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7693 DISCUSSION

Extension of the Tórshavn breakwaters

S. LANGVAD & T. SØRENSEN

Mr W. A. Price, Hydraulics Research Station

I am the head of the Coastal Engineering Division at the Hydraulics Research Station. The HRS in Wallingford and the Danish Hydraulics Institute have enjoyed good relationships and excellent co-operation for many years. In coastal engineering, engineers learn by mistakes or failures caused by exceptional circumstances. In either case, a study of what happened is a very worthwhile exercise. On this account alone the Authors are to be congratulated on producing such an interesting paper.

81. As Mr Sørensen has said, wave disturbance studies and wave flume studies would nowadays be conducted using random seas, the advantage being that quantitative as well as qualitative assessments can be made. However, such facilities were not available at the time of these studies. At that time the size of armour units was chosen by subjecting model slopes to regular seas, with a design wave height of a value equal to the average of one-third of all the largest waves.

82. That brings me to my first questions. In the case under discussion, why was the maximum wave height chosen rather than the significant wave height? Secondly, do the Authors think that random sea testing would have produced a larger stone size? In a random sea there would be higher waves than the ones used in the tests.

83. One point to settle in tests of this nature is the damage criterion. Should this be no damage, 2%, or some other figure. I should like to ask what the damage criteria were in this case.

84. Referring to wave measurements (§29) the Authors state 'It was felt that the chances of success of such measurements within the short time available would not warrant the expense involved'. I should like to ask whether, with hindsight, they would have made the same decision today.

85. Even during the construction of a scheme such as this there is a case for wave recording, for instance to help settle contractor's claims or as an aid in checking the design. Perhaps the Authors would comment.

Mr J. Palmer, Consultant, Rendel, Palmer and Tritton

I was delighted to learn that the design of this harbour was produced by the harbour authorities, as I am afraid that I shall have to be critical of one or two points in the design; and the Authors will appreciate that my criticisms are therefore not directed against them.

87. Mr Langvad mentioned that the cost of the breakwater was approximately £1·6 million though the Paper itself does not deal much with costs nor the tonnages of trade passing in and out of the harbour, nor any discounted cash flow calculations. Nevertheless, there was one vital economic statement in §7: 'Ships could not stay safely in the old port during south-easterly gales'. There is the complete economic

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justification! In §70, however, there appears to me to be an economic misapprehension. The statement is: '... it is considered to be normal and economically sound practice to construct armour layers of rubble mound structures in such a way that some damage will occur in the event of very rare storms' (Mr Price has suggested 2% damage per year).

88. First of all, so far as §35 dealing with quarrying is concerned, I should like to thank the Authors for giving this essential information which is frequently omitted. Bench heights in the quarry varied from 25 to 55 ft and it would be interesting to learn what percentage of 8–15 ton stones were obtained from the various blasts. Did the Authors in fact obtain a significantly higher percentage of the armouring stone from the 25 ft falls than from the 55 ft heights?

89. The second point concerns the armour-placing crane referred to in §§17 and 25. A common practice of contractors is to persuade the client that it would be better to use the crane which is available, and to adjust the design of the breakwater so that their existing crane can be used. But some contractors would never make that mistake, e.g. the breakwaters for Europort were built with two specially built floating cranes which cost £1 million each. With a specially built crane for this breakwater it would have been possible to reach far enough out to place the armour at the much safer slope of 2:1, and at the end of the job, there would be available a crane with say 50% of the cost written off against this job, and the firm owning it would be in frequent worldwide demand for building further breakwaters!

90. My third point concerns the wave height. The shape of the channel, from the open waters of the North Sea, up towards the point where the harbour is, may be acting as a funnel, and in fact the waves may be building up as they move NW from the SE. Personally, I would have designed this breakwater for a 5 m wave, plus a 33⅓% margin of safety. But it is very easy to be wise after the event.

