2009

The Sea versus Wick Breakwater 1863-77 – an instructive disaster

Roland Paxton Prof Dr, School of the Built Environment Heriot-Watt University
Vice-chairman ICE Panel for Historical Engineering Works

Introduction

Wick [Breakwater], *the chief disaster of my father's life was a failure; the sea proved too strong for man's arts: and after expedients hitherto unthought of and on a scale hyper-cyclopean, the work must be destroyed, and now stands a ruin in that bleak, Godforsaken bay.* [Robert Louis Stevenson. *Memories & Portraits*, Chatto & Windus, London, 1887.135][1]

In this paper the project and its sea damage failure mechanisms are identified from unpublished and other primary sources and reviewed in an historical engineering context. Repeated damage led to the loss of nearly one-third of the length of the breakwater in 1870, with abandonment following destruction of its 2642 t composite replacement end in 1877.

In the 19th century Wick was for a time the largest herring fishery in Europe. Its development progressed rapidly from 1807 when the British Fishery Society planned and laid out the model settlement of Pultney Town with its two harbours engineered by Telford [Figure 1].

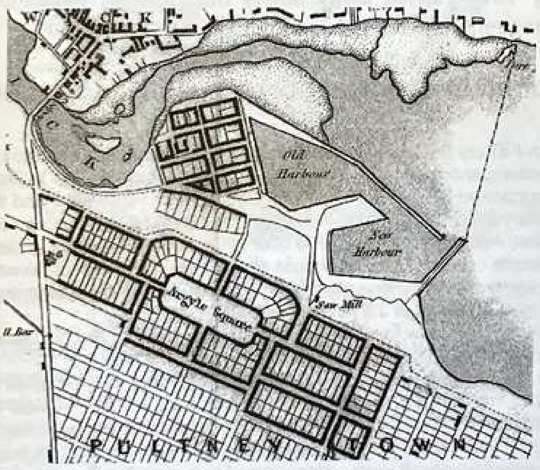

Figure 1. Wick harbours 1832[2]

The old harbour was completed in 1811, but its capacity soon proved insufficient. The new or outer harbour constructed from 1825-34 was achieved with great difficulty against the force of the sea during storms by ingenious contractor/civil engineer James Bremner[3] - a precedent perhaps insufficiently appreciated by Thomas Stevenson four decades later.

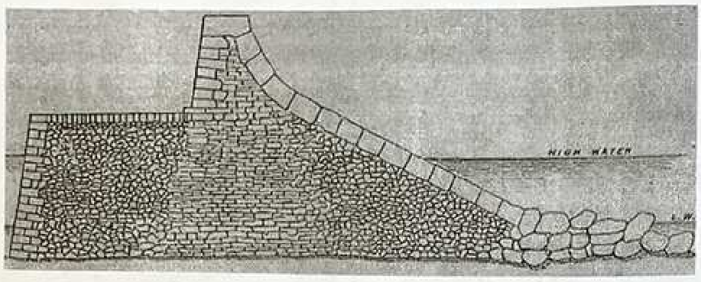

Figure 2. Cross-section of South Pier outer harbour[4]

The outer harbour is protected by Bremner's substantial South Pier 9.8 m high [Figures 2&3] later extended. This pier comprising vertical and inclined coursing and founded just below low water on a wide base has survived many gales, but often suffered damage to the roadway, hearting, and inner wall from water falling from a great height after wave impact.

By 1858 the fishery had 'vastly outgrown' the capacity of the harbours[5], from which more than 1000 boats were fishing in 1862. In 1857 the British Fishery Society proposed extending the harbour by a canted pier [Figure 3 - ABC], a proposal overtaken by an ambitious Royal Commission on Harbours of Refuge scheme for a breakwater, founded 3.7 m below low water on rubble at about the 7 fathom [12.8 m] bed contour[5], which came to nothing.

In 1861, a compromise was approved for a third harbour protected by a breakwater 457 m long located between the proposals of the Society and Commission [Figure 3][5,6,8] . The breakwater was designed for the Society in 1861-2 by leading engineers D. & T. Stevenson of Edinburgh. It was begun in 1863 but had no prospect of completion after a south-easterly storm in February 1870 carried away nearly one-third of its length at the seaward end. Further major damage in 1877 led to abandonment after a total outlay of about £132,000.[9]

Chronology of main events at breakwater and recorded data

1861	The British Fishery Society obtained a harbour/breakwater proposal from D. & T. Stevenson.[9]
1862 Aug	Plans, sections and specification drawn up for the Society by D. & T. Stevenson for the Fishery Society[6] supported by engineers Sir John Coode, John Hawkshaw and the Admiralty gained parliamentary approval. £62,000 loan approved by A.M. Rendel, Engineer to Public Works Loan Commission. Acceptance of £105,000 offer by Messrs. Macdonald (Glasgow) to carry out the work.[9]
1863 Apr	Planned length - shore to new lighthouse at end - 460 m + inner breakwater. Construction began.[6,8,9]
1864 Oct	91 m of staging carried away – greenheart timber substituted for memel piles – walls founded on top of rubble base at a level of 3.6 m below low water .[8]
1867 Oct	Length 250 m. Walls now founded 5.5 m below low water. Rubble base now extended to 326 m.[8]
1868 Sept	Greatest length of completed breakwater reached – 320 m.[8]
1868 Oct	A 75 m length partly demolished by the sea. Rubble base washed down to 4.6 m below low water.[11]
1870 Feb	Seaward 116 m length destroyed to 1.5 -1.8 m below low water. Waves 12.8 m from crest to hollow during 3-day storm. Materials and workmanship not at fault being throughout of 'superior' quality.[9,10]
1870 Oct	A 55 m length now rebuilt to new composite end – overall length 259 m instead of 480 m planned.[10] Parapet omitted on rebuilt work – stepped end to remainder. Top rebuilt in concrete – full breadth now coursed work. Sea end face vertical. Introduction of large concrete blocks tied by iron bars.[10] Storm as severe as in February 1870 - waves 6 m high and 80 m apart with a velocity of 36 kph.[10]
1872 Feb	Face stones shattered by sea – 'unparalleled'.[8] Waves about 9 m high - spray about 60 m high.[12]
1872 Dec	Replacement composite concrete and stone end of 1372 t demolished. Resident Engineer M'Donald saw it 'slewed round by successive strokes until removed and deposited inside pier - foundation 10 feet below low water uninjured'. Followed by destruction of adjoining 46 m length 'of solid structure set in cement'. Water 7.6 - 9.1 m deep passing over parapet + 8 t & 10 t stones.[8,11] [Figures 16-20]
1875 Nov	Breakwater 252 m long (from shore high water mark).[10] [Replaced by heavier concrete end in 1873]
1877 Jan	Sea demolition of 2642 t end - adjoining length destroyed in storms. Project abandoned in August.[13]

