the consequences to a bridge exposed to a collision of this nature may have the character of a catastrophe.

In this contribution, the author discusses the position of relevant problems, and elucidates same through a series of case-records on such collisions, and conclusions are drawn which are relevant to construction of large bridges across waters open to international shipping.

Résumé

Ces dernières années, on constate un accroissement constant du trafic par bateaux et une augmentation remarquable du tonnage des navires. Il en résulte des risques plus grands de collisions entre bateaux et piles de ponts. En se rappelant qu'il existe peu de piles dont la masse dépasse celle des grands navires construits actuellement, on comprend que, pour un pont soumis à une collision de cette nature, les conséquences puissent être catastrophiques.

Dans sa contribution l'auteur discute l'état actuel des problèmes principaux et il en éclaircit quelques-uns en analysant les données d'un certain nombre de collisions. Il présente des conclusions applicables à la construction de grands ponts franchissant des voies navigables internationales.

Zusammenfassung

In den letzten Jahren stellt man eine ständige Zunahme des Schiffsverkehrs und eine bemerkenswerte Zunahme der Größe der Schiffe fest. Dadurch steigt natürlich die Gefahr von Schiffskollisionen mit Brückenpfeilern, und in Anbetracht dessen, daß nur eine kleine Anzahl von bestehenden Brückenpfeilern größere Maße aufweisen als die Großschiffe, die zur Zeit gebaut werden, weisen die Folgen einer solchen Kollision für die Brücke den Charakter einer Katastrophe auf.

In diesem Beitrag diskutiert der Autor die heutigen Kenntnisse über Schiffsstöße gegen Brückenpfeiler und erläutert durch einige Beschreibungen die Folgen solcher Kollisionen. Zum Schluß werden noch einige Folgerungen gezogen im Hinblick auf den Bau großer Brücken über von der Seeschiffahrt benützte Wasserstraßen.

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