Mr J. W. Hunter, Independent consulting engineer

I became interested in what happened at Tórshavn Harbour soon after the storm occurred. One thing that surprised me was that the tides at Aberdeen and Reykjavik in Iceland have approximately the same range. But moving northwards, the range decreases by half by Lerwick in Shetland, and almost all the tidal range is lost at Tórshavn, where the highest astronomical tide rises only to about 0·35 m. This was important when I considered the heights of the wave tops at Tórshavn. However, waves were being reported at the North Sea oil rigs of 25–30 m.

92. In these circumstances I was surprised to read that the Tórshavn design allowed only for wave heights of 4 m. If the design had been for 8 m the tops of the waves would have been above the wave screen wall.

93. This led me to wonder if the waves were hitting the wave screen wall on a vertical face. I was previously associated with a design for a breakwater where it was intended to have a small vertical face at the top mound slope. The client however would not accept any vertical face and wanted the slope right up to the top. This worked well.

94. At Tórshavn the rubble appears to have been laid without a berm at the top of the slope, and in some cases the top of the rubble seems to be higher than the wave screen wall. I wonder whether this was done purposely, or whether it just arose from the way the rubble was placed.

95. Another thing that surprised me was that there is no protection for the inside toes of the caissons. This may be quite satisfactory, but is it possible that propeller wash from ships may disturb the toe of the caissons?

96. I agree with Mr Palmer that the slope appears steep, but I appreciate that rubble mound breakwaters need fairly heavy maintenance and the extent of the maintenance can cater for the slopes being a little too steep.

97. It is mentioned that 32 caissons were built for the job; 20 are shown in Fig. 5

and with the five damaged, that totals 25. Does it mean that the other seven caissons were used in the western breakwater?

98. I am interested in the quarries, having quarried stone for breakwater purposes in the old-fashioned manner using gunpowder. What was the pattern of holes used for blasting in the quarry, and what was the arrangement of delays in detonation; also what type of explosive, quantity and strength, was used?

Mr B. E. Griffin, Griffin Mellors and Associates, Birmingham

I should like to ask two questions on the construction and project management.

100. The Paper mentions the use of a CAT 988 loader, along with open bottomed dumper barges, as the only main pieces of plant used. In repairing the breakwater, how were the displaced units moved either out of the way, or put back into their design position?

101. The second question is directed to the type of contract? If it was a fixed price contract, who paid for the extra costs of repairing the breakwater?

Mr J. S. Brindley, Binnie & Partners

I was interested that the storm which caused the damage occurred after the breakwater had been constructed to its full length. If the storm had occurred earlier, the breakwater would have been far more vulnerable to damage, because the ends presumably would have been open to attack, unless some temporary form of protection was used during construction. I would also be interested to know what form of protection the Contractor or the Designer provided during construction and what were the contractual implications of the damage which occurred.

Mr N. Rodda, British Petroleum

I should like to comment on the breakwater cross-section. It would appear that the leeward side consists of caissons providing berths for cargo vessels, and that there is a width of apron of 13 m. Is it envisaged that this quay wall will be used to work cargo, or is it a lay-by berth only? It seems a little narrow.

104. Were the caissons provided to keep the breakwater volume low? If there were no caissons presumably it would be necessary to have more sloping rockfill and I suppose the caissons save the quarried rock. Presumably the caissons do help in giving a satisfactory width for construction equipment, that is for dumpers and lorries.

Mr H. L. Wakeling, Rendel Palmer & Tritton

I should be grateful if the Authors could clarify what they mean by design wave height of 4 m. Is it the maximum wave height or the significant wave height? If it is the significant wave height, then the maximum wave which occurred during the storm, which is estimated at 6·6 m would be the maximum wave corresponding to the significant wave height of 4 m.

106. Since the breakwater design was tested in a wave flume model with regular waves of 4 m height it could be expected that the primary armour stones should have been reasonably stable.

107. On the question of the armour stones, in Fig. 4 only one armour stone layer is shown, whereas on most breakwater sections a secondary armour stone layer is provided. No details are given of the grading of the core material, but I believe it appears to be fairly coarse. Perhaps this is the reason why a secondary layer was not thought necessary. However, if it was fine, perhaps the reduction in porosity underneath the primary armour layer may have contributed in some measure to the failure.

