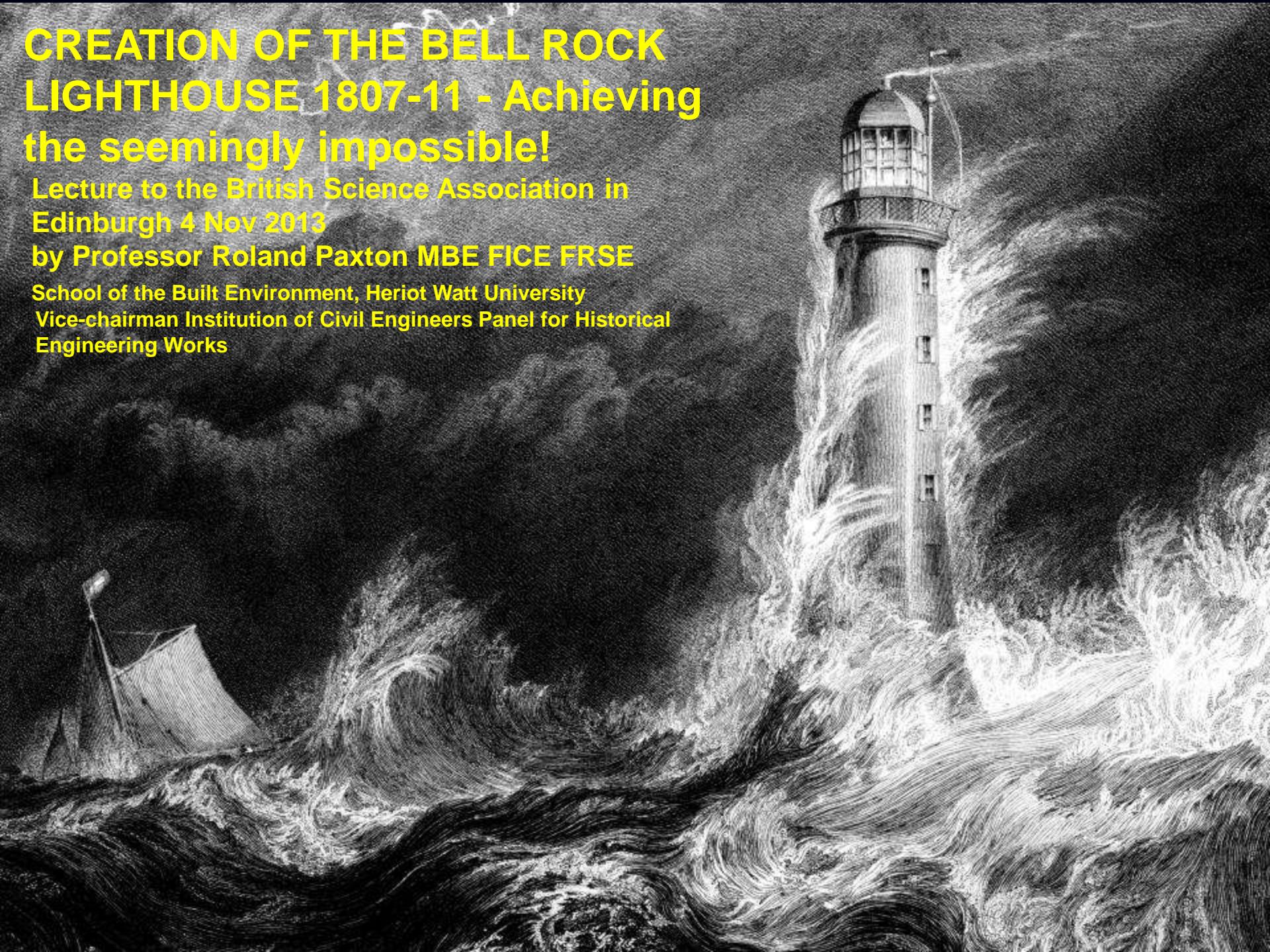


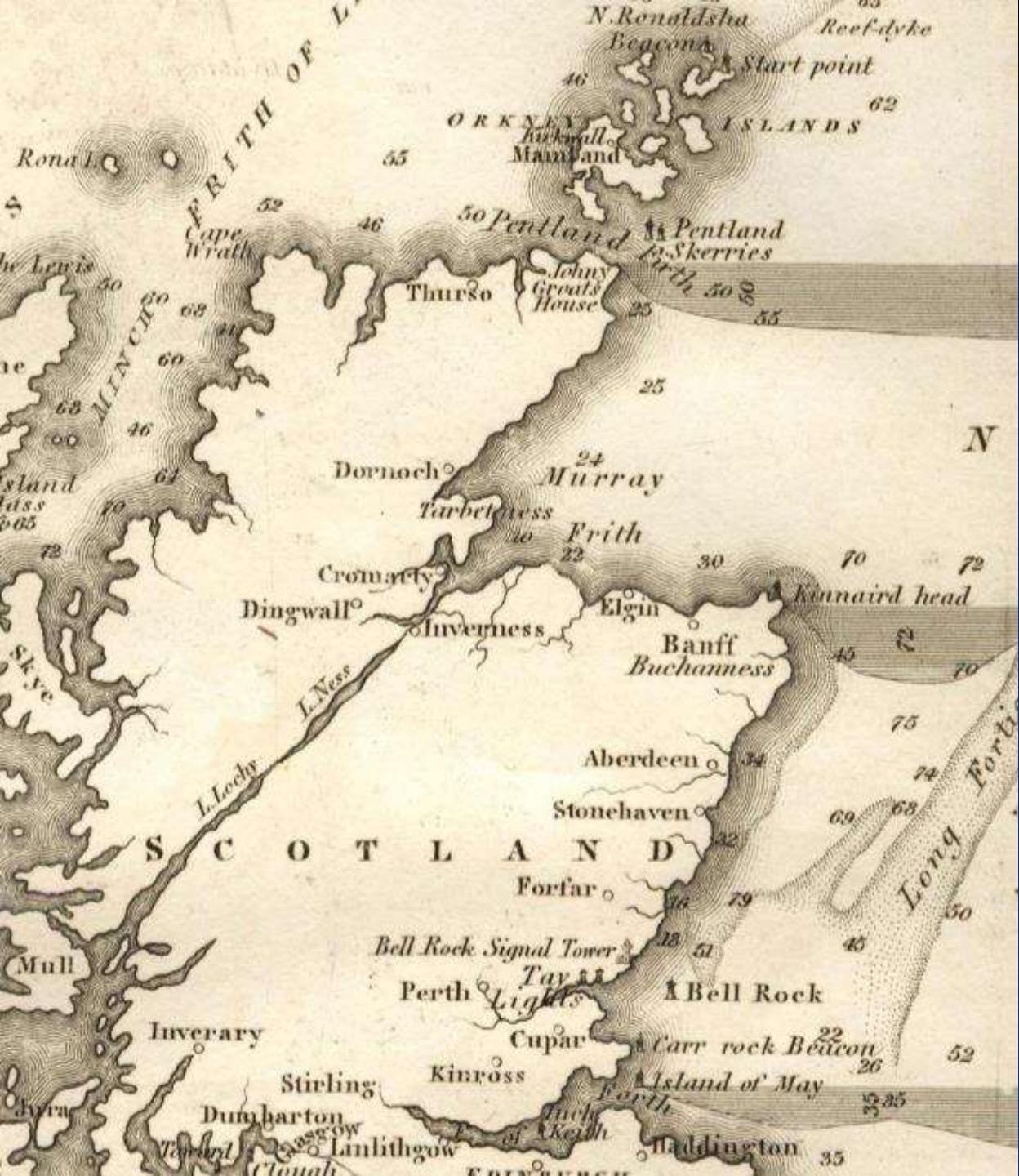
CREATION OF THE BELL ROCK LIGHTHOUSE 1807-11 - Achieving the seemingly impossible!

Lecture to the British Science Association in
Edinburgh 4 Nov 2013

by Professor Roland Paxton MBE FICE FRSE

School of the Built Environment, Heriot Watt University
Vice-chairman Institution of Civil Engineers Panel for Historical
Engineering Works





NLB formed in 1786 to improve maritime safety.
Engineer - Lamp manufacturer Thomas Smith

Kinnaird Head LH 1787
Mull of Kintyre LH 1788
N. Ronaldsay LH 1789
Island Glass LH 1789
Pladda LH 1790

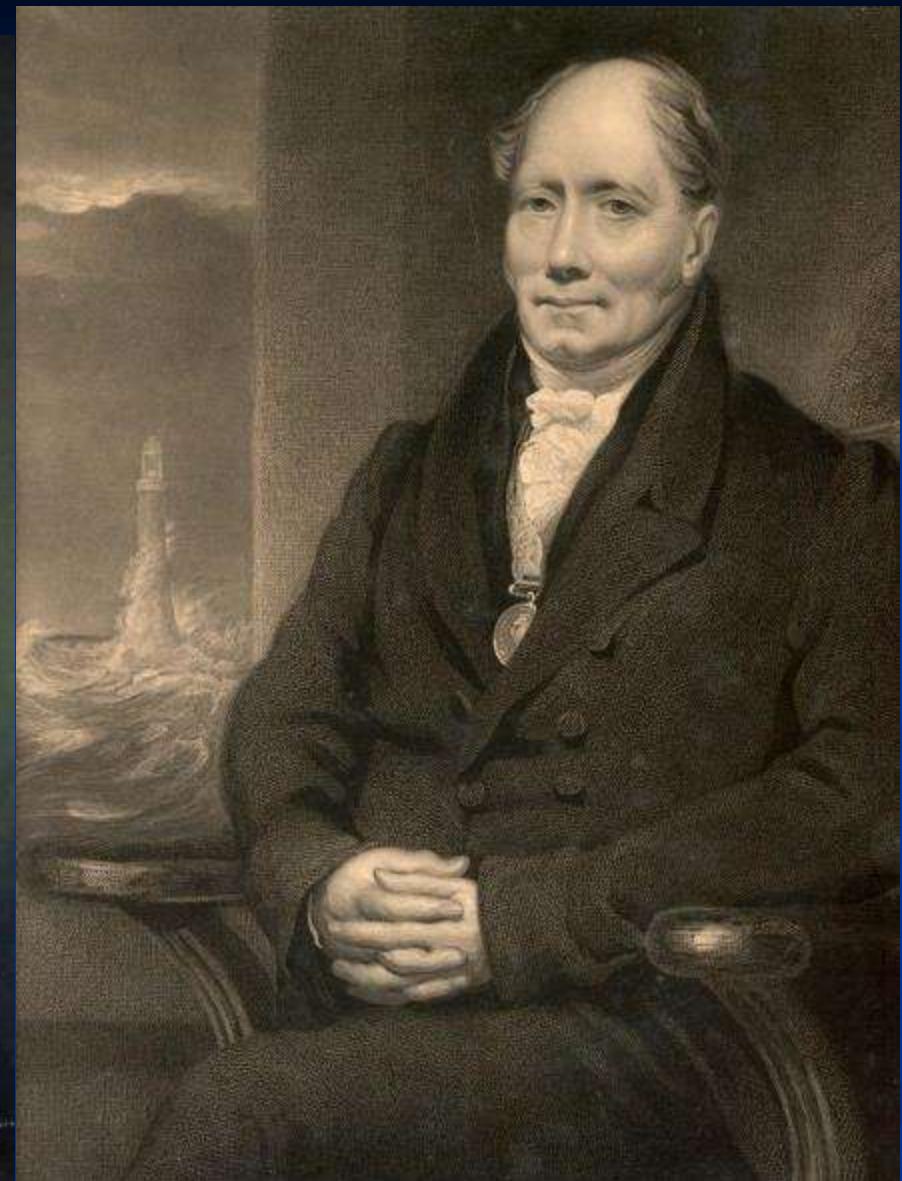
1791 Robert Stevenson's tinsmith career with his step-father Smith began

Little Cumbrae LH 1793
Pentland Skerries 1794
Cloch LH 1797.