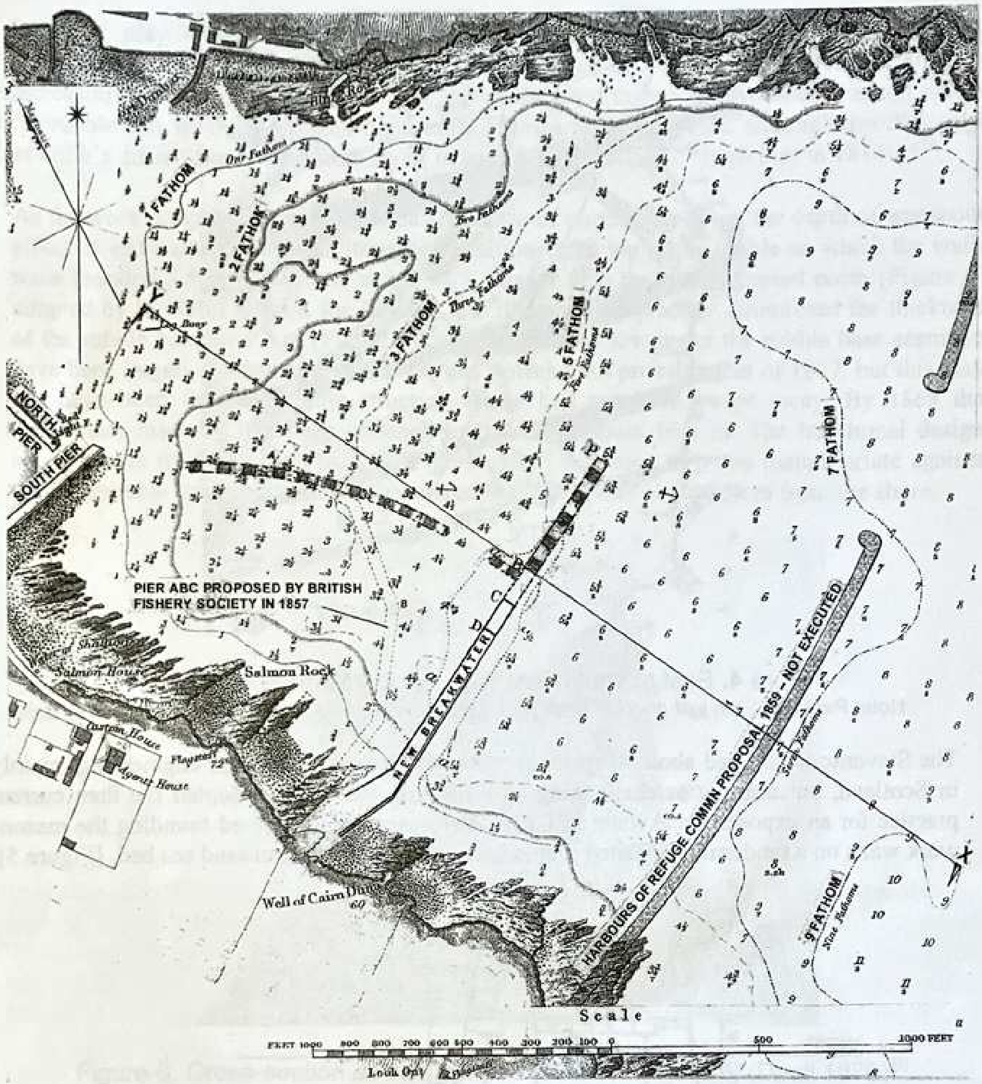

Figure 3. Composite plan of D. & T. Stevenson breakwater as built [5,6,8]

Key:
- A Outer limit to which rubble base formed – dotted line 'a' shows 1870 extent
- B Greatest length of superstructure actually built [320 m]
- C End of 1871 reconstruction and 1873 restoration. February 1870 breach point
- D End of breakwater left standing after 1872 storm destruction [Figure 17]
- P Length planned in 1862 + inner breakwater (wide broken lines - unexecuted)
- X-Y Line of longitudinal section along Wick Bay [Figure 20]

Design considerations

Thomas Stevenson, about to publish his text-book on the design and construction of harbours, was aware that Wick was an exposed site with a fetch of several hundred miles. Applying his soon to be well-known approximation for maximum wave height (w) in strong gale conditions = $1.5\sqrt{d}$ (the fetch [Figure 4]) he would have expected waves of 7 - 9 m.[4]