108. Can the Authors comment on the exact mode of failure? It seems that most of the failure has been attributed to waves overtopping the wave wall and causing erosion behind it. Can the Authors say how much damage was caused to the armour layer where the section was completed and erosion did not occur?

DISCUSSION

Mr G. W. Morrey, Binnie & Partners

I should be interested to know whether the Authors made any allowance for a rise in sea level due to the large wind forces from the south east, making for us in Southern England a negative surge. Further, I should like to know whether they made any estimate of the amount of overtopping, because it seems that lifting the armour stones over the top of the wave wall and depositing them behind must have required a great deal of water. Were any armour stones carried right over the wall and deposited where vessels would have been lying? If there were small vessels lying alongside, they might have been in some difficulty, and the crews would be in danger of their lives trying to reach the vessels.

110. In view of this, would the designers have chosen a higher wave wall? The cost of raising the wall even an extra metre would be relatively small compared with the cost of the breakwater foundation itself.

Mr D. L. Pope, Frederic Harris & Partners

My question is psychological rather than technical. In my experience, whenever one goes to construct harbour works, the local population is very keen to tell you that the breakwater is in the wrong place, or in the wrong orientation. In view of what happened before the breakwater was completed, what was the reaction of the local population? Was there a howl of protest?

112. On the question of wave heights, the 100 year wave of course always occurs either during the construction period or within six months of a work being completed. The next 100 year wave must occur sometime during a 100 years, but it is bound to appear during the 5 year period one is concerned with!

Mr M. R. Clarke, Charles Brand & Son Ltd

I should be interested to know whether the caisson bed was prepared by the divers, for the whole length of the breakwater, or immediately ahead of the next caisson to be placed, and what method was used for the clearing work? Lastly, what was the method of towing and lowering the caissons into position?

Mr P. Ackers, Binnie & Partners

The Authors deserve thanks for presenting a Paper which frankly admits that the works suffered unexpected damage, and any questions at this stage come from those who did not have the responsibility for preparing an economic design on the basis of the limited information available at the time.

115. My remarks arise from an analogous case concerning the slope protection of the east cofferdam at the High Island water supply project, Hong Kong. The site is similarly situated in that it is part way along a narrow inlet like Nolsø Fiord. The High Island site is also very exposed, as it faces directly the South China Sea, a typhoon area. The rough similarity naturally leads to comparisons.

116. At Tórshavn the breakwater was designed for gale-generated waves that were 25–35% of those at the entrance to Nolsø Fiord. Although each case is dependent on local bed topography and water depths, this appears to be a large reduction and it would be of interest to learn whether this was a result of special features of topography or bed roughness. The reduction factor for shoaling and friction applied to the High Island design was not so low, being about 0·6. Refraction there was difficult to assess, because it was judged that although the offshore bed topography would tend to refract some wave energy to the sides of the inlet, there could also be reflexions from steep rocky shores that could reconcentrate energy. No additional reduction for refraction was therefore made in assessing the design wave height. Have any records been obtained at Tórshavn that elucidate the reduction of wave height in such an inlet? Have any concentrations of wave energy due to the configuration of the coast line and its steep shore line been observed?

117. Comparison may also be made with the information in the recent publication of the Department of Energy giving guidance on the design of offshore structures.[1] The Faroe Isles are near the edge of the areas for which wave heights are recommended. These recommendations are based on studies by the National Institute of Oceanography following observations from weather ships and other sources. It may be significant that according to these guidance rules, offshore installations in the area should be capable of withstanding 33 m waves.

118. The Paper describes how the damage to the breakwater became serious because of failure of the back slope. This also proved to be an important feature in the High Island scheme which is designed to be overtopped by waves when mean water level is elevated above normal high tide level by a surge. Was there any abnormal increase in sea level at Tórshavn during the January 1972 storm? A storm surge can give more severe attack because the increased water depth allows a greater proportion of wave energy to reach the structure.

