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Pier Protection by Man-Made Islands for Orwell Bridge, U.K.

Protection des piles du pont de l'Orwell (GB) à l'aide d'îles artificielles

Künstliche Inseln zum Schutz der Pfeiler der Orwell Bridge (GB)

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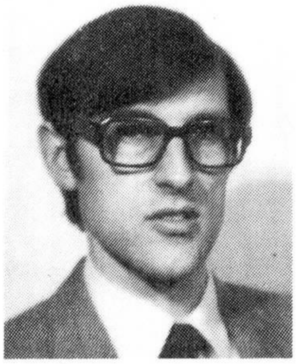

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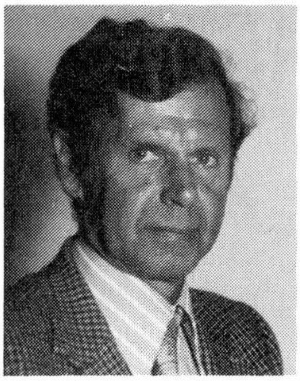

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SUMMARY
The paper describes the investigation, design and model testing of man-made islands for protecting bridge piers against impact from ships. Particular reference is made to the procedure adopted for Orwell Bridge, England, where islands of this type have been built to provide protection against ships of up to 11.000 tons loaded displacement.

RÉSUMÉ
L'article décrit la recherche, la conception et les essais sur modèle réduit d'îles artificielles pour la protection de piles de ponts contre l'impact des bateaux. Les principes adoptés pour le pont sur l'Orwell, en Angleterre, sont décrits où de telles îles ont été construites pour protéger le pont contre des bateaux de 11.000 t.

ZUSAMMENFASSUNG
Der Beitrag behandelt die Untersuchung, Modellversuche und den Entwurf künstlich hergestellter Inseln, die als Schutzeinrichtung für Brückenpfeiler gegen Schiffsanprall dienen. Insbesondere werden die Schutzmaßnahmen für die Orwell-Brücke in England beschrieben, wo Inseln dieser Art als Schutzeinrichtung gegen 11.000 Tonnen Schiffe gebaut wurden.

1. INTRODUCTION

1.1 There are now sufficient examples of the consequences of a ship striking a bridge pier to justify making protection of the piers a fundamental design requirement for any new bridge over a navigational channel.

1.2 The type of protection adopted depends upon the size and speed of the ships passing the bridge site, the profile of the river or sea bed, the arrangement of the piers within the water and the cost of the pier protection system in relation to the cost of the bridge.

1.3 Protective islands form a cheap and relatively maintenance free method of protecting piers, particularly where material to build the islands is readily available and where the profile of the river bed is favourable. These two factors determined the adoption of islands around the piers of the recently completed Orwell Bridge.(1)

2. DEGREE OF PROTECTION ADOPTED

2.1 In UK the most recent significant accident was in 1960 when two barges demolished a pier and two spans of the 80 year old Severn Railway Bridge. In the discussions on this accident Boyd (2) stated 'If there were water at a danger spot, ships would go there when they were out of control; they were like that!'.

2.2 For Orwell Bridge, which has eight piers in the approach channel to the port of Ipswich, it was decided that if it were possible for a vessel to approach a pier then that pier should be protected against such a risk, however small the statistical probability of an accident might be.

3. THE DESIGN SHIP

3.1 In order to design a protection scheme for a bridge crossing it is first necessary to define the type and size of ship that presents the greatest potential danger to the bridge : this is termed the Design ship.

3.2 Limitations on the dimensions of the Design ship may be created by the depth of water in the navigational channel; the space required upstream of the crossing to turn the ship around; the vertical clearance after the bridge has been built.

3.3 All states of the tide should be considered for both loaded and in-ballast conditions. For a given draught, a ship in ballast may have a greater displacement than a smaller ship which is laden; thus ballast conditions may provide the most critical design case for piers in shallow water.