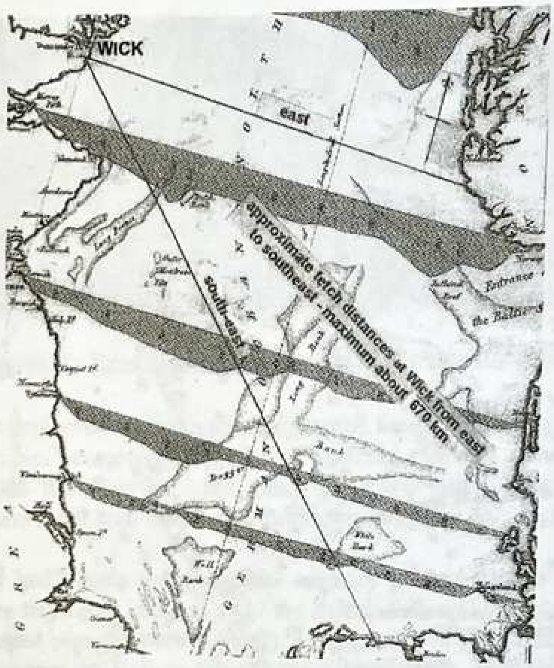

Figure 4. East to south-east fetch across North Sea to Wick[14]
Note: Pentland Firth just north of Wick with tidal currents of up to about 22 kph each way daily

The Stevensons had had about 40 years previous experience of harbour engineering, mainly in Scotland, but nothing as challenging as Wick, for which they adopted the then current practice for an exposed breakwater in fairly deep water. This involved founding the mason-work walls on a randomly deposited rubble base resting on the clean sand sea bed. [Figure 5]

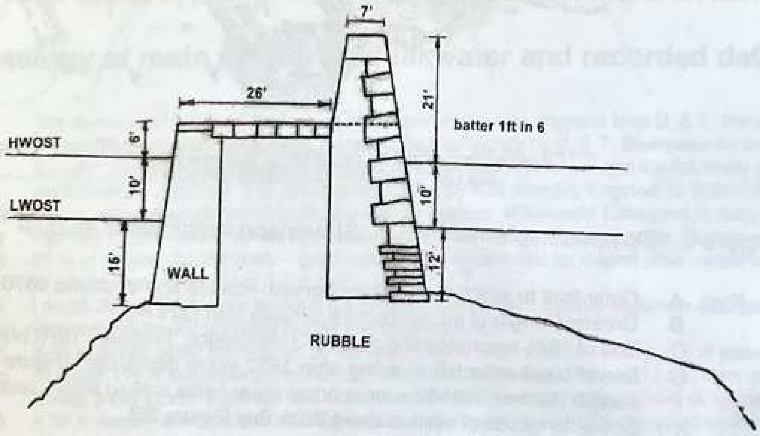

Figure 5. D. & T. Stevenson 1862 cross-section 268 m from shore (1862)[6]
NB Tidal range (m) 1984-9: HAT 0.0; MLWS +0.7; MLWN +1.4; MSL +2.0; MHWN +2.8; MHWS +3.5[7]

Thomas Stevenson knew from his pioneering experimental work on wave force in the 1840s[15] that as the solum of the breakwater was more or less on the 5 fathom bed contour, it would encounter maximum wave pressures at times of about 325 kNm^2, normal or nearly so to its face from waves more or less parallel to its line. However, he had little idea how the forces at play would vary with depth, different angles of impact, and wind strength. Stevenson was aware that the wall would be subjected to a horizontal hydrostatic pressure increasing in strength with wave height and of the need to prevent hydrostatic action within the rubble core by means of leak-tight joints. He was probably aware, although insufficiently, of Gibb's difficulties arising from scour in completing Aberdeen North Pier in 1814-15[16].

As the work progressed out into the bay, because of uncertainty about the depth of any scour effect of wave action, D. & T. Stevenson positioned the top of the rubble on which the walls were founded 5.5 m below low water, 50% deeper than the then accepted norm [Figure 5] adopted by Sir John Rennie, the Rendels and others.[8] This practice diminished the thickness of the rubble base to 3.7 m [Figure 6]. At 5.5 m below low water the rubble base seems to have been largely undisturbed by the various storms until probably that of 1877, but this may not have been the case if the structure above had not been swept away. By 1868 the breakwater masonry had been widened by 1.7 m to about 16.3 m. The traditional design adopted with its 4.6 m high parapet [Figures 5&6] was soon to prove inappropriate against the exceptional sea conditions it encountered beyond a point about 150 m from the shore.

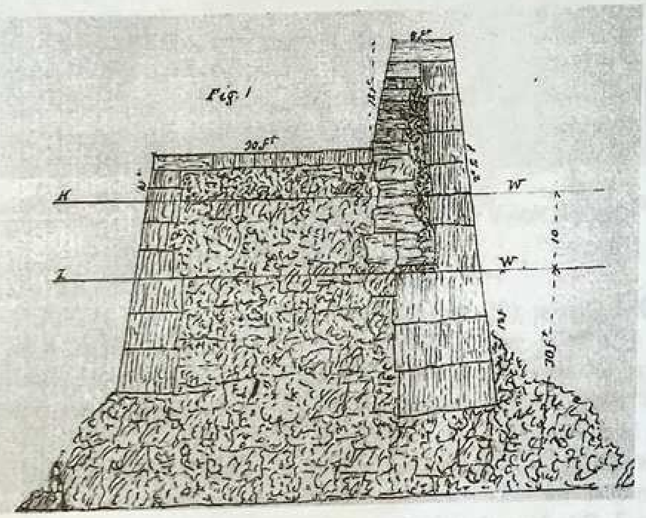

Figure 6. Cross-section as built by1868 [at 'D' on Figure 3] (Doull 1870)[10]

Construction

The rubble base consisted of large stones from the adjoining South Head quarries [probably similar to those shown in the foreground of Figure 16], transported by railway [Figure 7] on to an open timber staging on the line of the pier to the required discharge point and deposited. The top of the staging, supported on long greenheart piles from the bay bed, was about level with the top of the parapet. The tipped stones comprising the base were allowed time to be spread by the sea and form stable natural slopes before the walls were founded on it.