119. The Authors state that if they were dealing with a similar problem with today's laboratory facilities they would use irregular rather than uniform waves. This is especially important where overtopping is involved because it is the largest waves in the spectrum that are the most damaging on the back-face, with their much greater than average volume of overtopping.

120. The Authors' opinion on the desirability of ventilating a crest block on a permeable breakwater would be valued. Was any such provision considered necessary with the final design of wave screen? What criteria determined the ventilation shown on the concrete apron in Fig. 4?

121. The Paper is a valuable addition to the literature on the design of coastal structures. Useful lessons are to be learned from the experience of others in carrying out such difficult projects economically.

The Chairman, Mr P. A. Cox

It would be useful in understanding the mechanism of damage to the breakwater if the Authors could state the alignment of the waves relative to the breakwater.

123. Reference was made to the question of porosity of the core, but the Paper contains no reference to the fine material being removed from it. It is usual to take out the fine material, and if this was not done in this case, it could have affected the porosity.

124. Were any special precautions taken at the quarry other than delays between explosions to limit the amount of vibration of the house?

125. The thickness of the caisson walls is 250 mm on the outer face. Did the Authors have to make any allowance for the effect of ice on the caisson walls? Also, was freezing of the seawater a problem that has to be taken into account in considering the ventilation of the breakwater?

126. The Authors say they launched the caissons in such a way that they took in some water to avoid pumping it in. This seems a brave system to adopt. Were any model studies made to determine how much water would be taken in during the launching?

Mr Langvad and Mr Sørensen

In reply to **Mr Palmer**, the production of the large stones took place in the quarry with the 55 ft bench height. Here the quality of the rock was superior. The drilling pattern was $2{\cdot}25 \times 2{\cdot}25$ m^2 and two rows of holes were ignited in each blast. Each hole had different delay detonators: the hole in the foremost row detonated before the hole immediately behind in the second row, thus establishing a diagonal front in the bench.

128. The amount of explosive was 0·3–0·4 kg/m^3. The types used were fabricated in Norway, one-third Dynamite (60%) and two-thirds Geomit (10%).

129. Mr Palmer's remark about how to get the client to pay for a costly crane

was interesting indeed. We must admit that we have not been able to accomplish such a deal. In this case the result would have been that no breakwaters would have been constructed in Tórshavn—remember, the work had to be paid for by only 40 000 people.

130. Referring to § 97, Fig. 5 does not show the breakwater as built. The following summer it was extended by four more caissons and one of the partly damaged caissons was used on the ocean side of the breakwater head. Seven caissons were used on the western breakwater and four were damaged beyond repair.

131. In reply to **Mr Griffin**'s queries, the displaced caissons were emptied of stones by a KL-250 crawler crane (equivalent to a RB-30) using a clamshell. Then the caissons were floated and dragged to the correct position.

132. The contract was a fixed unit price contract based on the actual quantities, with an escalation clause. The works were covered by a 'CAR' insurance, the Owner, the Engineer and the Contractor all being insured. All the cost deriving from the January storm—amounting to 2·5 million Danish kroner—was paid by the insurance company.

133. **Mr Brindley** has asked about protection to the breakwater. During the construction of the breakwater the best protection we could obtain was to place as many large stones as high as possible on the ocean side of the breakwater. Before the onset of the last winter we placed two caissons (nos 19 and 20) provisionally to protect the open end.

134. As to the width of the breakwater remarked on by **Mr Rodda** it must be remembered that it is intended primarily as a breakwater and the amount of goods going into and out of the harbour is limited. The caissons were provided to obtain berths for cargo and fishing vessels.

135. Replying to **Mr Clarke**, the bed for the caissons were prepared by divers immediately ahead of the next caisson to be placed. The divers were assisted by a KL-250 crawler crane working from the end of the breakwater. The caissons were towed by different fishing vessels from the launching site and were lowered at their final position by waterfilling.

136. **Mr Cox** asked about precautions during blasting. When considered necessary the bench was covered before blasting by used fishing trawls.