Stevenson at Bell Rock in 1800. Lighthouse erected 1807-10



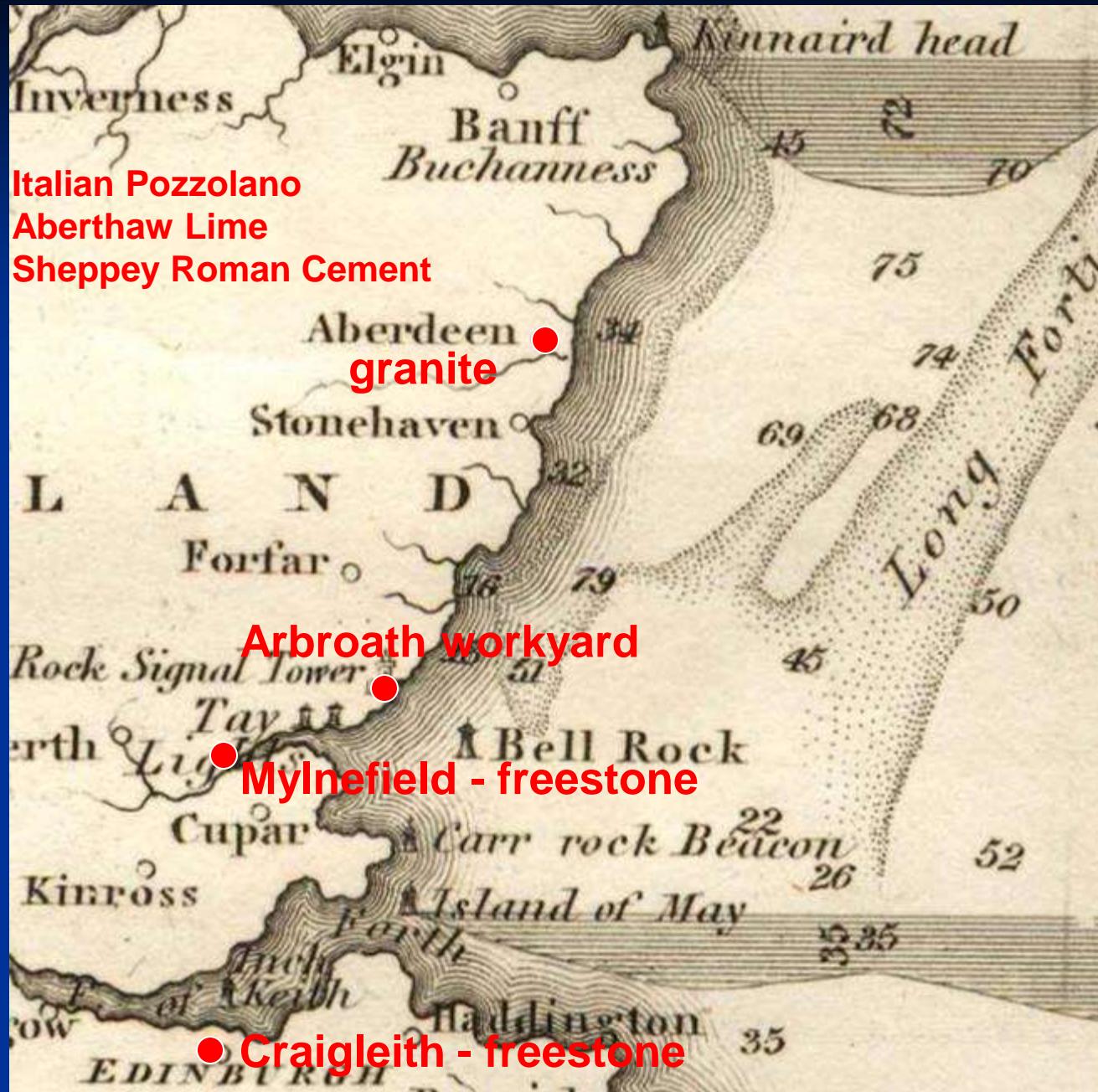
John Rennie (1761-1821)
Chief Engineer



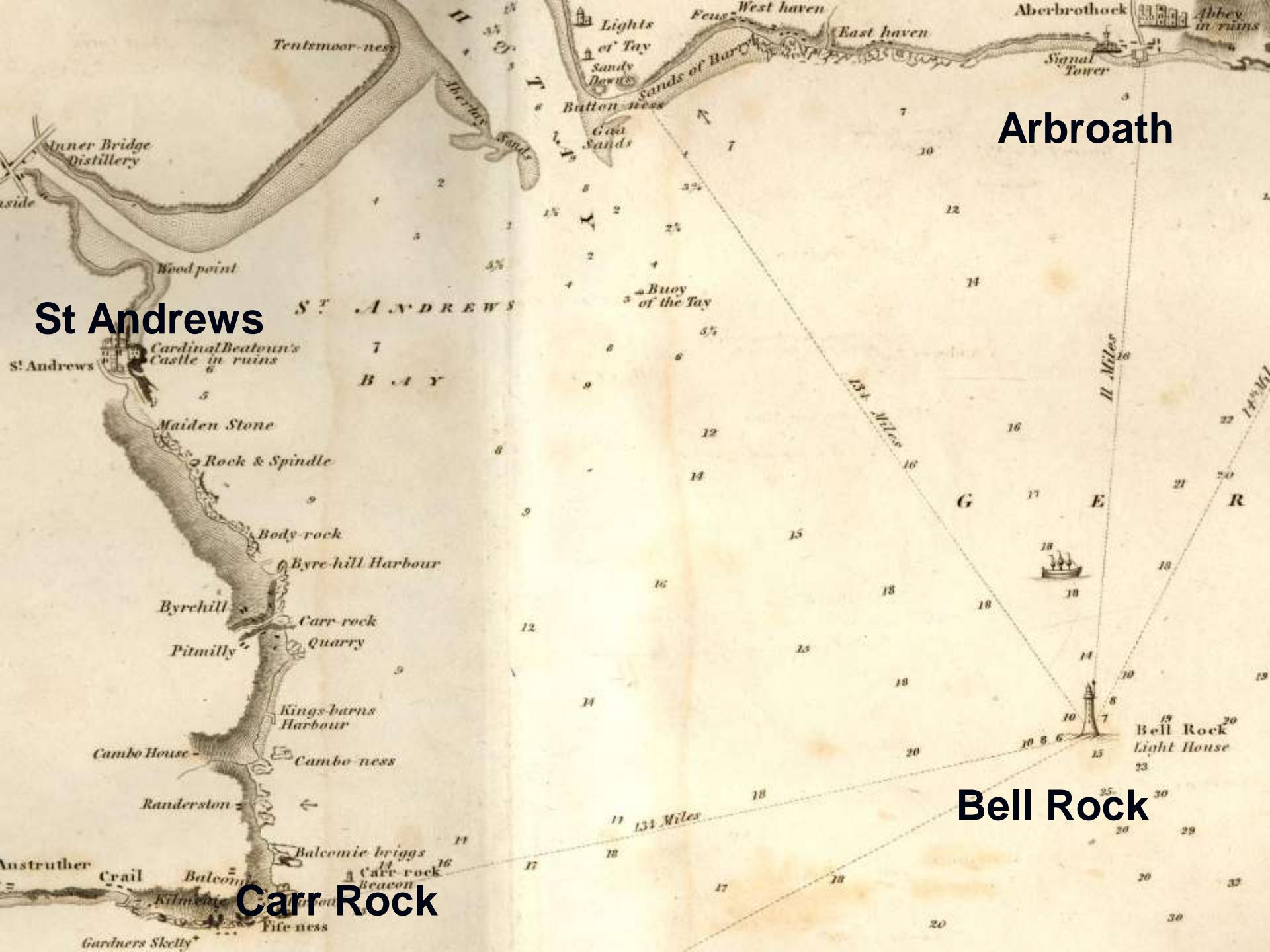
**Robert Stevenson (1772-1850) Assistant
/Resident Engineer [NLB Engineer 1808]**

BellRock Lighthouse

Sources
of the
main
building
materials
used



Arbroath

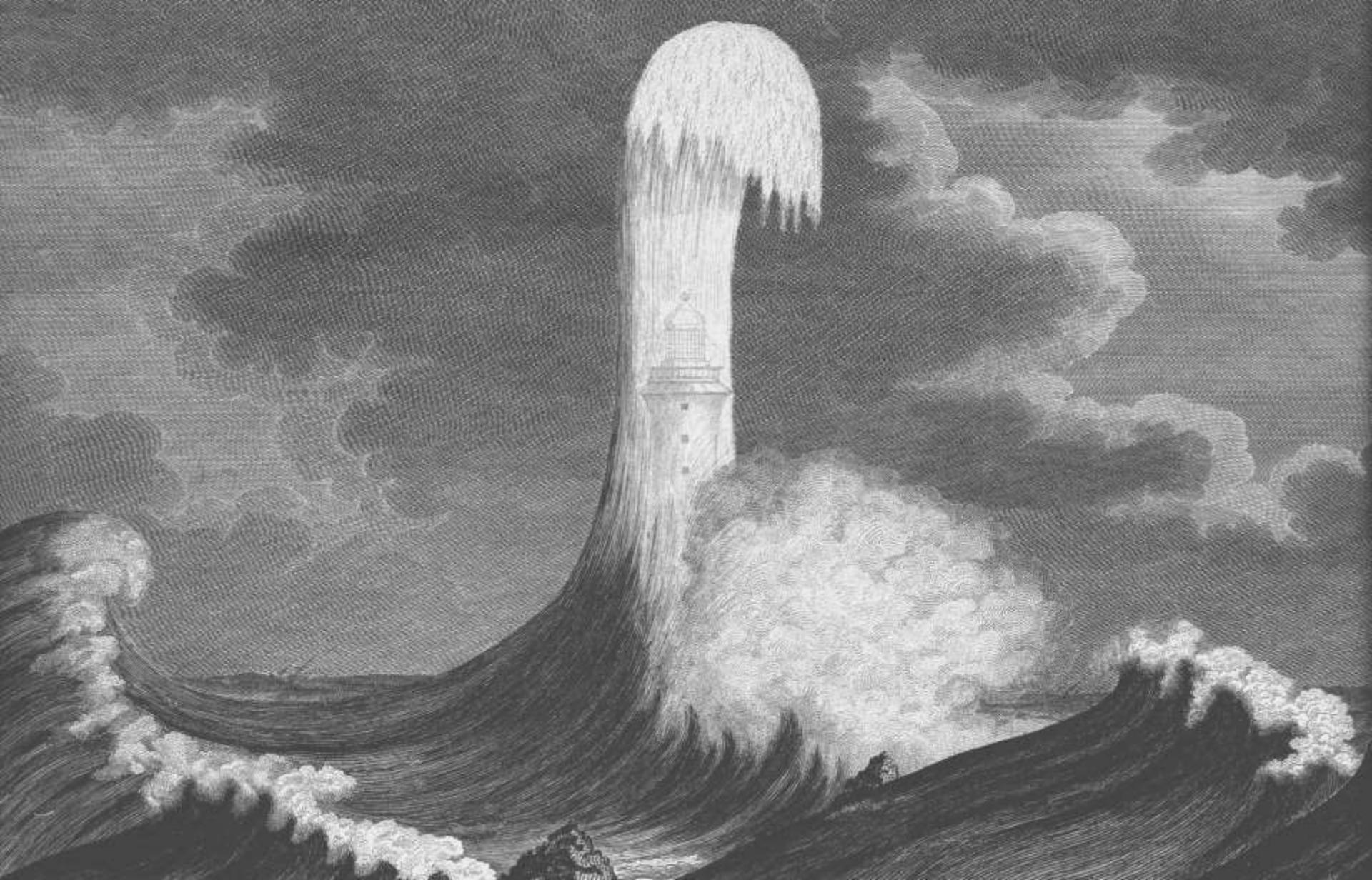


Carr Rock

Bell Rock



Bell Rock(low tide - 1986). In 1799, 70 vessels were stranded or lost in the area, many of which might have been saved by a lighthouse here. Creating one was a daunting challenge.



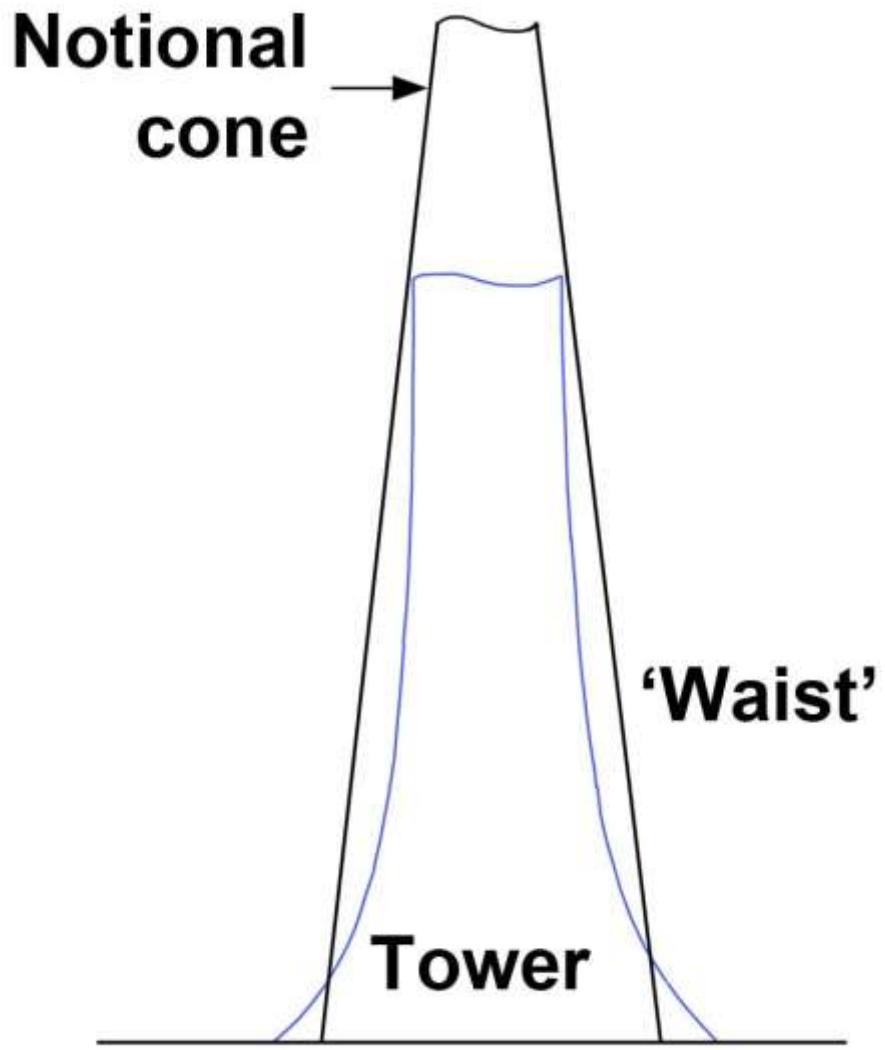
**Eddystone Lighthouse 1757-59 (nr. Plymouth) in storm in 1759, by
the ‘father’ of civil engineering, John Smeaton (1724-92) FRS**

From
Smeaton's
Narrative of ...
The Edystone
Lighthouse
1791

Fig. 2.

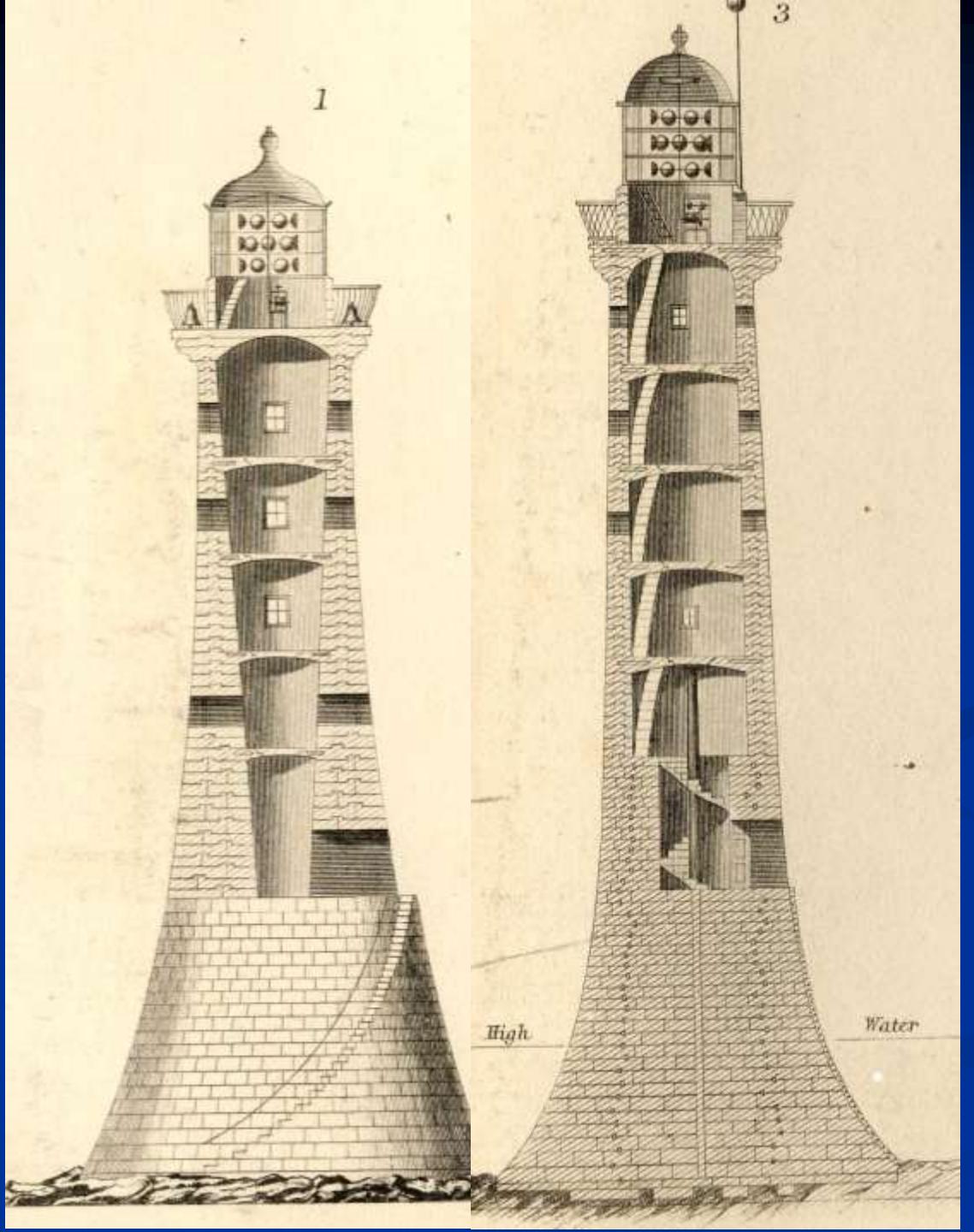


Smeaton promoted his design as structurally analogous to the trunk of an oak tree, which is arguable, but correctly propounded that the ultimate stability of a tower depends on the lowness of its centre of gravity – on the general notion of a cone – the horizontal forces on which ‘decrease towards its top in a rapid ratio.’ He regarded dovetailed masonry as essential.



Smeaton's
conical design
concept for
Eddystone
Lighthouse
in 1757 and, as
he would have
preferred but for
which there was
insufficient room
(in blue)

Stevenson's undovetailed design 1800-06 (left) and the tower as-built 1807-10 under Rennie's overall direction as Chief Engineer. It is 20% slenderer at 30ft height and its cycloidal curvature at the rock rises at about 40° to the horizontal - features to dissipate wave force. Outside stair omitted. Thinner walls - more internal space. Lateral dovetailing adopted.





ANNO QUADRAGESIMO SEXTO

GEORGII III. REGIS.