By 1870 the mound occupied the area indicated on Figure 3. Two small steam locomotives were used to haul wagons carrying the stone and other materials [Figure 10]. At the seaward end of the staging, travelling timber gantries or 'travellers' running on rails were erected, on the top of which 'Jenny' cranes moved transversely – an operation which fascinated the young R. L. Stevenson when working on site in 1868.[1] This efficient method of operation, probably its first use in Scotland on such work, was influenced by J. M. Rendel's earlier adoption of it from 1838.[8] The walls consisted of flagstone blocks from 5-10 t set on edge slanting with a 1 in 6 batter [Figure 8&15], a practice in which Stevenson was probably influenced by that of Bremner in building South Pier and Gibb and Telford at Aberdeen North Pier. It was impracticable to joint blocks under water, but above high water they were set in Roman and later Portland cement. Working operations are shown in Figures 7-10&14.

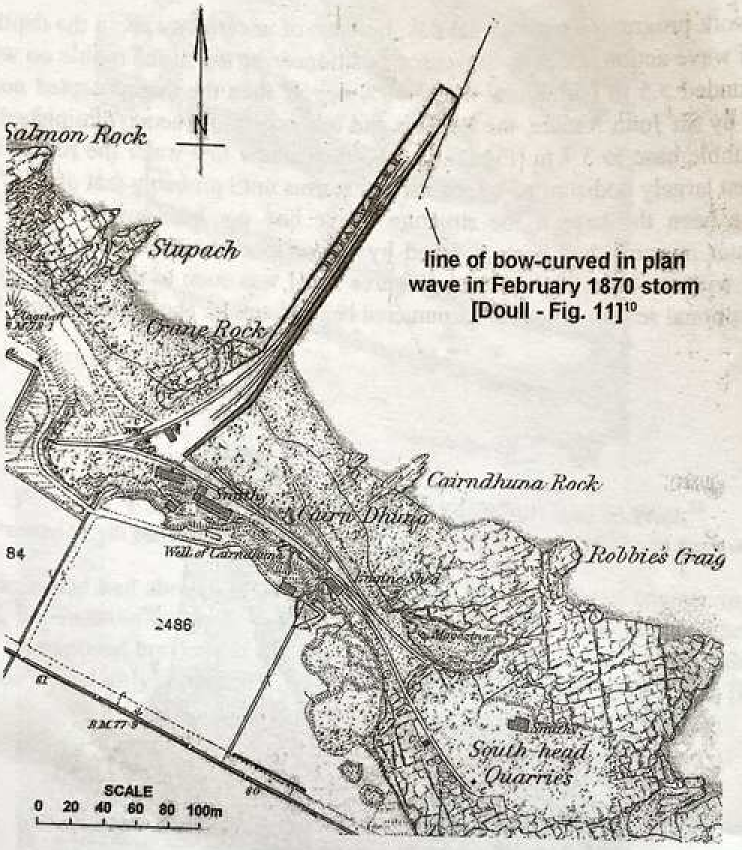

Figure 7. Site layout, quarries, railways in 1872 [Ordnance Survey 1/2500]

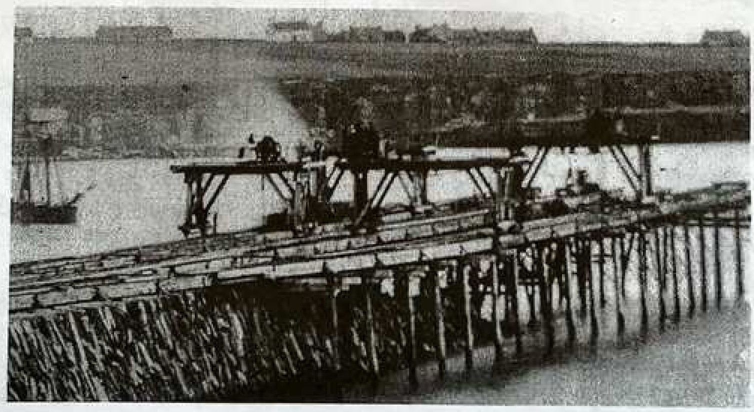

Figure 8. 'Travellers and jennies' in 1865 ©The Wick Society[17]

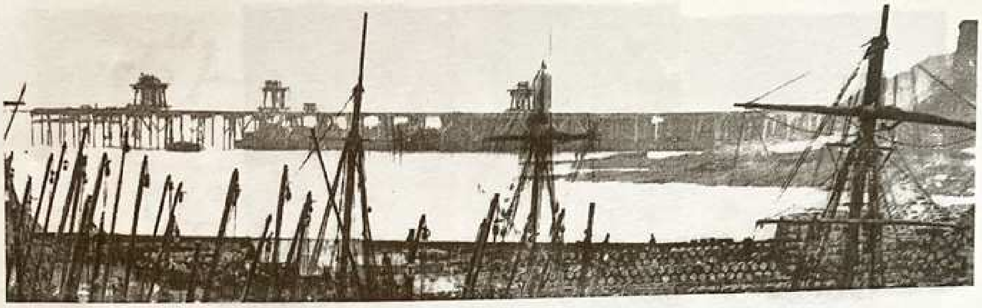

Figure 9. Progress by 1865 - four 'travellers' in operation ©The Wick Society[17]

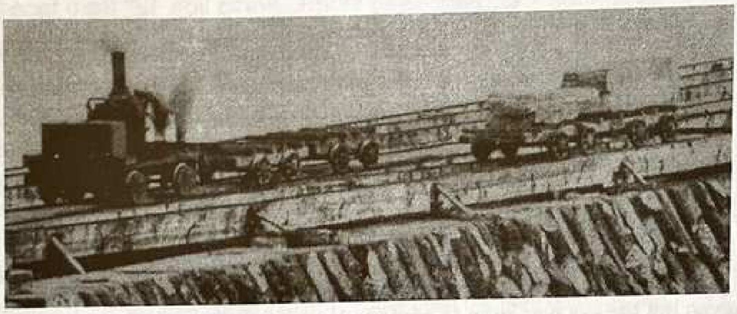

Figure 10. Materials haulage in 1865 ©The Wick Society[17]