137. There are no icing problems in Tórshavn. Cold winter weather usually lasts for only a couple of weeks and does not have any significant influence on the temperature of the Atlantic. No model studies were made—only to a 1:1 scale at the site. The solution adopted was reached gradually through experience.

138. We were dealing with a major piece of work which cost a great deal for a very small population. The work was carried out in different circumstances from those which prevail today in relation to feasibility and availability of measuring and testing methods, including experience.

139. **Mr Price** asked whether we would do the work in the same way today. Of course we would not. As to wave heights, the 4 m mentioned in the Paper is the maximum wave height, and the significant wave height is lower. It is a small figure, but how it was arrived at has been described in the Paper on the basis of some very crude reasoning, and why this was not gone into further at the time is also explained in the Paper. There was the additional reason that this is not the first breakwater that has been built at Tórshavn. This gave us a full-scale model test, and it may be of interest that the first evaluation of the wave heights to be used for the design was so significantly higher that we could prove that the existing structure could not exist!

140. Strong emphasis was put upon reconciling our theoretical work with almost 20 years' practical experience which had been gained with the existing structure, and wave measurements are currently made on recent and smaller jobs than this. Wave recording should continue during construction.

141. With regard to the armour layer, it may not be clear from the Paper that

the damage to the armour layer as such was not crucial. It has been suggested that the armour layer should have been more solid, but basically the damage to the uppermost part of the armour layer was in the same places as the other damage. Which came first or last is uncertain but there is a connexion. At least a significant part of that damage arose from the combination of the flows of water under the wave wall that were caused when the water behind eroded the fill.

142. Essentially the armour layer stood up to the conditions. There was damage, and that damage to some extent could have been avoided if there had been larger stones. But then again, in the opinion of the local people and in the opinion of various other people concerned, the damage was not any greater than was acceptable as a very rare occurrence. In other words, it is a maintenance problem.

143. The refraction of wave energy from the sides of fiords with steep slopes does occur in various places in the Faroes, but from aerial photographs it appears that the conditions have to be unique for the refraction to be of any significance. In this particular case the fact that the direction of approach was almost parallel to the shore reduced the action of refraction.

144. **Mr Hunter** mentioned the berm at the top. The design provided for this, but it does not appear in the photographs. As to protection of the inside toe, experience had shown with the existing part of the breakwater (which had been used extensively by shipping), that when fill was made from quarry run rock, such protection was not necessary.

145. In **Mr Morrey**'s comments the question of overtopping and the throwing of stones over the wave wall was mentioned. There would be no question at all today that one would build such a breakwater after having studied it in random seas. There is a certain risk of armour stones being washed over the wall, as they were in this particular case, but they did not reach as far as the inside face. This happened on the existing breakwater also, but never to the extent of damaging ships.

146. To raise the wall by 1 m would have been possible, but it would have increased very considerably the overturning force on the wall, so it would have increased the cost, especially if it were done without raising the entire seaward slope correspondingly, and this could not be done very cheaply.

147. As to the reaction of the local population, in this particular case it was not so much one of saying 'We knew all along this would happen', but rather 'This was extremely unfortunate in unusual circumstances'.

148. **Mr Ackers** talked of a reduction coefficient of 50 to 60% in Hong Kong. but said he had not taken refraction effect into account. If this is so, there is no disagreement between our figures. A 60% reduction, if this is so, would be almost the same as the coefficient of reduction we used.

149. The design wave height of 33 m at the Faroes is probably a high figure, but compares with the design wave height which is intended for the investigation of offshore structures. The disaster that occurs when an offshore structure is damaged or destroyed with people on board, etc., is totally different from what happens when a few stones in an armour layer rush into the sea. This is a very important element in the selection of design wave conditions. There is little point in ventilating the wave wall under these conditions.

150. As to the porosity of the fill, this was investigated during the initial stages when a special investigation was made of the grading of the core rock that would come from blasting in these sites. We did try to reproduce the porosity in the mole.

Reference

1. Department of Energy. *Guidance on the design and construction of offshore installations.* London, HMSO, 1974.