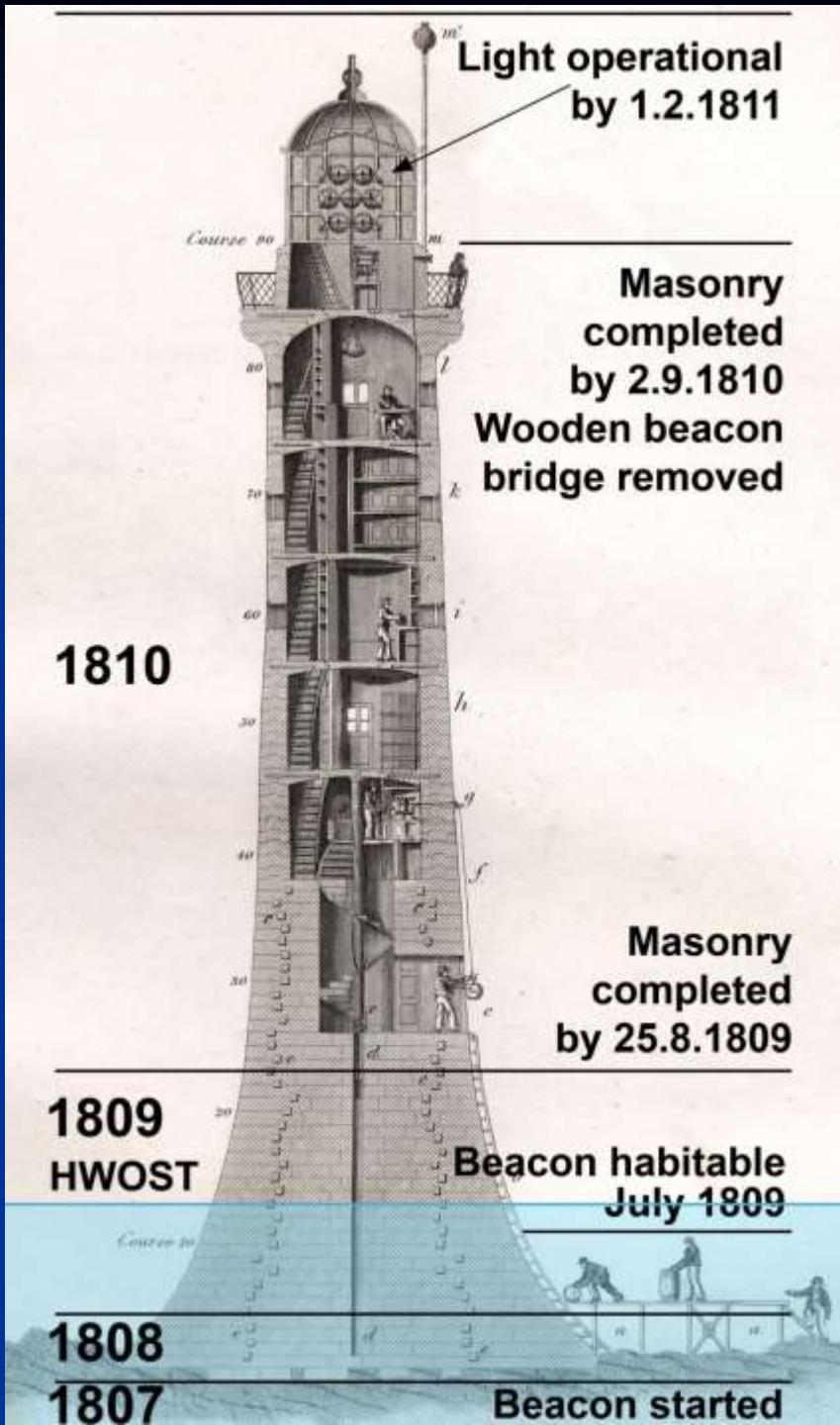
C A P. CXXXII.

An Act for erecting a Light House on the *Bell* or *Cape Rock*, on the Eastern Coast of *Scotland*, and for enabling the Commissioners of the Treasury to advance a certain Sum of Money out of the Consolidated Fund of *Great Britain*, towards that Purpose.

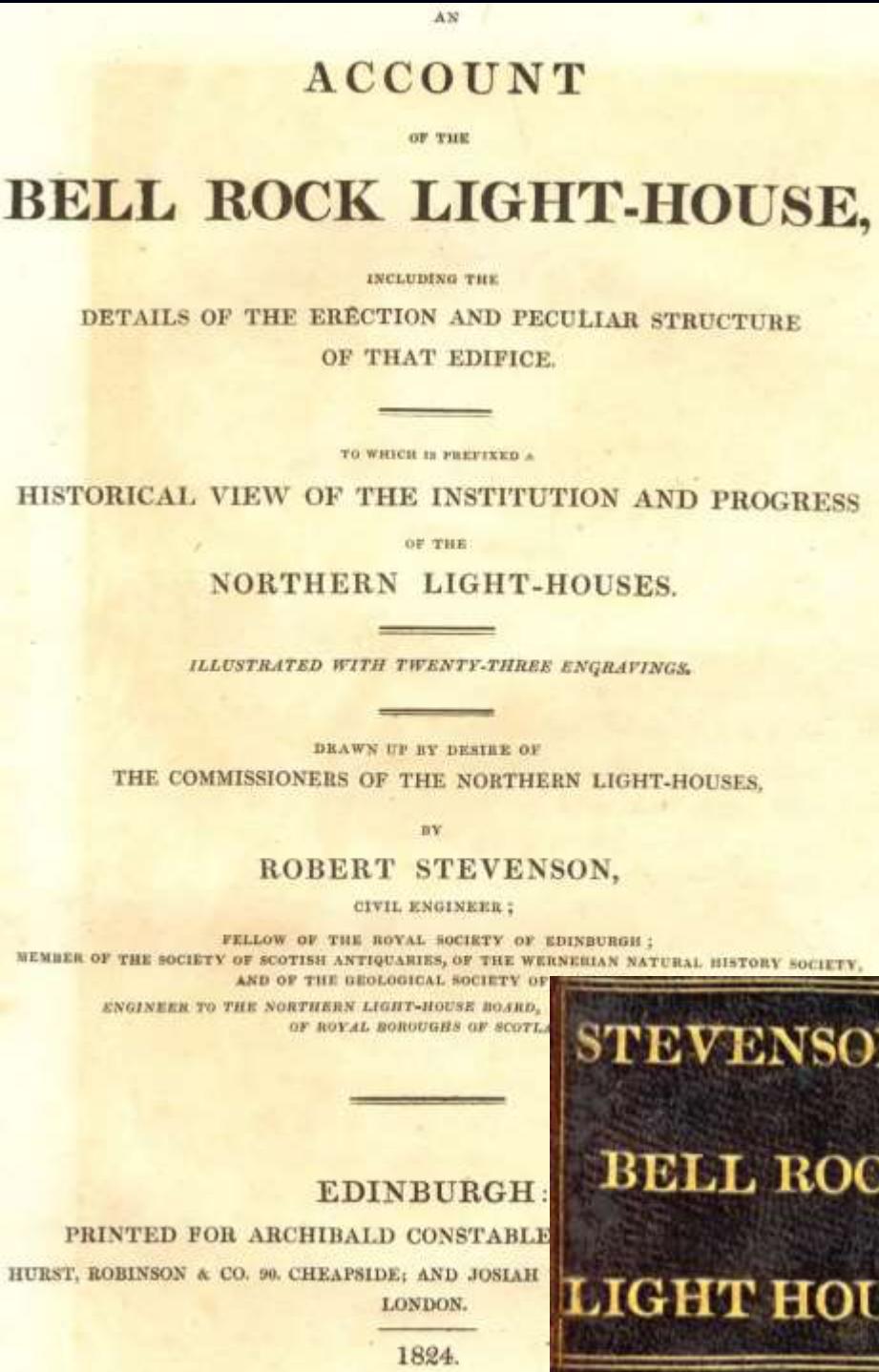
[21st July 1806.]

WHEREAS by an Act, made in the Twenty-sixth Year of His present Majesty's Reign, intituled, *An Act for erecting certain* 26 G. 3. c. 1021

After an attempt for an Act in 1803 based on Stevenson's plan failed. With Rennie's backing an Act was obtained in 1806 - financed by shipping dues of 3d/ton.



Bell Rock Lighthouse – erection chronology.
Completion achieved in 4 working seasons from 1807-1810. At first the work was carried out from ships which was inconvenient and time consuming. Much faster progress was made after the innovative temporary expedient of a beacon barrack alongside the light- house became operational in July 1809



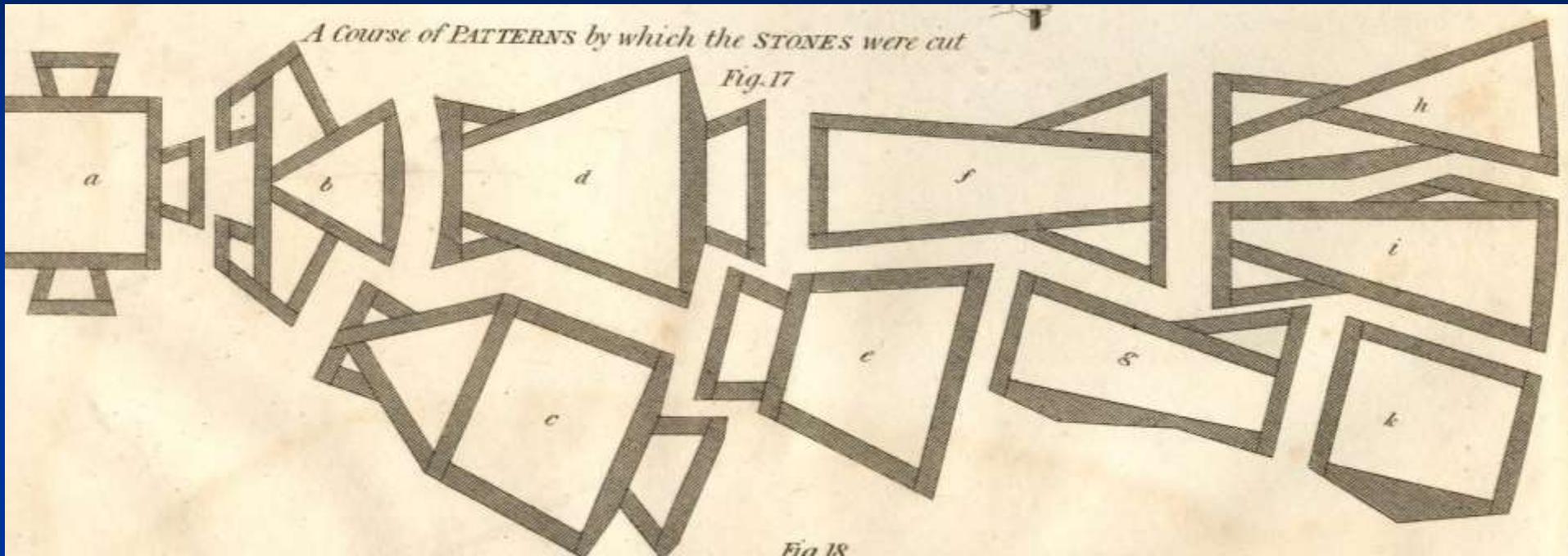
Stevenson's account of building the lighthouse is a classic of civil engineering modelled on Smeaton's Eddystone Lighthouse Narrative.
It is a masterpiece of engineering description, but is short on 'strength of materials' design consideration and acknowledgement of his Chief Engineer's contribution!
The book much enhanced Stevenson's reputation.

Harbour

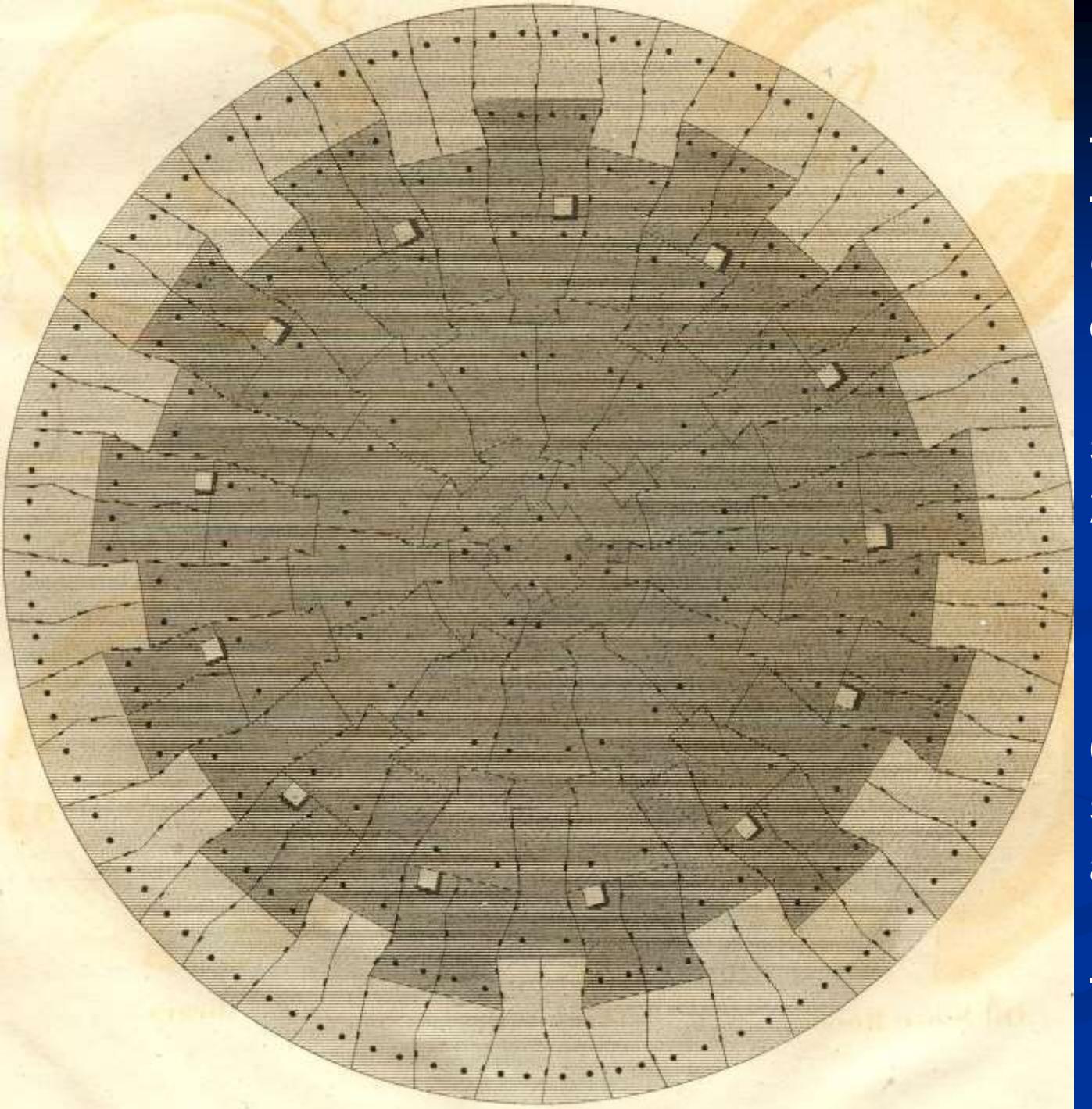
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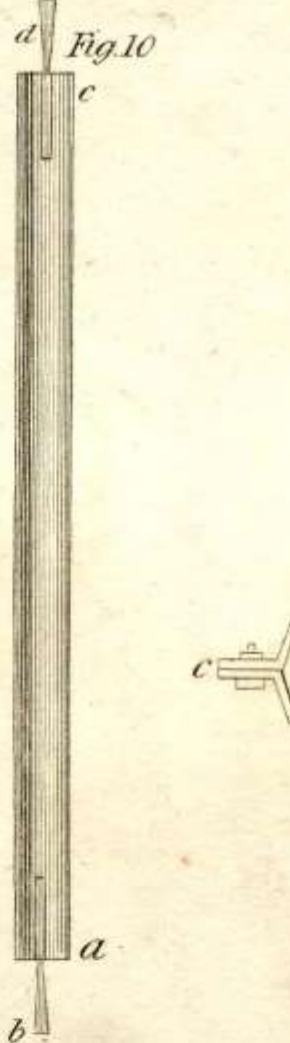
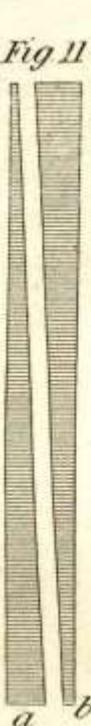
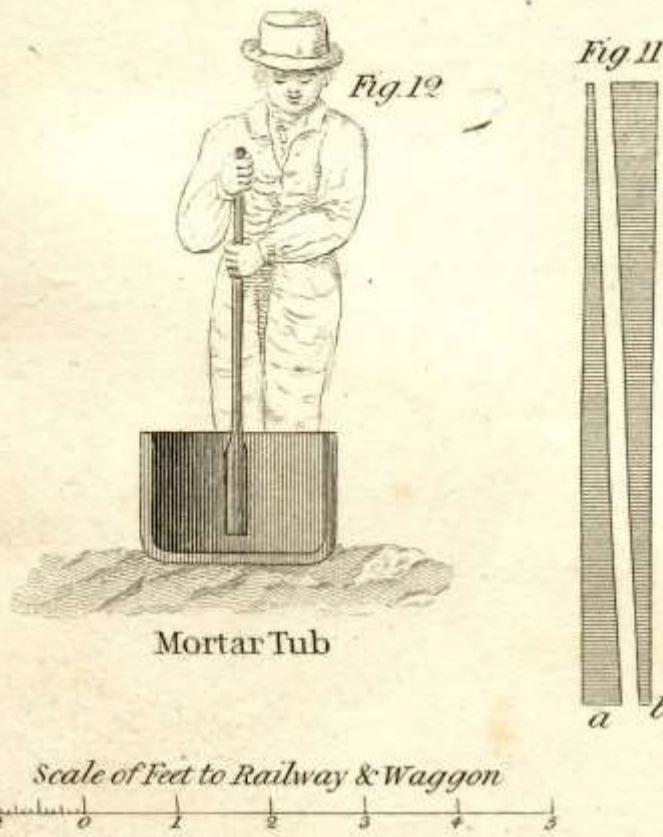
Wooden patterns used at Arbroath Work-yard to enable each stone in a course to be dressed to the right size.