Failure and remedial expedients

In 1870 an experienced Alexander Doull (Associate ICE 1845-72), possibly employed by the contractor, gave an invaluable description of the action of near 6 m high waves in the February storm, noting that the horizontal line of each is curved across the bay with its bow front providing the "first and most severe blow" to the outer end of the work "as it had to cut the advancing wave asunder [Figure 7]. The portion of the wave separated and passing up the bay would expand laterally the moment it had passed the parapet wall and [the portion projected upwards] fall down with considerable fury upon the end of the quay roadway."[10]

Doull continued, "Figure 2 [Figure 11] is a plan of the outer end of the work as left by the storm. The quay wall being cut away 20 ft [6 m] farther than the outer wall topped by the parapet bears out the (above) remarks . . . greatly accelerated by the heavy timbers of the staging which were built into the quay wall . . . acting as powerful levers in carrying away the front of the roadway leaving the hearting unprotected. When a wave struck heavily against the outer angle of the wall, the water rose about 20 ft [8 m] high and the portion kept ran backward along the face of the wall and increasing in height as the wave [in Figure 11] fed up to the wall. Frequently, when this wave reached the wall and came into collision with the wave running at right angles [about 75°] to it, a considerable body of water was projected to a height of about 60 ft [18 m]. This did not appear to affect the outer wall to any extent. But the earliest symptom of destruction was effected by the mass of water projected over the wall and carrying away considerable portions of the staging and of the front of the quay wall, thus leaving the hearting exposed to every successive downfall of an immense body of water from a great height . . . the first breach was at or near the spot where the staging was carried away . . . about the centre of the work destroyed [116 m in length] . . . the rubble base 18 ft [5.5 m] below low water is said not to have been much disturbed."[10]

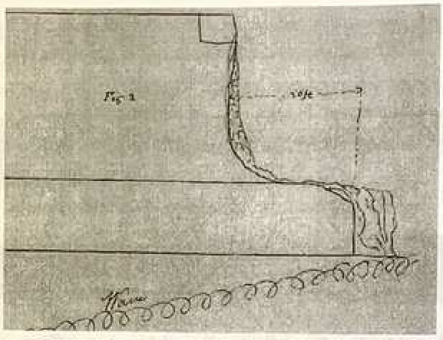

Figure 11. End after February 1870 storm - wave line 12° from face [Doull][10]
Waves at other times parallel to face but curved in plan to 5°-9° at landward end[8]

The D. & T. Stevenson response to this failure was to modify the breakwater length to just over half that planned and rebuild a 55 m length without parapet with a novel monolithic end. John Hawkshaw and the firm reported jointly to the Fishery Society on remedial work.[18] In an attempt at more homogeneous construction this end comprised 3 courses of 80-100 t blocks deposited in a shallow trench in the rubble surmounted with in-situ mass of rubble concrete measuring about 7.9 x 13.7 x 3.4 m thick, weighing more than 800 t. This was secured to the foundation blocks by 90 mm diameter iron rods, passing through holes in 3 intervening courses of flagstone - a combined mass of 1372 t [Figures 12 & 13]. The new end was achieved but the sea was soon to exploit planes of bond weakness at the back and below.

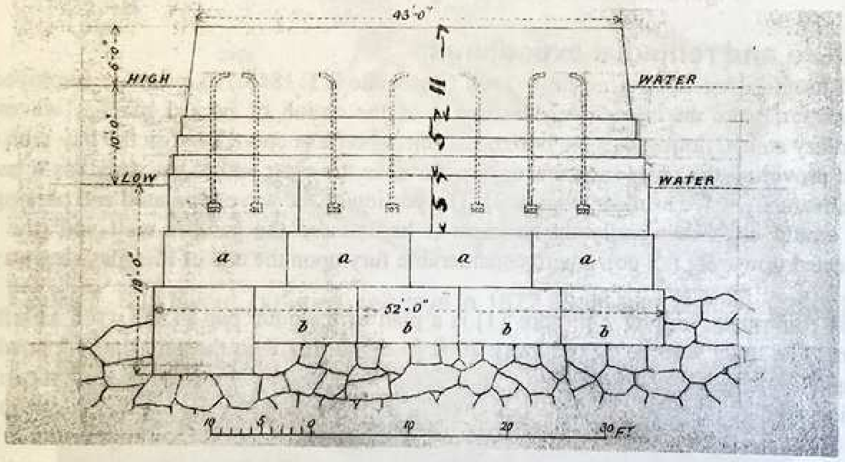

Figure 12. Original drawing of end elevation 1870-72 [Stevenson][19].
[a - concrete blocks removed by sea. b - not moved by sea]

This use of massive pre-cast Portland cement concrete blocks was innovative. Dimensions varied but a large block measured 1.7 x 4.0 x 6.7 m. A mix of 1(cement):7(sand/stone) was used. The blocks were made on 12 platforms 0.6 m above low water and transported to the rubble by a specially made pontoon with corner winches [Figure 14] with final placing by divers. The weight of this block was 1002 kN in air and 544 kN in sea water. This near halving of weight under water was an experience in which trainee engineer R. L. Stevenson revelled when diving. He also noted a block being accidentally lowered on to a diver's foot![1]

Figure 13. Longitudinal section 1870-72 end [Stevenson][19] [Plan area about 120 m^2]

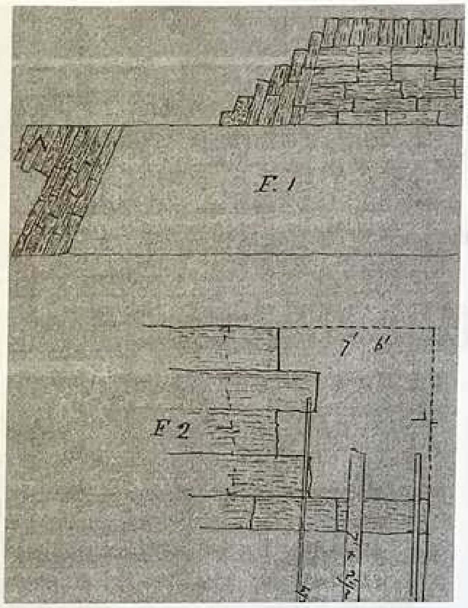

Figure 15. October 1870 end [Doull][10] [the main bar bent upwards was 178 x 64 mm]