3.4 For bridges over estuaries or navigable inland waterways the likely speed of ships passing the bridge can be obtained from pilots or regular users of the waterway.

3.5 For the eight river piers of Orwell Bridge it was necessary to consider a range of Design ships. The heaviest ships which could approach a particular pier were tabulated and then rationalised into three types:

(1) 11,000 ton displacement with 6 m draught.
(2) 9,000 ton displacement with 5 m draught (corresponding to vessel (1) in ballast).
(3) 1,000 ton displacement with 2 m draught.

These were compared with a survey of the records of ships using the port upstream of the bridge.

3.6 The maximum speed thought by users to be reasonable for the reach of river in which the bridge is located is 8 knots (4.1 m/sec). It was assumed that a ship out of control was travelling at this speed when it approached a pier.

3.7 An analysis of photographs of various accidents confirmed that, for the purpose of design, the ship should be assumed to approach any bridge pier at 90° to the line of the bridge.

4. PROTECTION SYSTEMS

4.1 Small fendering systems used in ports are designed to avoid damage to the ship and to themselves. The designer of a major bridge must ensure that no significant damage occurs to the bridge; he accepts that both the protection system and the ship may be substantially damaged in an accident.

4.2 Amongst the various options for protection are:-

(1) designing the pier to withstand the impact by providing sufficient mass or structural strength;
(2) providing independent fendering systems for all angles of approach;
(3) providing large independent sheet piled dolphins at the upstream and downstream ends of each pier;
(4) supporting nets or hawsers by means of independent piles;
(5) forming man-made islands around each pier using granular materials.

4.3 The relatively low cost of solution (5), together with its ease of construction, ease of repair and freedom from maintenance, make it an attractive answer for many shallow water bridge piers.

5. PRELIMINARY DESIGN OF PROTECTIVE ISLANDS

5.1 The materials available for construction were investigated, and it was decided that a well graded granular material with less than 10% of material passing a B.S. 200 sieve (0.07 mm) would be appropriate. Protection against wave damage is required, and may be provided by rock or by armouring units backed by a graded stone filter. As there was no rock in the region of the bridge, precast concrete tripods were adopted at Orwell.

5.2 A protective island needs to be large enough to bring a ship to rest before its bow strikes the pier of the bridge. The design calculations for the islands were based on a consideration of the energy changes that occur during an impact. As a result of the impact the initial kinetic energy of the ship is dissipated or redistributed in some or all of the following ways:-

SHIP	(1)	change in potential energy of the ship due to change in the vertical position of its centre of gravity.
	(2)	crushing of the hull of the ship.
WATER	(3)	change in potential energy of the water displaced by the ship.
	(4)	generation of water waves and turbulence.
ISLAND	(5)	change in potential energy of island material.
	(6)	displacement, shear and compaction of the island material.
	(7)	friction between the ship and the island.
	(8)	generation of shock waves within the island.
	(9)	crushing of particles of beach material.

5.3 The inclusion of many of these factors in hand calculations proved difficult and so some simplifying assumptions were made. Bouvet's (3) analysis of tanker collisions and groundings indicates that much less damage occurs when a ship grounds than when it collides. In 69% of the groundings studied the plates of the ship were damaged to a depth of less than 0.5 m. It was therefore decided that the crushing of the hull of the ship (item (2) above), which depends upon the type of construction, would be ignored in the design calculations.

5.4 When a ship decelerates the inertial force due to the added mass of the water tends to oppose the slowing down of the ship. However in a sudden impact only a small amount of kinetic energy will be transferred from the water to the ship, the remainder being dissipated by turbulence and waves; therefore item (4) above was not considered in the calculations.

5.5 Neglecting these two items the energy balance becomes

$$KE_s = PE_w + PE_s + IE$$

where KE_s is the kinetic energy of the ship

PE_w is the change of potential energy of the water

PE_s is the change of potential energy of the ship

IE is the impact energy, equal to the total work which the ship does as it penetrates the beach, the sum of items (5) to (9) above.