**1st entire course
[1ftx42ft dia. 104
tons] 123 stones
from 11 patterns.
Outer stones Ab-
erdeen granite,
inner - Mylnefield
sandstone. Note:
246 oak trenails,
13 joggles & 378
pairs of wedges
used. Mortar
(grout)1:1:1 parts
sand, Pozzalano
and Aberthaw
lime, secured at
the sea face by
Roman Cement
mortar**

Tools and equipment used

Mortar tub



**Oak wedges
(used in pairs)**

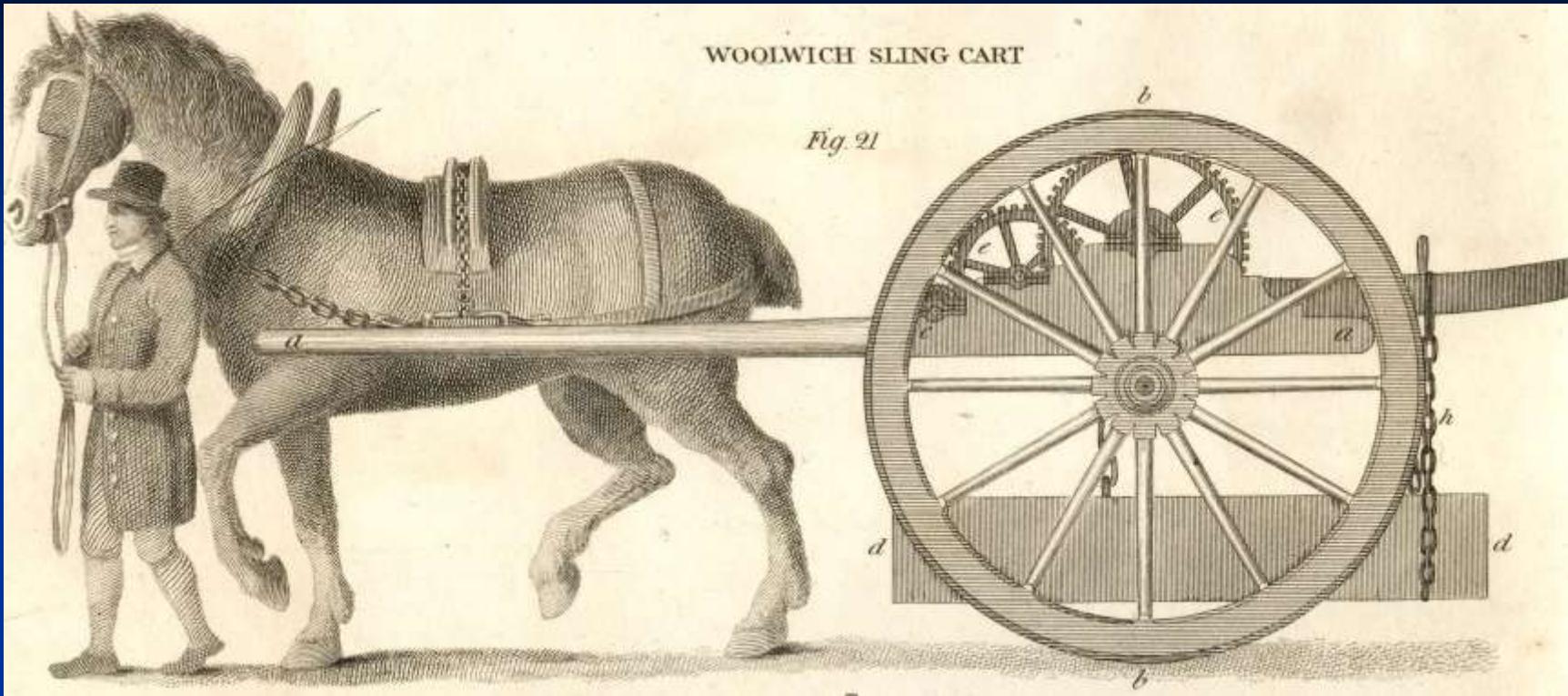
**Oak trenails
(inserted 6" into
course below)**

**Boring tools
($1\frac{1}{2}$ " diameter)**

Hole scraper

Fig. 8

Fig. 9



**James Craw with 'Bassie' hauling stone in and around
the Arbroath workyard and to and from the harbour**



Shipping: Sir Joseph Banks – Smeaton – Patriot and praam boats

Original drawing of Bell Rock Lighthouse operations – Summer 1810

© Nat. Lib. Scot.