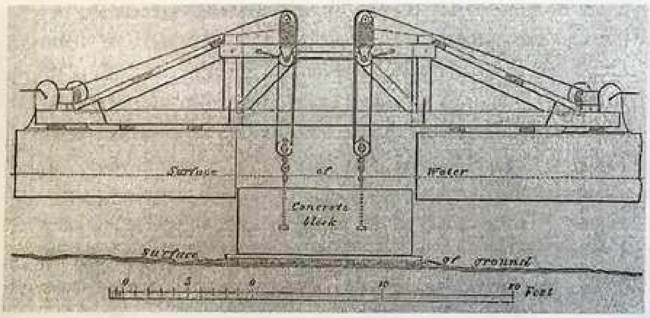

Figure 14. Lowering concrete block from pontoon [Stevenson][8]

Doull's sketch [Figure 15] shows the new stepped parapet end standing firm and four courses held by the ironwork at 'A' after an October storm. His plan below F2 shows the torn off corner of the breakwater exposed to the full force of the waves. He noted that "the fractured ends are bent up proving that the blow was upwards". The destruction of the parapet was "prevented by its sloping end which deflected the waves and it is probable that had the end of the work been sloped in a similar manner it would have resisted the violence of the storm".[10]

In December 1872 the 1372 t end block and 46 m of adjoining breakwater were swept away by the sea [Figure 16]. This work was replaced in 1873, with the bolts extended to course 'b' [Figure 12], the whole end now weighing 2642 t. In a January 1877 storm this replacement too was displaced and broken into two pieces, followed by destruction of the adjoining length including the stepped parapet end. It was not until July that the sea was sufficiently calm for divers to do a thorough inspection after which the project was formally abandoned.[13]

Figure 16. Detached end from North Pier Spring 1873? ©The Wick Society[17]

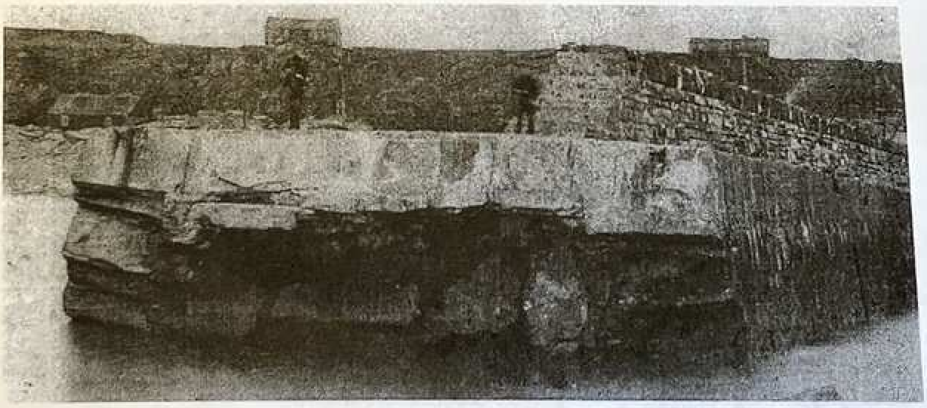

Figure 17. Stump end after December 1872 storm ©The Wick Society[17]

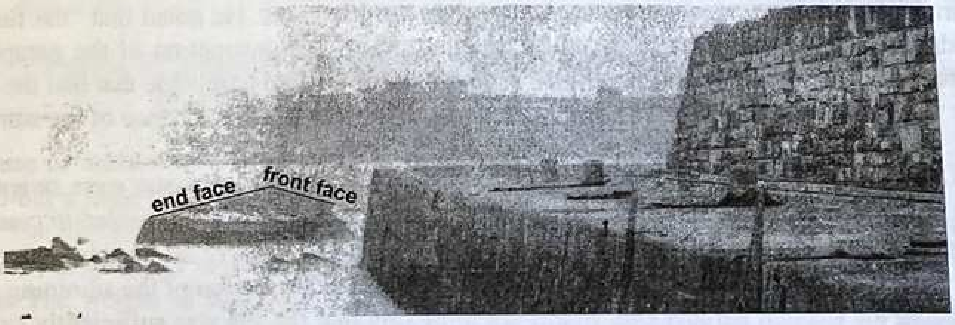

Figure 18. Part of detached end after December 1872 storm. ©The Wick Society[17]

about 290 kNm^2 slewed and removed the 1372 t end pivoting it about the northwest corner of the stub. In 1877 the pressure carrying away its 2642 t replacement was about 340 kNm^2. Horizontal resistances were about 110 and 200 kNm^2 respectively.

The failures are attributable to the inadequacy of the traditional design used. Wave effects during east and south-easterly storms were exacerbated by the long fetch, Pentland Firth currents, the bay's funnel layout and the breakwater's height and line on the 5-fathom bed contour nearly parallel to the waves. If the breakwater had been of uniform construction throughout down to the sea bed its resistance to wave pressure would have been significantly greater.

The failures from 1868 added to a growing awareness in breakwater practice for new structures where practicable to be of strong homogeneous construction down to the sea-bed and designed to meet the site's conditions including wave and scour effects. The use of Portland cement concrete was a significant contemporary development as exemplified in Cay's surviving Aberdeen harbour entrance built 1870-77 using massive blocks and in bags under water.

A new sustainable Wick breakwater was probably practicable from 1877 but at high cost.