6. GEOMETRY AND DESIGN CALCULATIONS FOR ISLANDS OF ORWELL BRIDGE

6.1 The islands were assumed to have side slopes of 1 vertical to 3 horizontal and flat tops coinciding with the level of High Water Spring Tide (+2.0m AOD). The three design vessels given in 3.5 were assumed to be travelling at 4 m/s when they struck the island.

6.2 Water levels above +2.0 m AOD have occurred in the tidal river during storm surges, and three water levels, +3.5 metres, +2.0 metres and +0.5 metres were chosen.

6.3 Two limiting cases were studied. In the first it was assumed that the island material was so rigid that the ship would be brought to rest by rotation about its centre of gravity and by friction between the hull of the ship and the beach material. The coefficients of friction adopted were 0.6 for steel hulls on dry granular material and 0.4 for steel hulls on wet granular material.

6.4 The second limiting case assumed that no rotation of the ship would take place and that all the energy would be dissipated by the ship ploughing into the material of the island. No account was taken of the resistance of the armoured layer on the face of the island.

6.5 The required size of the protective islands depends upon how far the ship can penetrete before coming to rest. For the limiting cases considered above, it was calculated that the bows should not penetrate more than 10 m into the horizontal section of the island. The prow of the ship was assumed to be 5 m forward of the point in the beach to which the bows had penetrated. The required horizontal distance between the top of the 1 in 3 slope and the bridge pier was therefore chosen to be 15 m.

6.6 A literature survey in 1976 did not provide sufficient data against which the various assumptions in the design calculations could be checked, so it was decided to commission a model investigation.

7. OBJECTIVES OF MODEL INVESTIGATION

7.1 The purpose of the study was to determine the size of the islands required to protect the piers of Orwell Bridge by:-

(1) modelling the proposed design of beach described in 6.1 and the three types of Design vessel described in 3.5.

(2) carrying out a series of tests at water levels of +0.5 m, +2.0 m and +3.5 m AOD.

(3) recording and analysing the movement of the ship in each test, and measuring the final position of the ship together with the shape of the impact hole it produced.

(4) determining from these results the maximum distance that a vessel could penetrate into one of the islands.

7.2 The model investigation was carried out by the Hydraulics Research Station, UK, early in 1978 and the results are published in the Study Report (4).

8. CHOICE OF MODEL SCALES

8.1 The relevant scaling laws for the model tests were obtained by considering the forces acting on the ship during its impact with the protective island. Analysis (4) indicated that the relative magnitudes of the inertial, gravitational and buoyancy forces would be reproduced correctly by a Froudian scale model in which the size of the beach material was determined by the linear scale of the model. It is also important to scale the resistance of the beach material correctly, because the path that a ship follows during an impact depends upon the magnitude of this resistance relative to the difference between the gravitational and buoyancy forces. The beach resistance can be divided into a static component and a dynamic component.

8.2 The static component is the force which the island would exert on a ship during a very slow impact, and depends upon the static shear strength of the material and the coefficient of sliding friction between the ship and the material. From Coulomb's law it can be shown that the ratio of the static resistance to the inertial force of the ship will be given correctly by a Froudian scale model provided the beach material is non-cohesive and the particles are geometrically similar to those in the prototype.

8.3 The dynamic component depends upon the relative incompressibility of the beach and becomes more important as the speed of the impact increases. The requirements for similarity of the dynamic resistance tends to conflict with the requirements for the other forces considered previously.

8.4 In the present study the tests were carried out according to a Froudian scale using a model cargo ship having an overall length of 1.66 m and a beam of 0.21 m. This model was able to represent the 11,000 and 9,000 ton Design ships at a scale of 1:100, and the 1,000 ton Design ship at a scale of 1:50. Fine sand was used for the model material in the protective islands, and the required gradings were obtained by scaling the grading of the prototype material according to the appropriate linear scale. However in both the 1:100 and 1:50 scale models it was necessary to make the materials somewhat too coarse at the fine ends of their ranges in order to ensure that they would act non-cohesively.