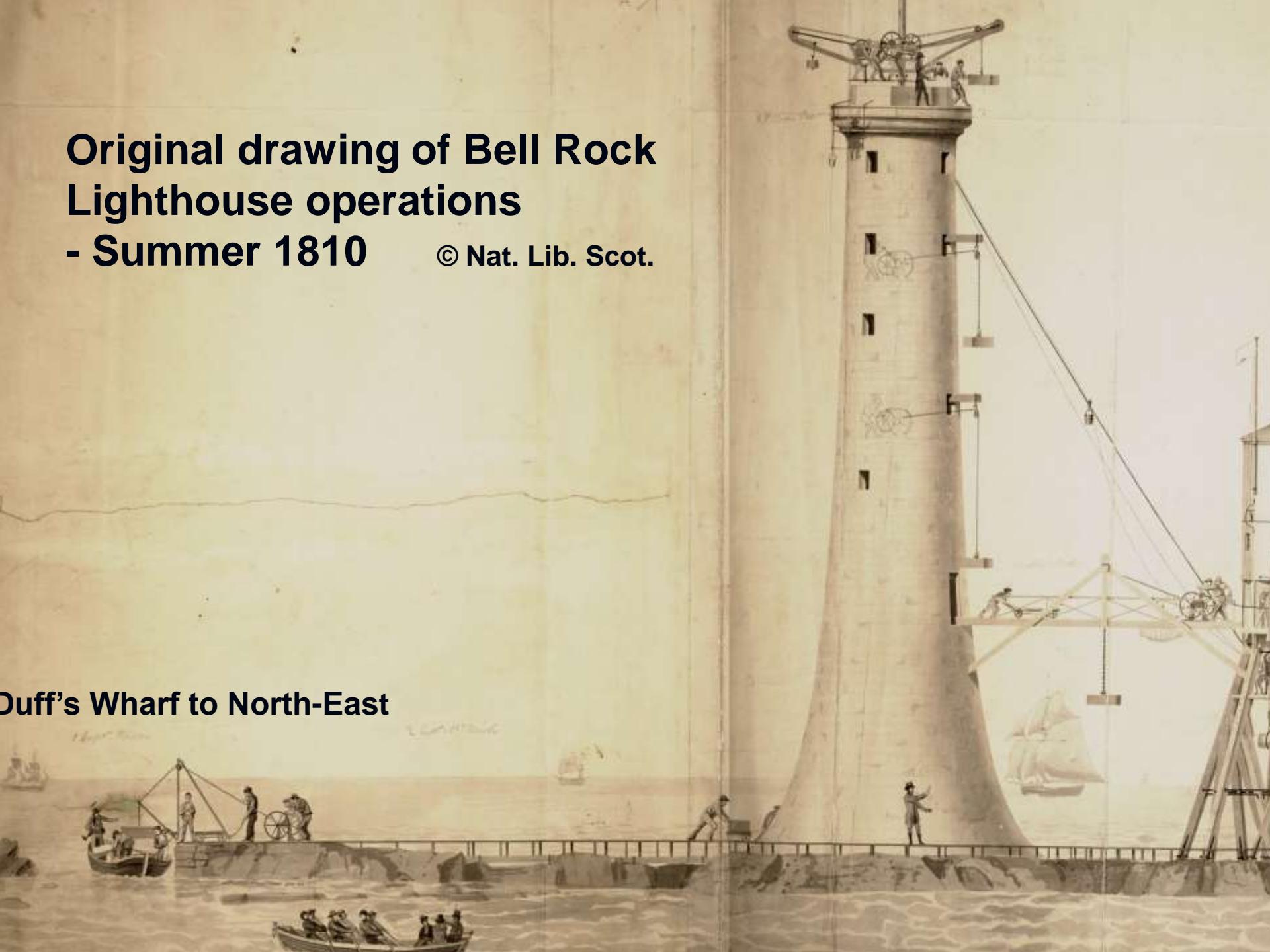
Railway South to Pitmilly Wharf >

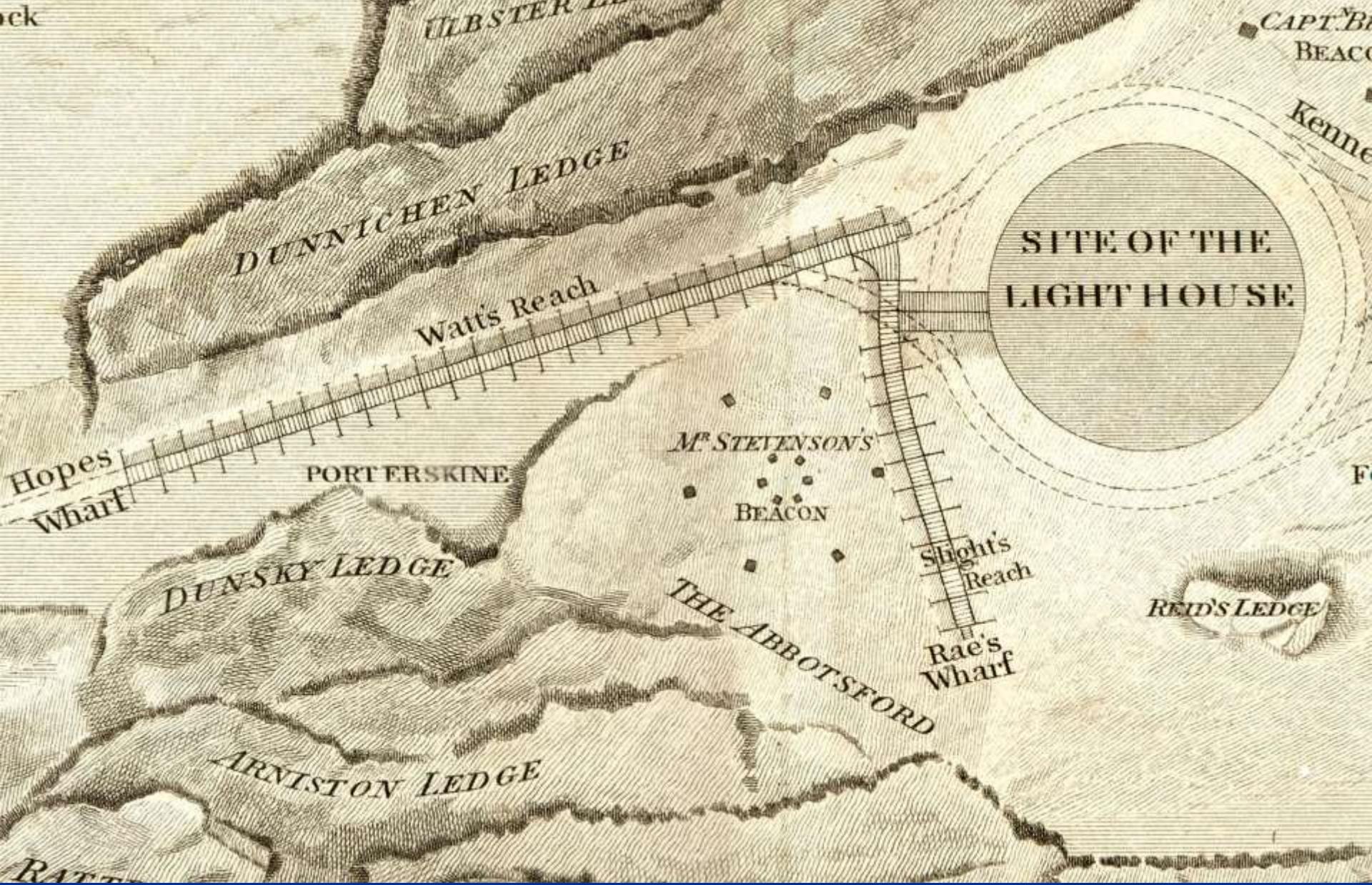


Original drawing of Bell Rock Lighthouse operations - Summer 1810

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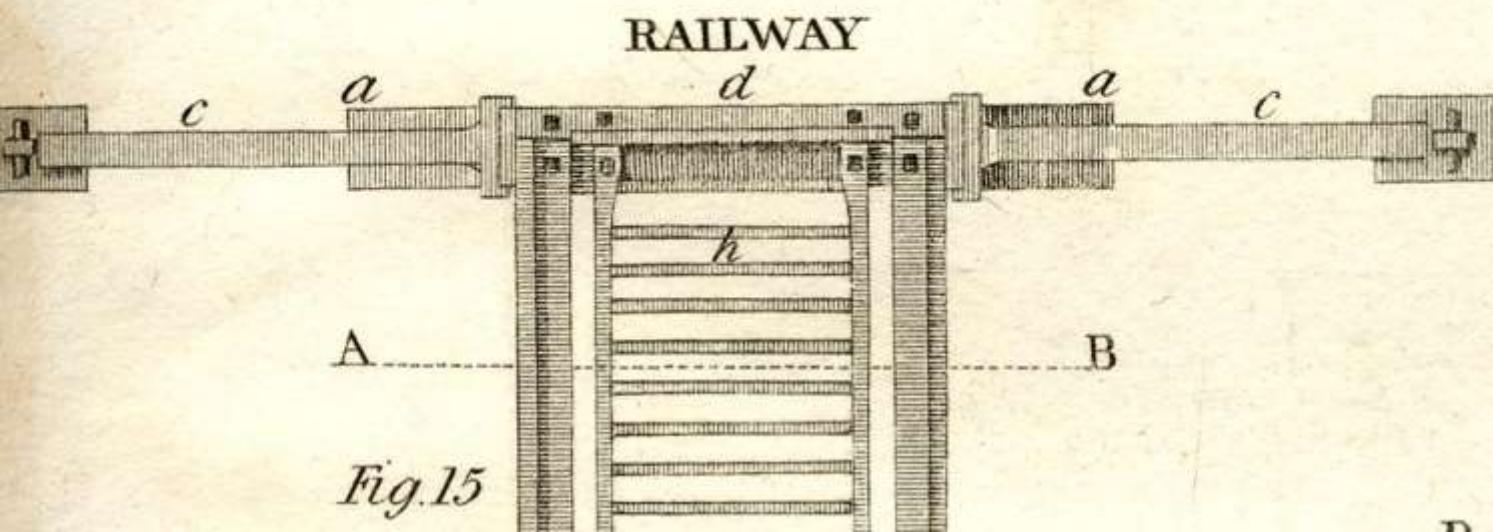
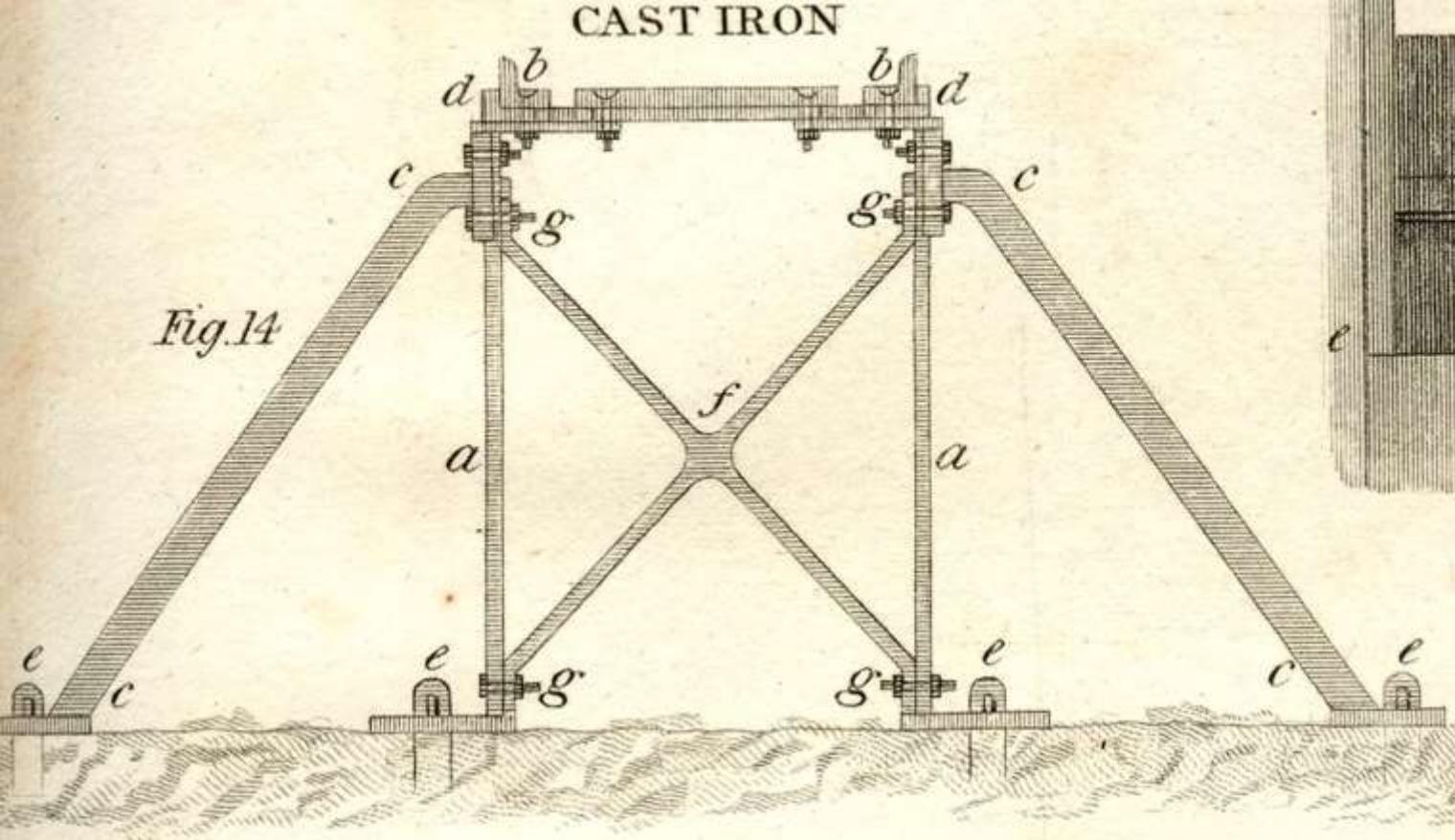
Duff's Wharf to North-East





Bell Rock - Plan showing the railway and temporary beacon innovations enabling completion of the tower by 1810

Railway
over
uneven
rock
surface
—
designed
by
Francis
Watt



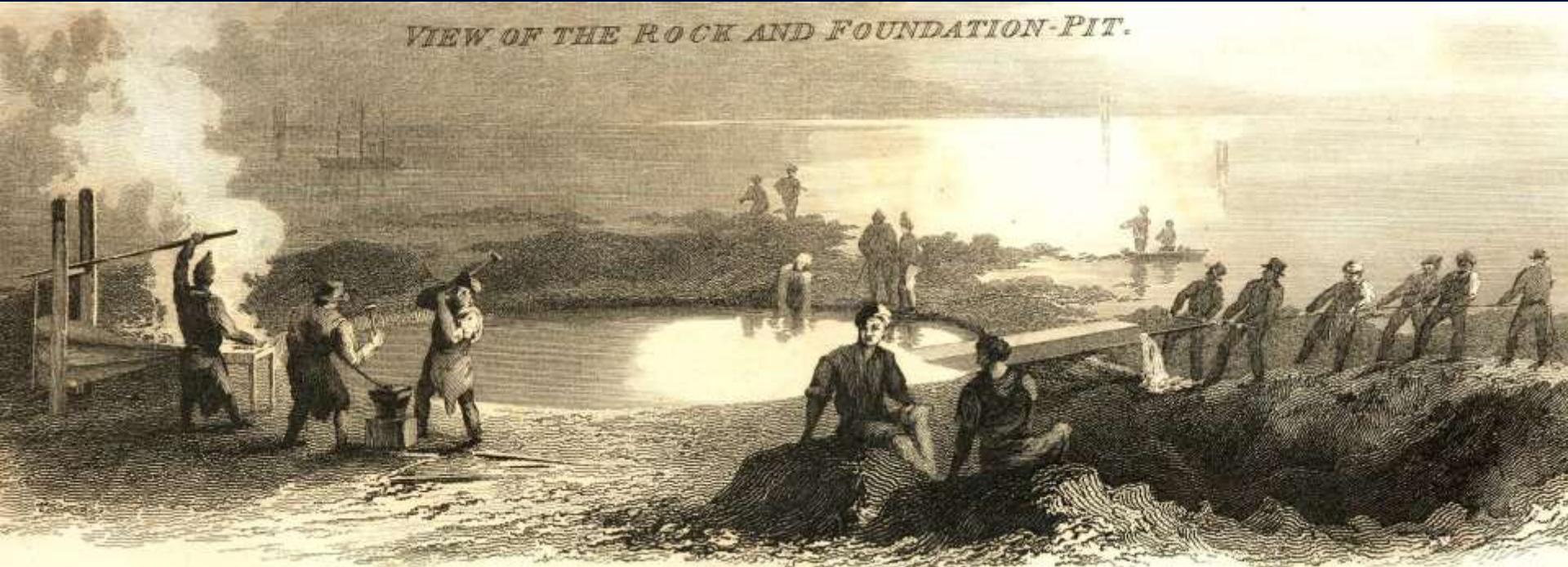


**Site cast iron railway as inspected by writer in 1986 -
still in use for access after more than two centuries.**



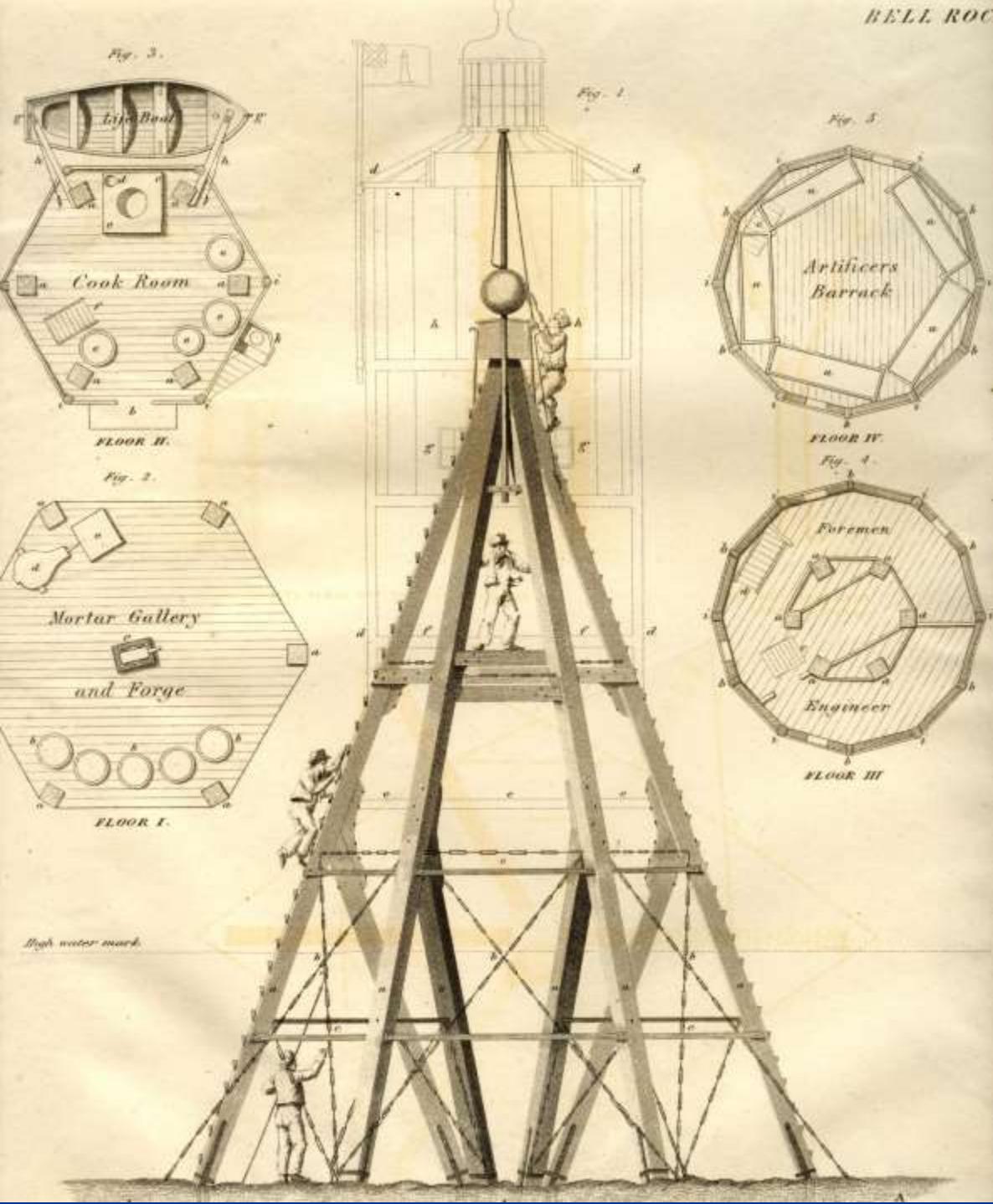
Transferring stone from praam boat to waggon on plate railway by sheer crane 1808-1810 - drawn by George Scott

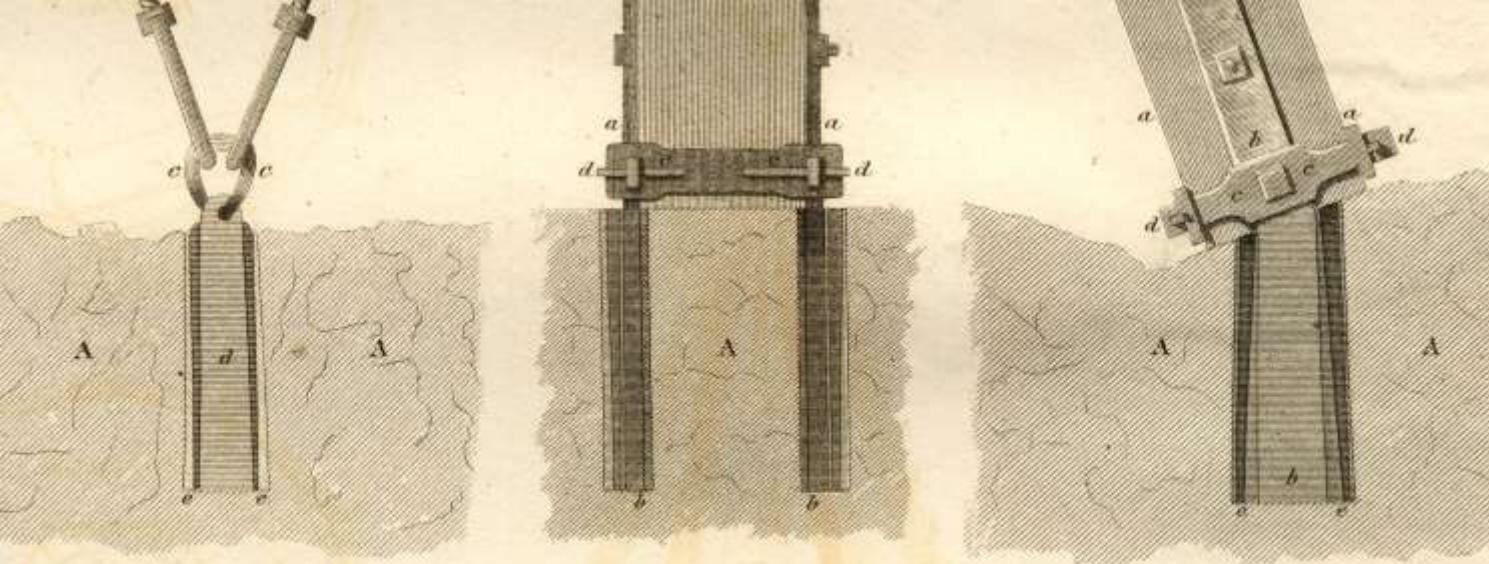
VIEW OF THE ROCK AND FOUNDATION-PIT.