References

1. As p.1. R. L. Stevenson was a trainee at the breakwater from 28 August 1868 for 40 days.
2. House of Commons. Great Reform Act Plans and Reports - Wick, London, 1832.
3. Mowat J. *James Bremner – Wreck Raiser*. Wick, 1973.
4. Stevenson T. *The Design and Construction of Harbours*. Edinburgh, 1864. Pl. IV, 21.
5. *Report to Commissioners on Harbours of Refuge*. HMSO, London, 1859. 205, pl. 6.
6. Stevenson D. & T. Ms. 'Pulteney Harbour. General specification of works proposed to be executed by British Fishery Society', 8 August 1862. NAS. PHP 145000/8/663.
7. *Admiralty Tide Table Volume 1 2002 United Kingdom & Ireland*. UKHO, Taunton, 2001.
8. Stevenson T. Op cit. 2nd ed. 1874, 45-47, 213-214, pl. XI. 3rd ed. 1886, 36-37.
9. Nicol R.G. [Aberdeen Harbour Engineer and consultant]. Ms. Report dated 12 April 1915 appended to Harbour Trustees Minute Book. 537-542. North Highland Archive, Wick.
10. Doull A. Ms. Draft unpublished ICE paper 1278 'Description of the partial destruction of the new harbour works in Wick Bay.' Wick, 28 February 1870. Addendum, November?
11. Stevenson D. Discussion contribution. *MPICE*. **XLIII.** Session 1875-6, pt. I. 38-42, 52.
12. Stevenson D. & T. Report to British Fishery Society 5 March 1872. NLS. Acc.10706. **40**.
13. Ibid. Ms. 11 August 1877. NLS. Acc.10706. **48**. 579-81.
14. Stevenson R. *Edinburgh Philosophical Journal*. **III**. Edinburgh, 1820. pl. II.
15. Stevenson T. 'Account of experiments on the force of waves'. *Proc. RSE*. **XVI**. 1849. 23.
16. Telford T. *Life of*. London, 1838. 129. AL. Falkirk Arch. Callendar Ho. GD171/1020/13.
17. From The Wick Society's A. Johnston collection of mainly unpublished glass negatives.
18. Ms. Report to British Fishery Society, 2 June 1870. NLS. Acc.10706. Reports, **14**. 660.
19. Drawings and notes by David Stevenson. Private collection.
20. Stevenson T. Op cit. 2nd ed. pl. XII.
21. Paxton R. and Shipway J. *Civil Engineering Heritage Scotland Highlands and Islands*. Thomas Telford, London, 2007. 90-93. Figures from W.D. Cay paper *MPICE*. **39** 1874-5.

Acknowledgements

Heriot-Watt University - Steve Hawkin and Brian Linfoot; ICE Archives - Carol Morgan; National Archives of Scotland - Ray Miller; National Library of Scotland Mss. Dept. and Map Library; The Wick Society - Donald Sinclair; George Watson; Prof. William Allsop.

Discussion on paper 69 (R Paxton)

Alice Johnson, Royal Haskoning

From experience can you please provide a list of the key failure mechanisms of breakwaters and what could have been done to prevent these?

Author's reply –

My experience in this field relates to my historical engineering study of Wick Breakwater, based mainly on unpublished first-hand contemporary accounts particularly those of Doull and the Stevensons, and a general structural engineering background.

The major breach in 1870 was caused by storm driven waves over a long fetch striking the breakwater at about 12° from its horizontal line. This action set up a secondary wave which in travelling shore-wards clashed with an incoming primary wave about 200 m from the shore forcing water up to a considerable height which, in falling, breached the traditionally designed several-element breakwater (Fig. 5).

The parapet wall was omitted on the rebuild which helped against the above failure mechanism. But further major destruction occurred in storms in 1872 and 1877 after wave impact forced water up to 60 m in height, lifting and severing the bond with adjoining stonework of the massive composite remedial ends, shearing them off at or near the top of the rubble base with an average pressure calculated from Stevenson data of about 290-340 kNm^2. This pressure was probably of greater intensity in the upper part of the wave. It is possible that local scour of the mound would have been a contributory factor.

Nothing more could have been done to save this breakwater. After severance of the remedial ends an adjoining length of breakwater was soon destroyed. It might be speculated that if its walls had been founded on the bay bed, and not the rubble base, it might have survived. The above pressures could probably have been accommodated by a well-designed breakwater built throughout of Portland Cement concrete, but the funds were exhausted by 1877.

Jonathan Simm, HR Wallingford.

What are the lessons for current practice from your interesting analysis of the failure of the Wick breakwater?

Author's reply –

The lessons of the Wick Breakwater failures dictated a requirement in new breakwaters for thorough site investigation, including taking into account wave characteristics, particularly in prevailing storm conditions, from local experience and records.

This failure also suggests that, in laying out a breakwater, a line more or less parallel to that of the prevalent storm waves should be avoided. If this cannot be managed, as at Wick, any structure should be designed to minimise wave loads, particularly the occurrence of impulsive loads. The structure should be strong enough in shear and bending to resist the worst case effects. The foundation should be resistant to local scour causing any loss of foundation support.

So, in addition to providing one of the most striking demonstrations of the mechanisms and force of the sea, this suggests that any new breakwater should be designed for appropriate loads, of strong homogeneous construction throughout, and, if practicable, keyed into the sea bed.

W. Dyce Cay who was almost certainly aware of the problems at Wick from 1868 is to be commended for achieving a sustainable outcome in similar but not as difficult conditions, with his innovative large scale use of in-situ concrete Portland Cement at Aberdeen Harbour in the 1870s.

Additional references

Vernon-Harcourt L F (1885) "Harbours and docks" Clarendon Press, Oxford.

Shield W (1895) "Principles and practice of harbour construction" Longmans, Green & Co., London.

END OF QUESTIONS FOR PAPER 69.

Roland Paxton MBE MSc PhD HonDEng CEng FICE FRSE (Presenter)
Vice-chairman ICE Panel for Historical Engineering Works
Hon Professor
The School of the Built Environment
Heriot-Watt University
Edinburgh EH14 4AS

PRESENTING AUTHOR BIOGRAPHY

Professor Roland Paxton, civil engineer and engineering historian, was born in 1932 and educated at UMIST and Heriot Watt University, Edinburgh. From 1955-90 he worked on highway and drainage design and construction with large local authorities. Since retiring as a senior principal engineer in 1990 he has taught and researched in engineering history and conservation at Heriot-Watt University and written and lectured extensively at home and abroad gaining the ICE Garth Watson Medal and the ASCE History and Heritage Award. He serves on the ICE Panel for Historical Engineering Works on recording and conservation, is a trustee of the Clerk Maxwell Foundation, and is chairman of the Forth Bridges Visitor Centre.