9. EXPERIMENTAL PROCEDURE

9.1 The tests were carried out in still water in a flume measuring 20 m long x 2.4 m wide. The model ship was driven by twin propellors powered by an electric motor, and was guided along the flume by twin wires to which it was attached at bow and stern. The protective island was formed in the dry by compacting the material in thin layers so as to obtain the voids ratio expected in the prototype islands.

9.2 The impact of the ship with the beach was recorded by means of a video camera viewing through a transparent window in the side of the flume. Replaying the video recordings frame-by-frame provided information, at intervals of 1/50 second, about the movement of the ship during the impact. The position of the boat at any instant was determined from the position of two pointers on the boat relative to a grid scale in front of which the boat was arranged to pass.

9.3 A separate series of tests was also made to estimate the static resistance of the beach material during a very slow impact. A horizontal wire was attached to the bow of the ship, and used to keep it just in contact with the beach whilst floating freely. A force was then applied to the wire causing the bow of the ship to penetrate slowly into the beach. The force was increased in steps and a video recording made of the position of the ship when it had come to rest after each increase in load.

10. TEST RESULTS

10.1 Analysis of the video recordings of each test enabled measurements to be made of the speed of the model ship prior to impact, and of the horizontal, vertical and angular positions of the ship during and after the impact. The primary result from each test was the horizontal distance that the ship penetraded into the protective island, and some typical results are shown in Fig. 1.

10.2 The tests showed that the distance penetrated by a given vessel increases as its speed is increased and as the water level relative to the top of the beach is increased. It was also found that the shallower draught of the 1,000 ton ship enabled it to penetrate further than the 11,000 and 9,000 ton ships under similar conditions. As a result the crest level of the prototype beaches was increased by means of a sloping section with a gradient of 1:29; the final design of the beaches is shown in Fig. 2.