View of foundation pit in 1807 being de-watered by six men and ironwork being forged to anchor the temporary beacon legs into rock. After about 2 hours work the tide began to rise and flood the forge. A 5 ft high cofferdam to prolong working time was modeled by Stevenson, but pumping out the pit sufficiently quickly on the ebb was considered impracticable

**Temporary
beacon to
facilitate work
October 1807 –
Watt's design.
Note: bracing
chains and
bars; four levels
– mortar gallery,
cook room,
engineer and
foremens and
workmens
rooms. *Inhabited*
by Stevenson
and up to 28 men
from July 1809
to Sept. 1810]**





ENLARGED VIEW OF
BRACING CHAINS

ENLARGED VIEW OF THE GREAT STANCHIONS

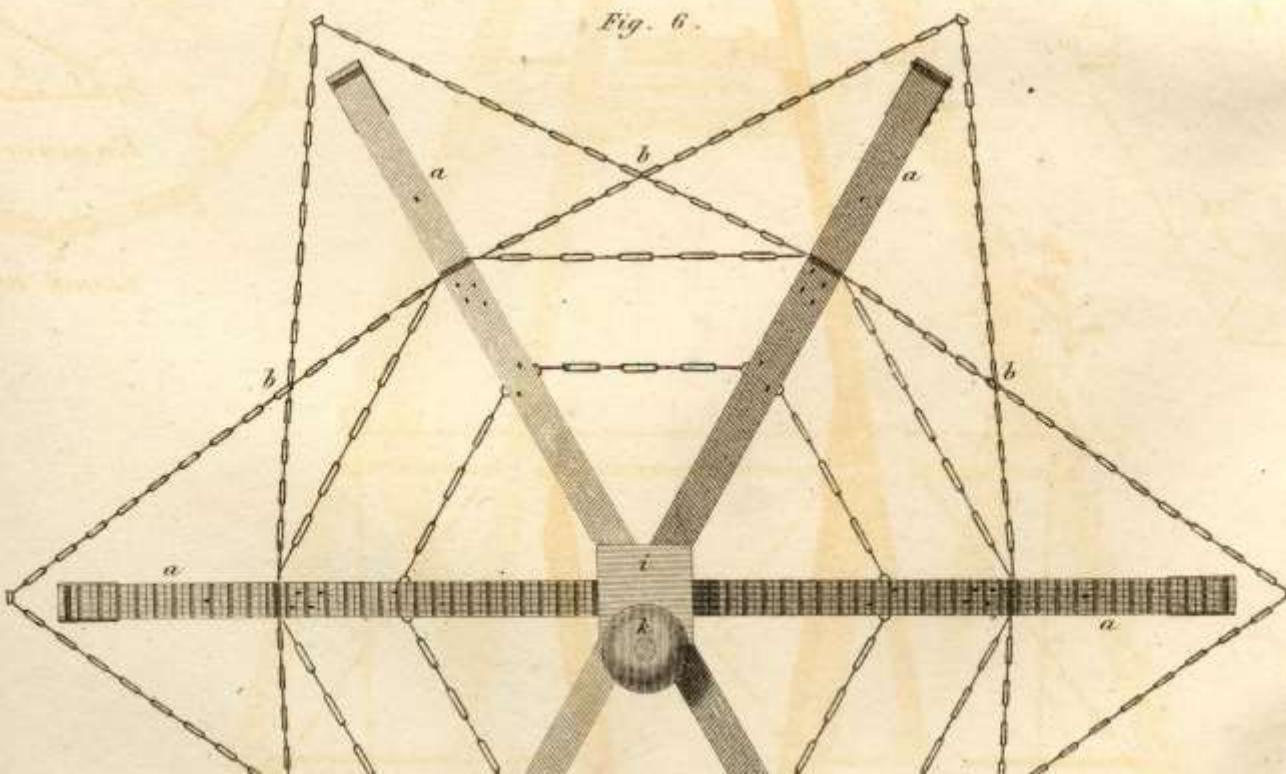
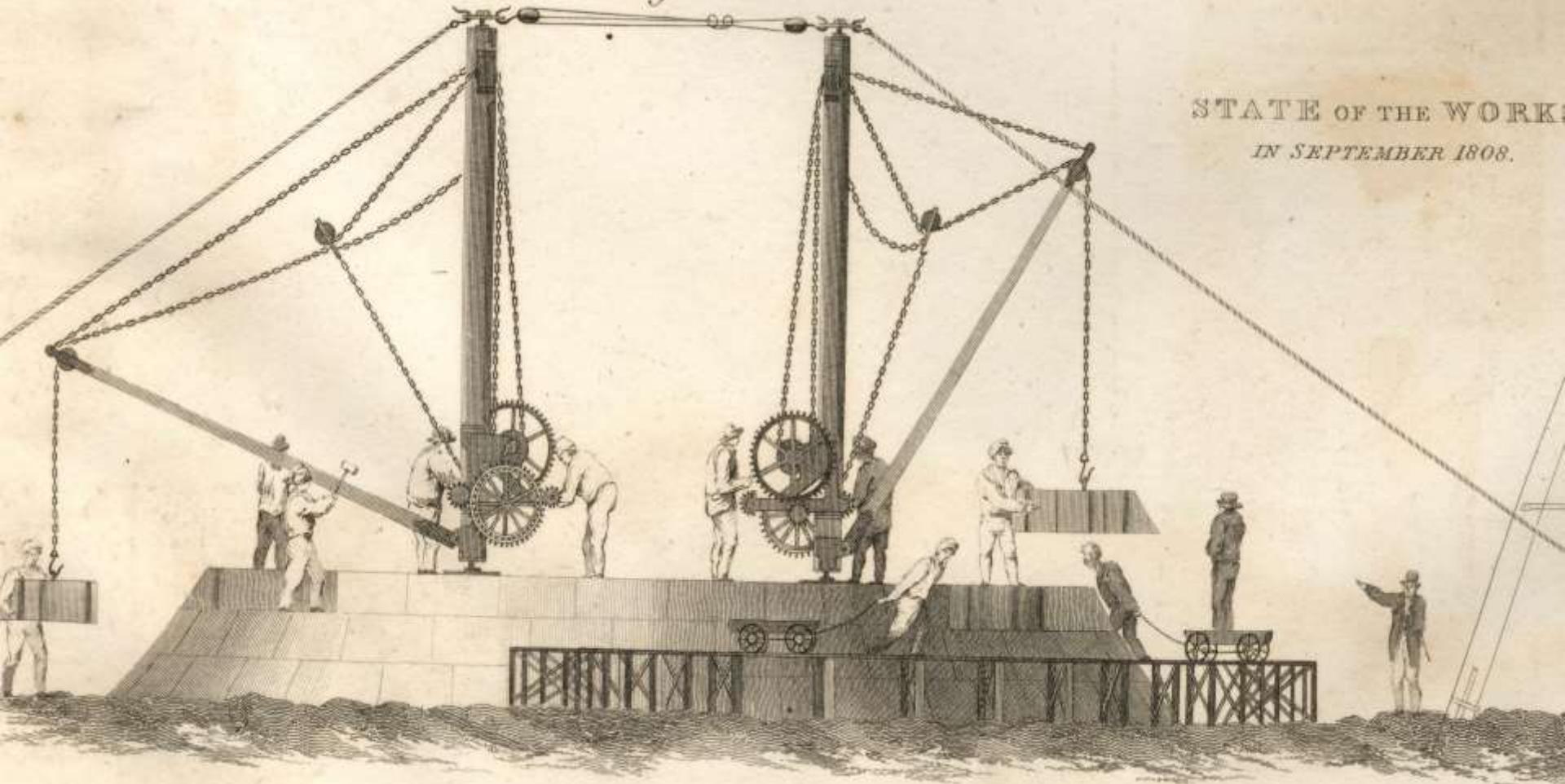


Fig. 6.

Details of
beacon
fixing and
bracing.
Stanchions
50 ft long x
1 ft square.

Fig. 1



STATE OF THE WORK
IN SEPTEMBER 1808.

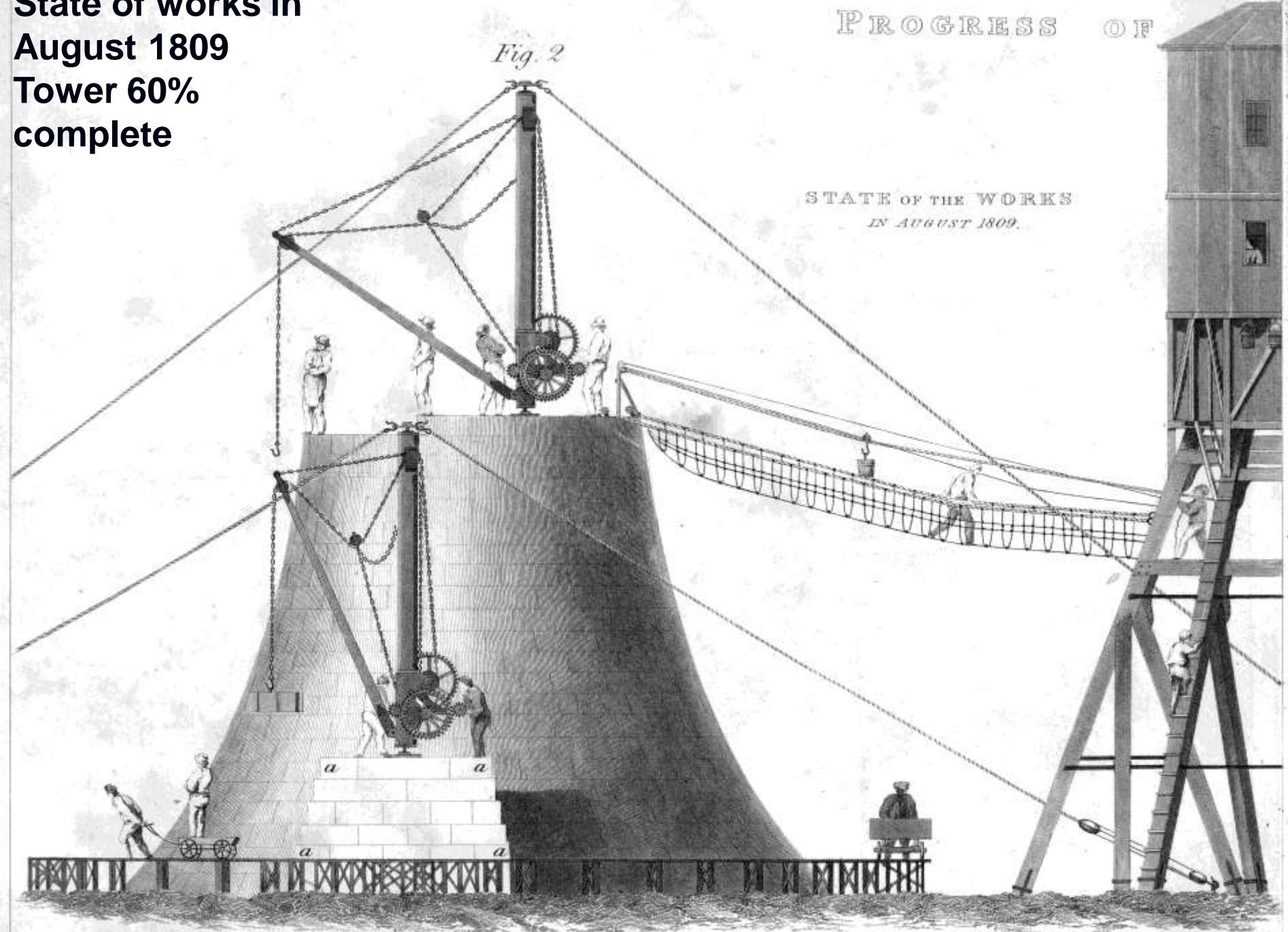
Operations at Bell Rock in September 1808 – innovative swivel jib cranes with Spanish windlass effect. Mechanical advantage 15:1 & 60:1. Designed by Francis Watt.

**State of works in
August 1809
Tower 60%
complete**

PROGRESS OF

Fig. 2

STATE OF THE WORKS
IN AUGUST 1809.





The base of the lighthouse with Rennie's innovation of cycloidal curves as inspected by the writer in 1986

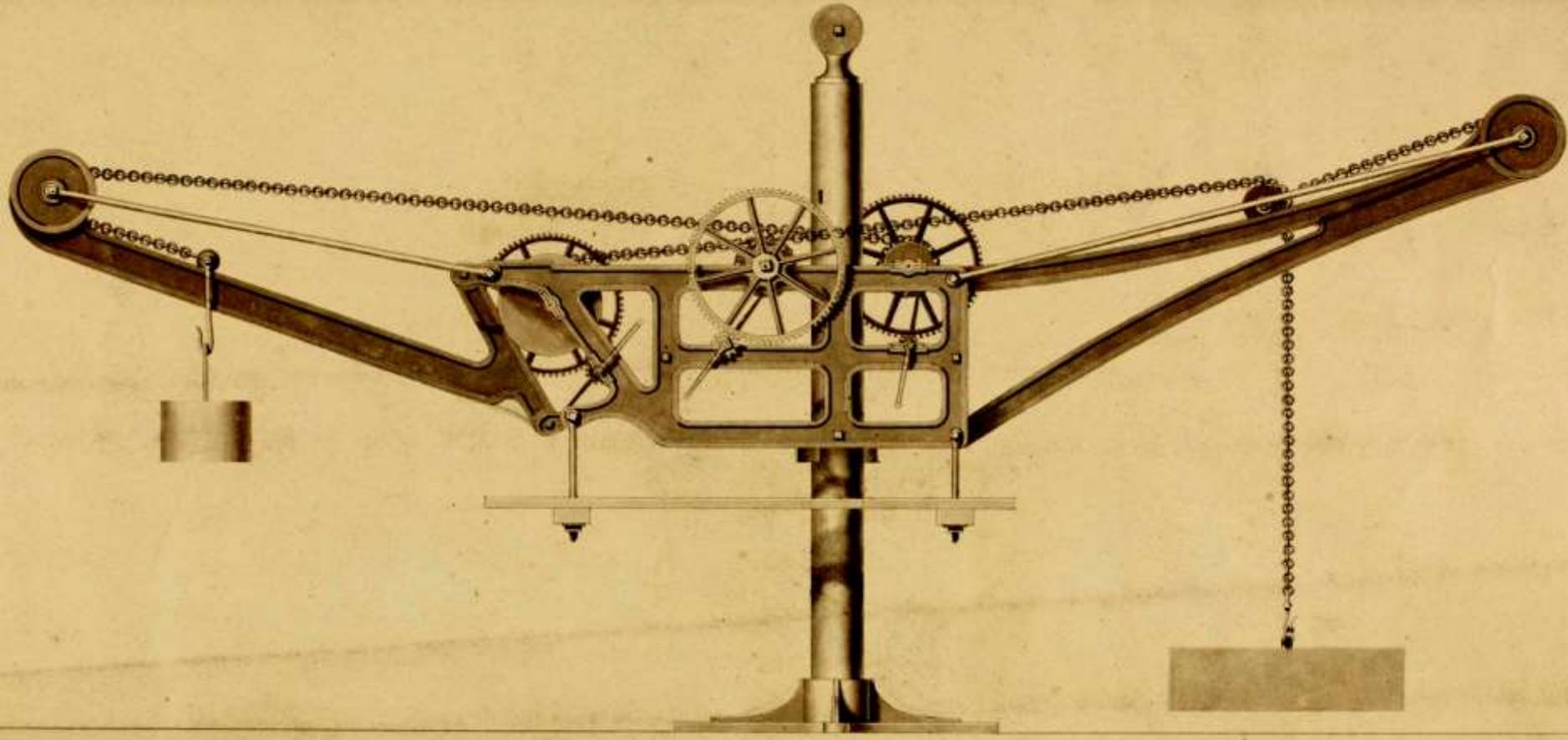
LL ROCK WORKS.

BIRDS-EYE VIEW OF THE SMEATON AND PRAAM BOAT.