From 1992-2002 he was a Commissioner on RCAHMS. He also initiated and served on Laigh Milton Viaduct Conservation trust which bought for £2 and saved from collapse the world's oldest surviving viaduct on a public railway. Until 2007 he was founder chairman of the ICE Historic Bridge and Infrastructure Awards Panel. He laid a Highland myth to rest by initiating with Radar World a successful image of horse and cart remains in Loch-nan-Uamh viaduct after an 1890s construction accident. His attention was drawn to the Wick Breakwater disaster when writing the book 'Bright Lights -The Stevenson Engineers 1752-1951'.

ABSTRACT

The repeated destruction at Wick Breakwater by the sea from 1868-77 in exceptional circumstances represented a landmark disaster. In this paper the project and two wave force mechanisms are identified and reviewed in an historical engineering context. The force of the sea led to the loss of nearly one third of the breakwater's length with abandonment following the displacement and destruction of two successive mass replacement ends by 1877, the latter of 2642 tonnes, for which the failure pressures and resistances have been estimated.

Traditional breakwater practice and its shortcomings at Wick are reviewed. The failures from 1868 highlighted the necessity for new breakwaters subjected to similar conditions to be of strong homogeneous construction throughout, specifically designed to minimise the wave and scour effects at the site and, if practicable, based on and toed into the sea bed. The harnessing of Portland Cement concrete to breakwaters was a significant contemporary development, particularly as exemplified by W.D. Cay's ingenious extension of Aberdeen North Pier from 1874-77 using ready mixed concrete founded on the sea bed in large bags.

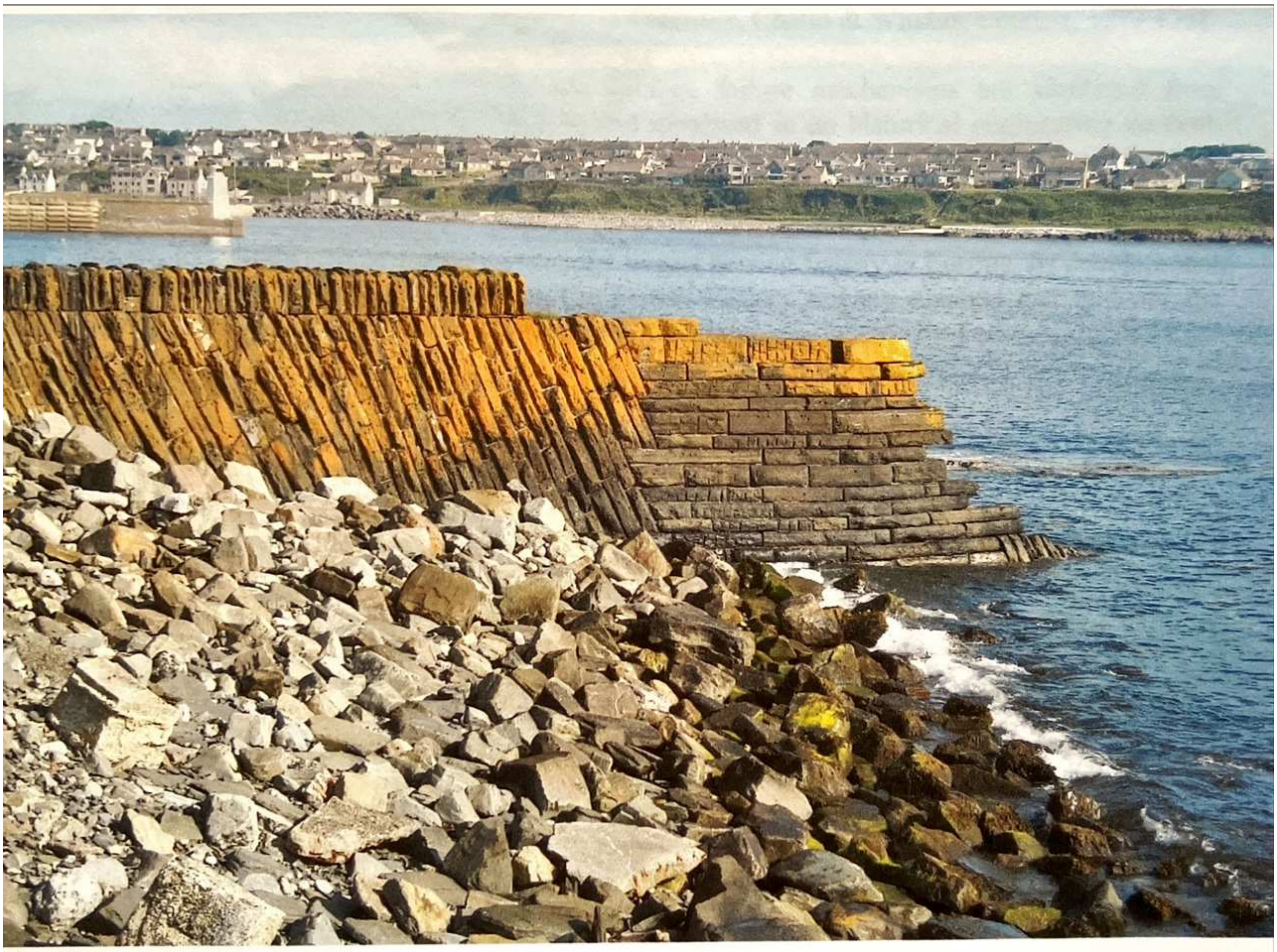

Figure 2c: Present stub of breakwater near low water [July 2009] © Author