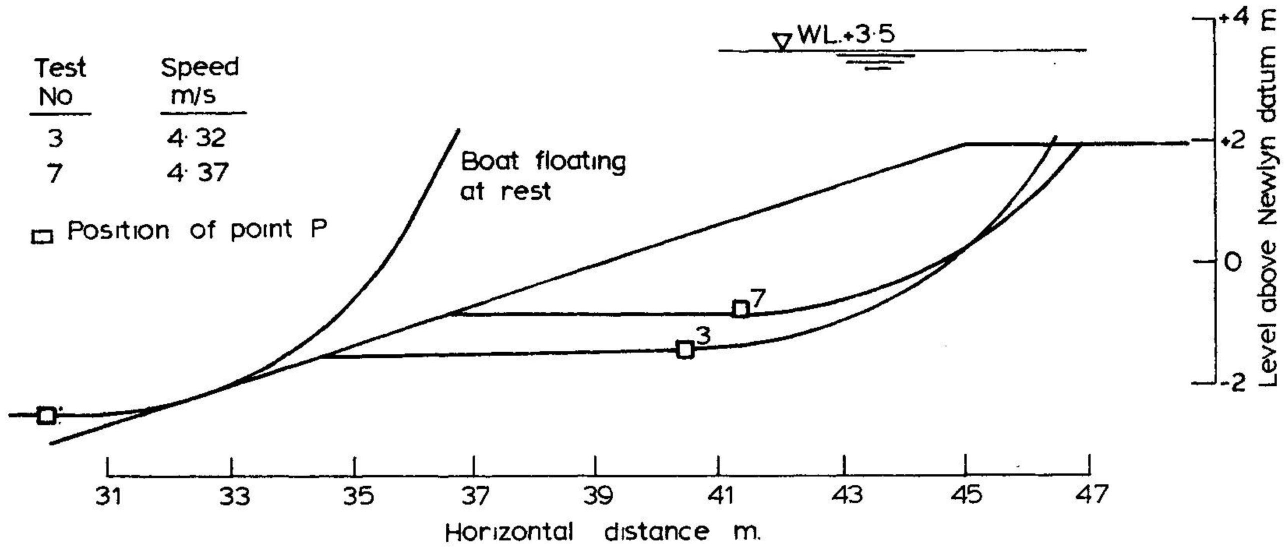

Fig. 1 Position of boat after impact 11,000 tons

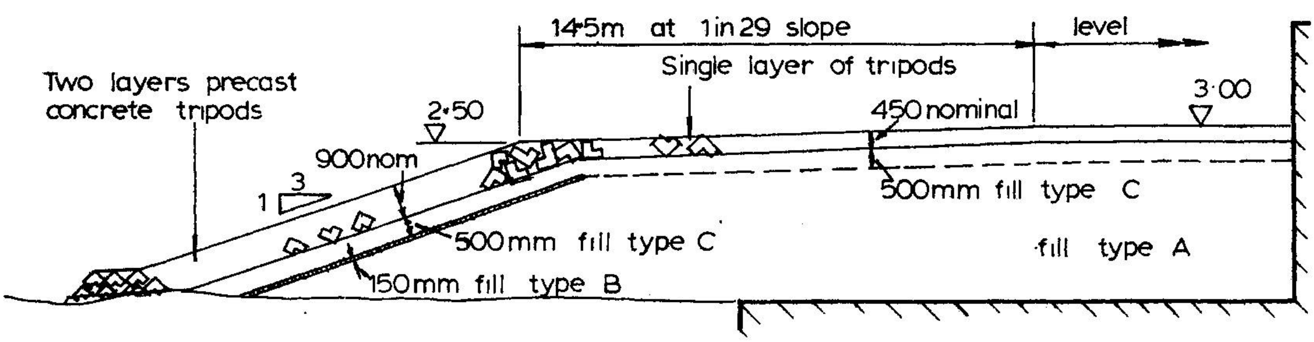

Fig. 2 Construction details of islands

10.3 The measurements were also analysed in terms of the approximate energy balance described by Eqn (1). Data from the video recordings were used to calculate the amount by which the ship was lifted and rotated by its impact with the island; knowing the cross-sectional shape of the ship then enabled $PE_S + PE_W$, the change in potential energy of the ship and the surrounding water, to be calculated (4). The results showed that, depending upon the test conditions, $PE_S + PE_W$ accounted for between about 3% and 14% of the initial kinetic energy KE_S of the ship, and that therefore the majority of the energy dissipated during the impact was absorbed by the island.

10.4 As described in 9.3 separate tests were carried out to measure the static resistance which the protective island provided to the penetration of the ship. Calculations of the work done in overcoming this resistance showed that it was equal to about 75% of the energy IE (calculated from Eqn (1)) required to produce the same penetration in an impact test. This suggests that the static resistance of the island was considerably more important than the dynamic resistance in bringing the ship to rest.

10.5 The results of the tests may be subject to some scale effects, because in the model the hull of the ship was too strong while the dynamic resistance of the material in the island was probably too high. However these two sources of error will tend to balance each other in terms of the distance that the ship penetrates into the beach.

11. CONSTRUCTION COST

11.1 The eight protective islands have been built to the arrangement shown in Fig. 2 for a total cost of £950,000. This cost includes the 45,000 precast concrete tripods used as armouring units.

12. CONCLUSIONS

12.1 The model tests confirmed that artificial islands can provide an effective means of preventing collisions between ships and the piers of a shallow water bridge.

12.2 The construction of the islands, using granular material protected by precast concrete armouring units, has been a relatively straightforward and cheap process. The future maintenance of the islands should be minimal.

13. ACKNOWLEDGEMENTS

Orwell Bridge was constructed for the Department of Transport. Consulting engineers and designers of the bridge are Sir William Halcrow & Partners, London. Model testing was carried out by Hydraulics Research Station Ltd, Wallingford, England.

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