Fig. 5

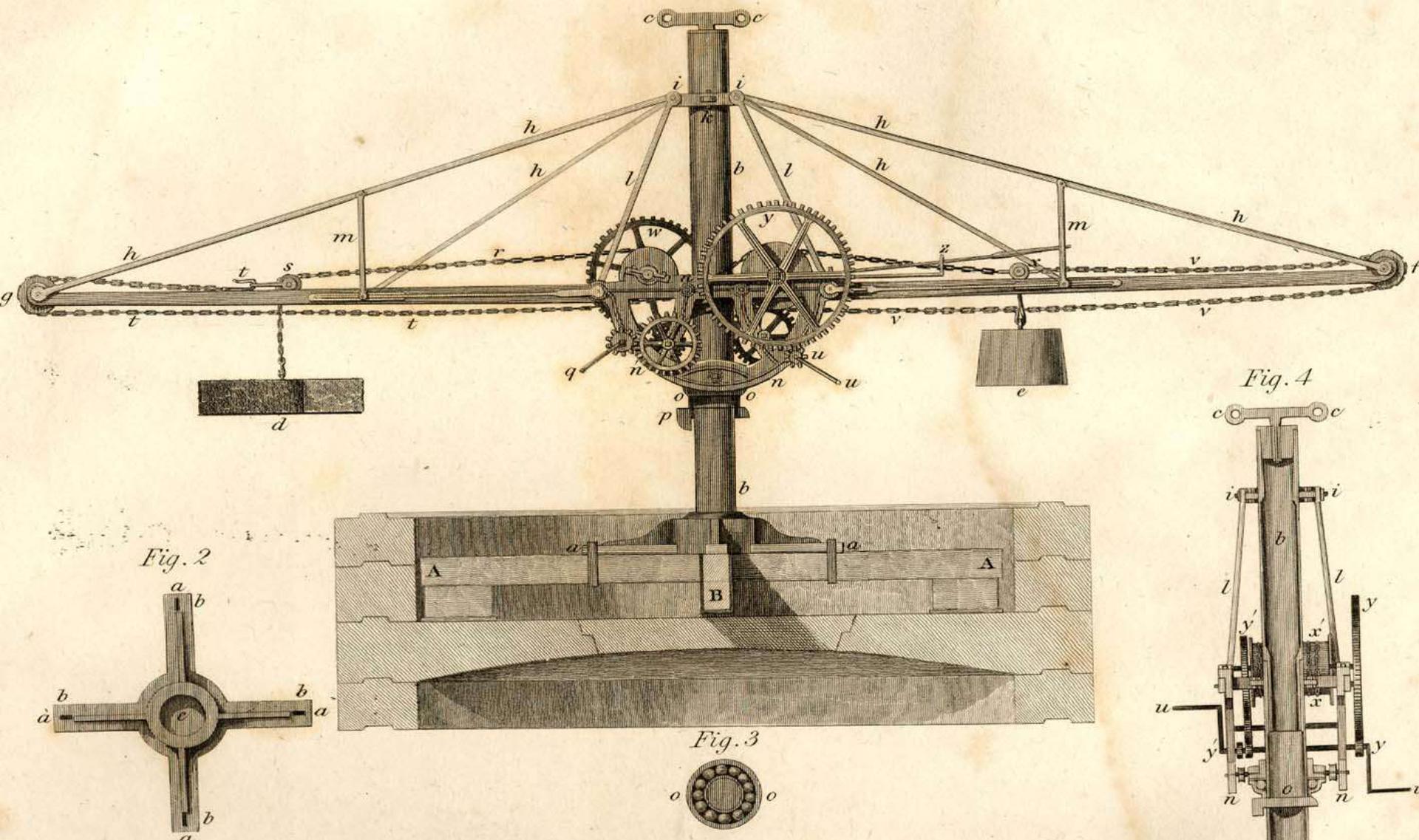


Off-loading stone from the Smeaton into a praam
boat and the state of the works in June 1810

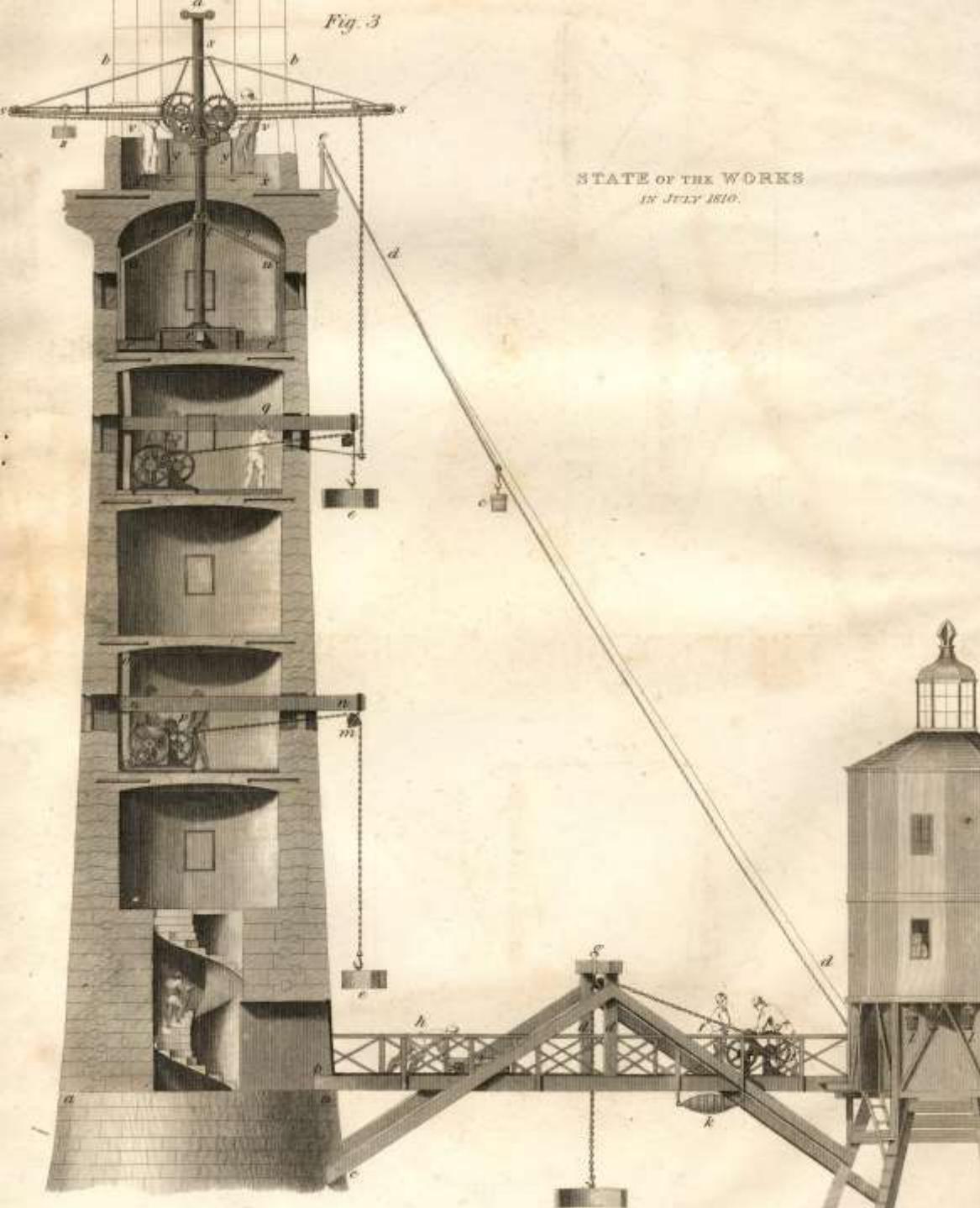


© NLS

Bell Rock Lighthouse – iron balance crane used to erect the tower. Designed under Stevenson's direction by Francis Watt, drawn by David Logan, Clerk of Works – More innovation - the world's first iron tower crane?



**Variant of Watt's balance crane used at Carr Rock in 1817
with horizontal travel beam (modified by James Slight c.1817
another competent assistant - later a civil engineer)**



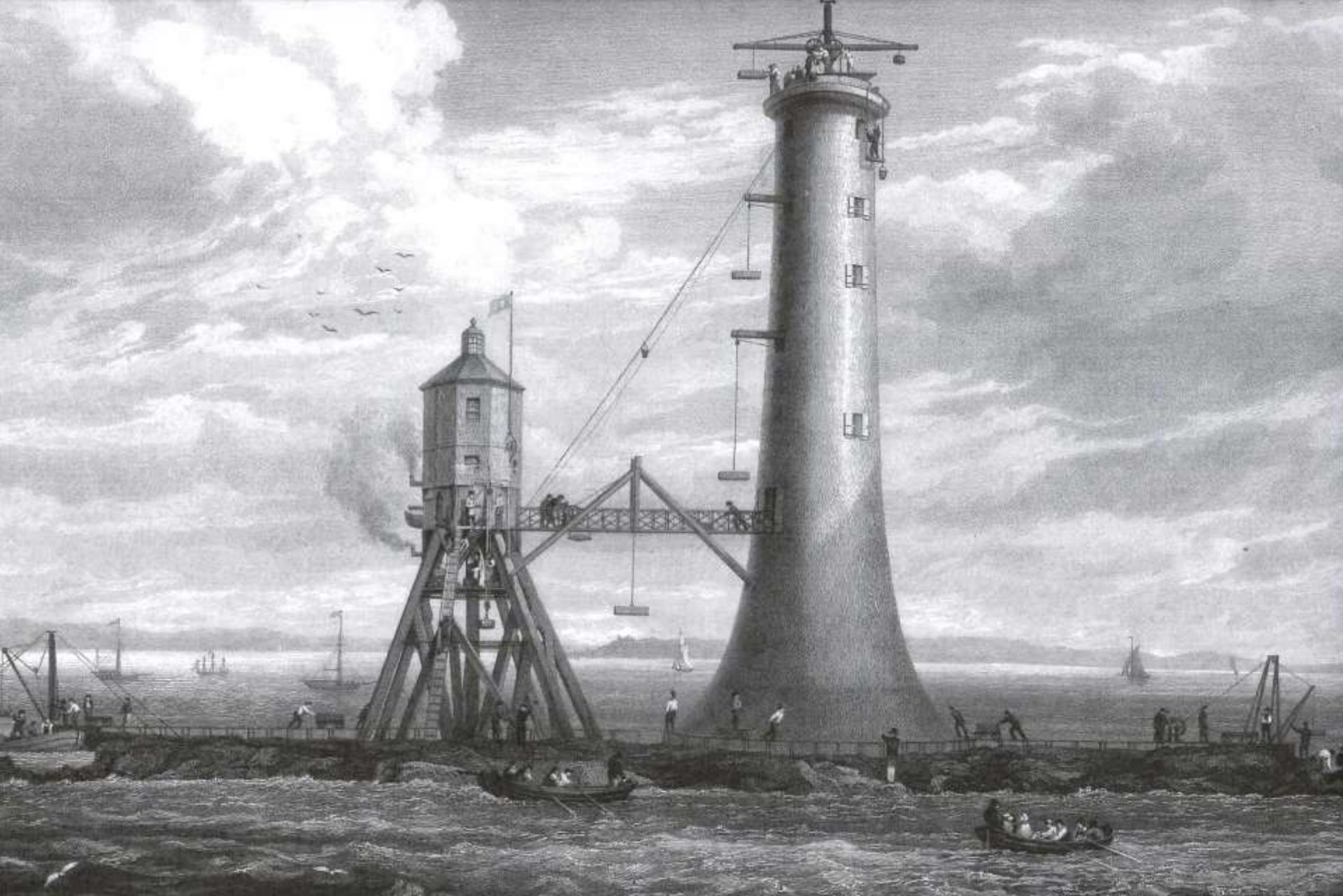
Operations at Bell Rock lighthouse in July 1810.
Note shaft of tower crane passing through light-room dome being used with the 3-winches arrangement to get the stones up 100+ ft from the railway to the light-room wall – note also the bucket in transit from the beacon mortar gallery to tower top.



The ‘Library or Stranger’s Room’ finely furnished under Stevenson’s direction. Included bookcase, books, tripod table, bible, antique lighting, Turkey carpet until 1960s – by 1986 it had become the kitchen!



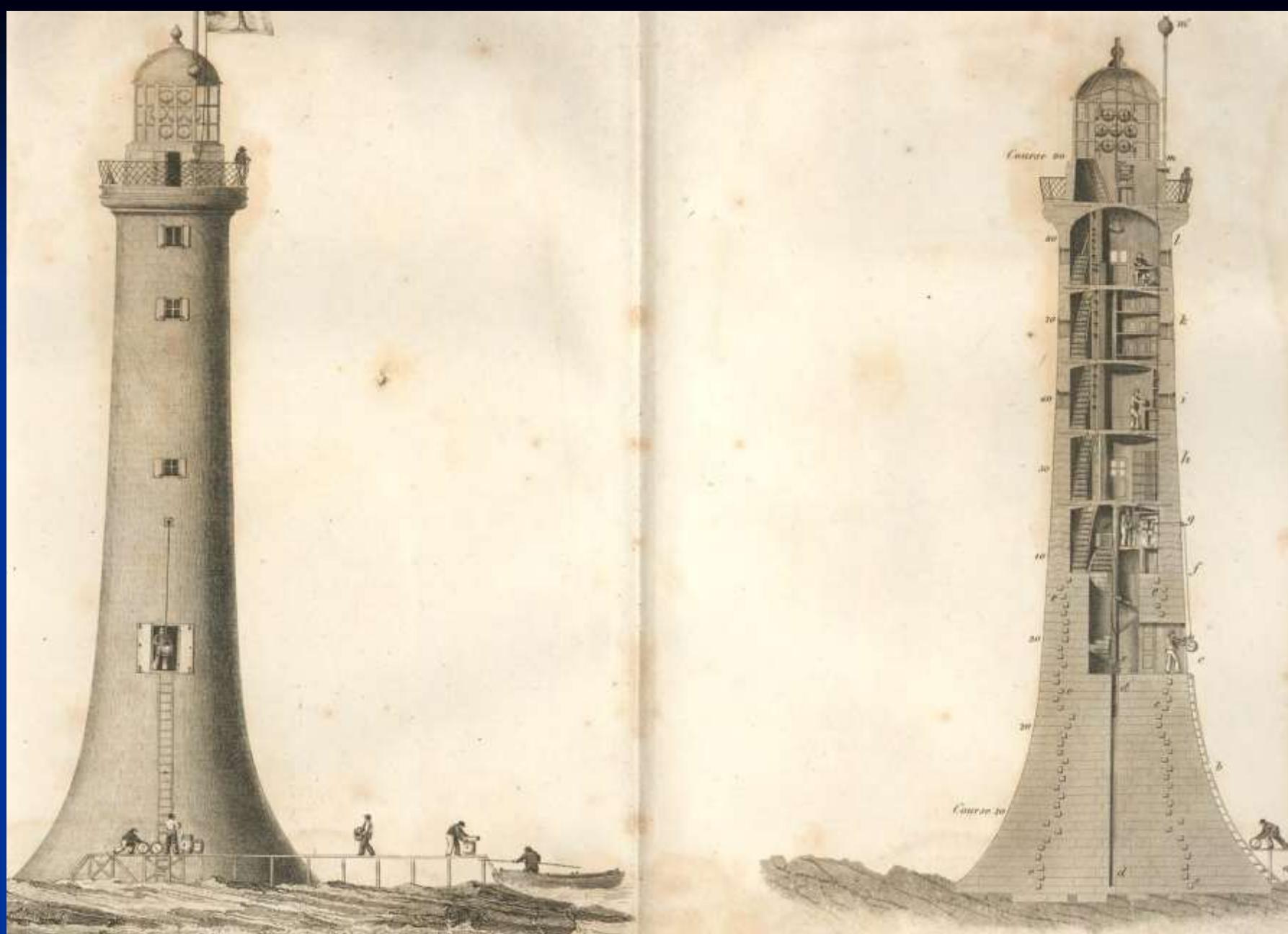
Finishings by Wm. Trotter, Edinburgh and Alex. Macdonald, Arbroath, painter



Overall activity at the Rock in July 1810



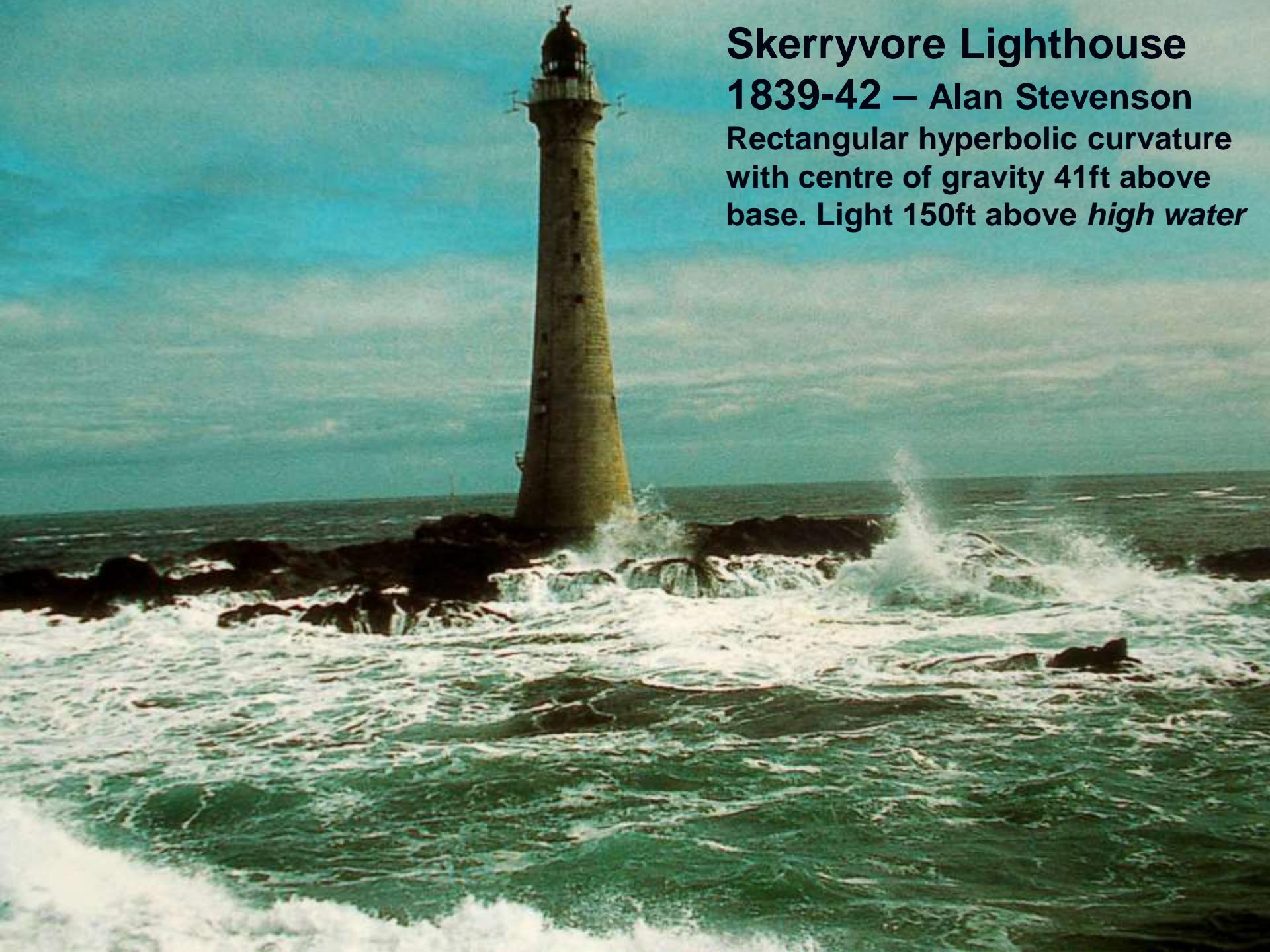
Light-room with on a revolving frame- 4-sided array of 20 silvered-copper reflectors and Argand lamps with red glass at 2 ends (at Cape Bonavista Canada,1843)
Note: gravity operated rotating mechanism to frame, signal ball, fog bells, ornamental cast-iron balustrade, kitchen chimney and, cantilever and suspended span floor and top of dome of 'Library or Strangers' Room built in Craigleith stone



**Completed lighthouse 1811. Cost £61,331. 9s 2d Contains 28,530 cu.ft
stone and weighs c. 2,076 tons. Light first exhibited 1 February 1811**

Findings

- Creation of the lighthouse was an heroic example of empirically based civil engineering before the ‘strength of materials’ design and steam-powered equipment age. Innovative temporary works enabled completion in four working seasons.
- the project influenced sea-washed lighthouse building, and maritime construction, for several decades e.g. Skerryvore (1839-42) and Dhu Heartach (1869-72). Watt’s ingenious cranes had a much wider application following leading articles in the *Mechanics Magazine* and other publications by 1825.
- contrary to nearly two centuries of public misunderstanding of Rennie’s role as Chief Engineer for the lighthouse (stemming from its being played down by the Stevensons) its as-built basic structural and hydraulic design was determined by Rennie who exercised an overall superintendence by giving advice and directions in reports, sketches, many letters and on site visits.
- the lighthouse, a development of Smeaton’s practice, was designed and executed jointly and competently by Rennie and Stevenson and their dedicated workforce headed by the talented Logans, and the inventive Francis Watt. Its success enabled Stevenson to establish the Scottish lighthouse service and found a family engineering dynasty which lasted until 1952.

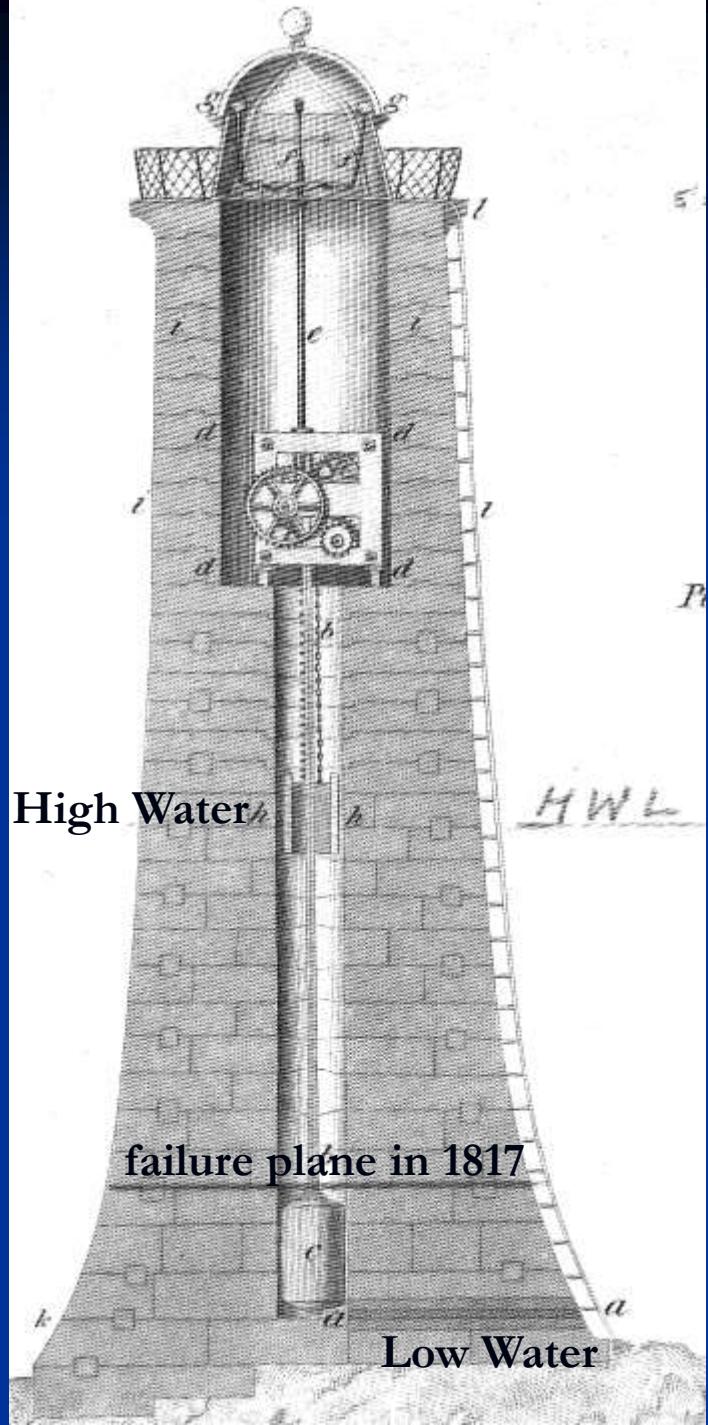


Skerryvore Lighthouse
1839-42 – Alan Stevenson
Rectangular hyperbolic curvature
with centre of gravity 41ft above
base. Light 150ft above *high water*

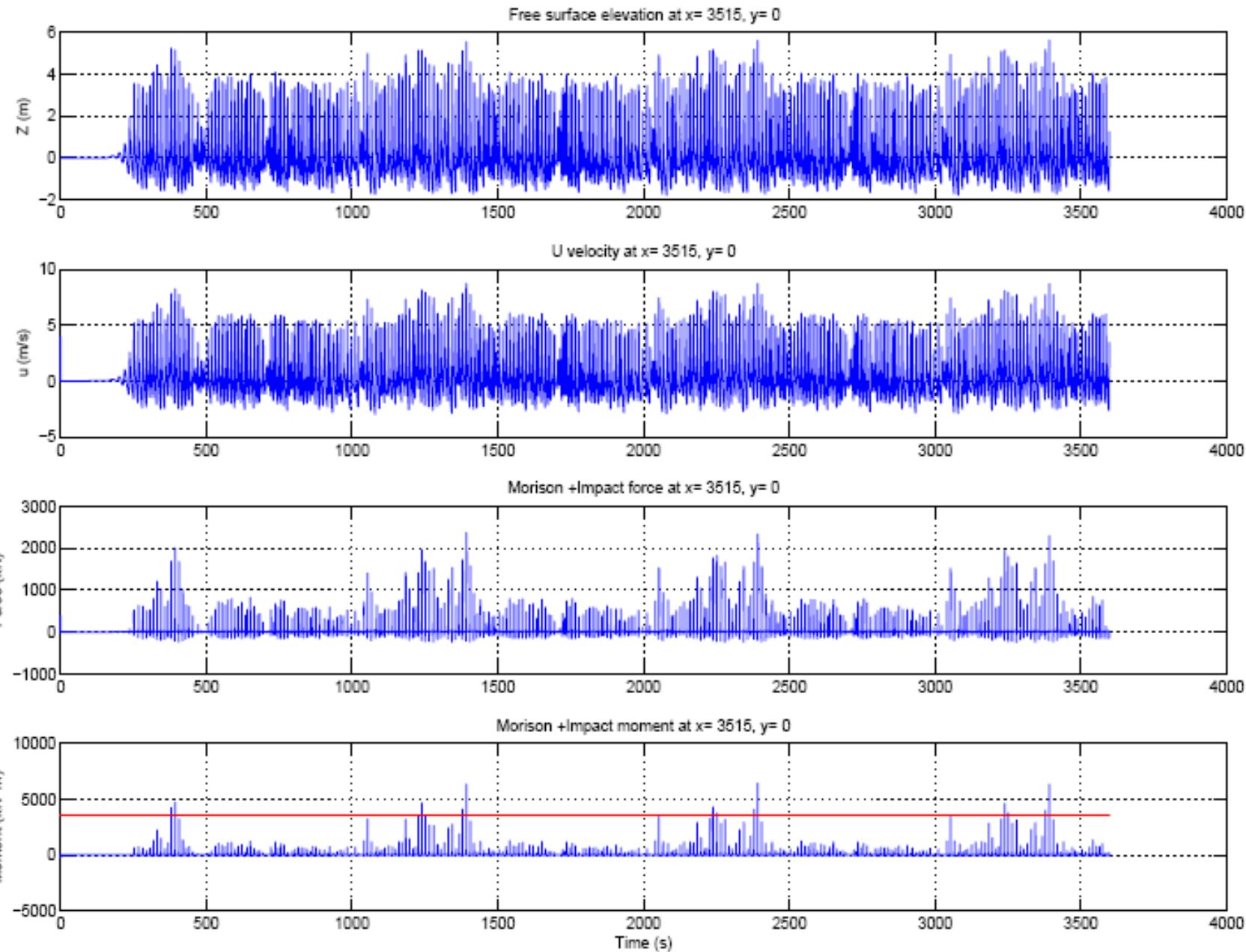


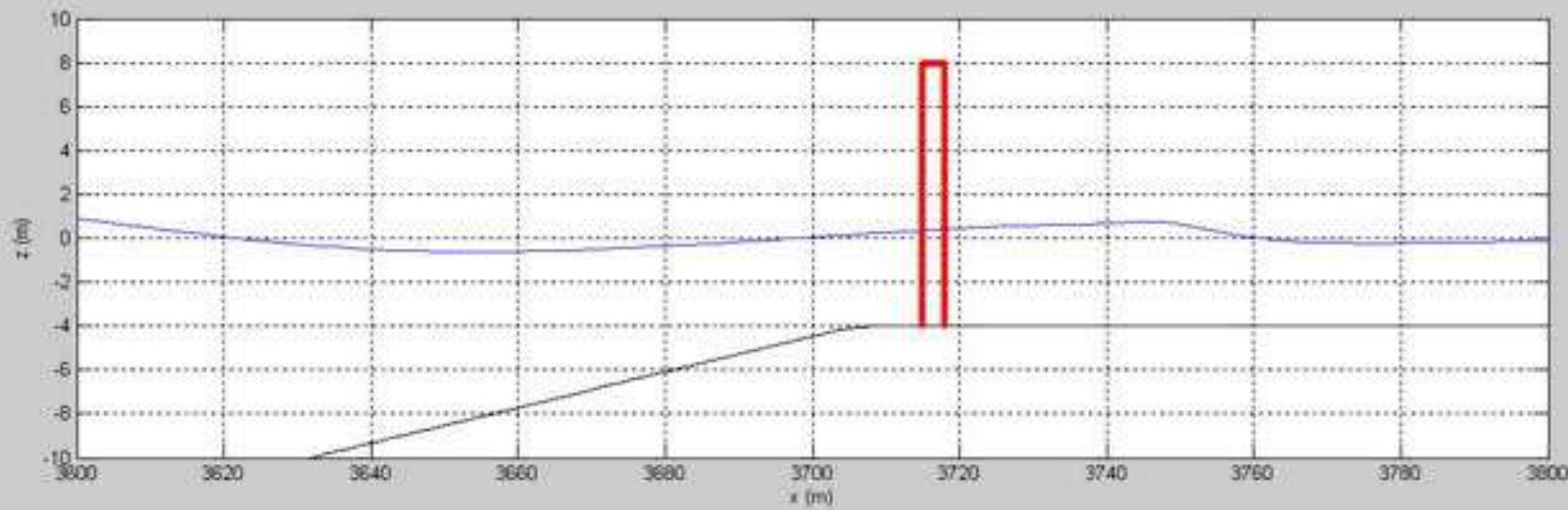
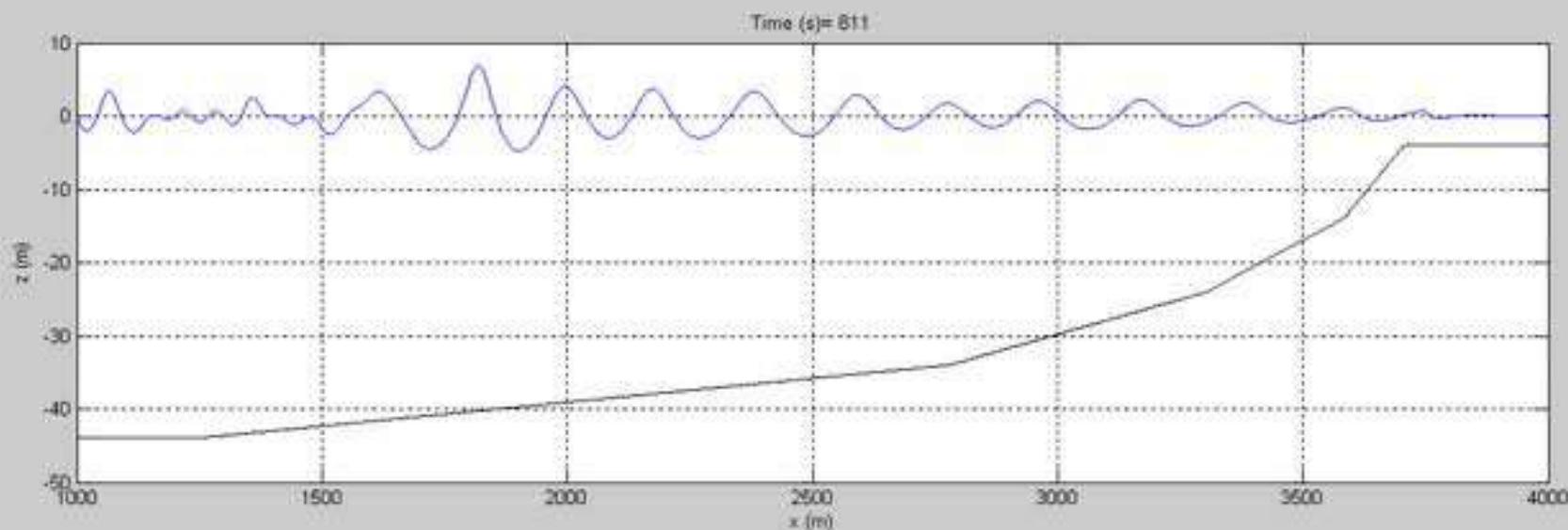
Dhu-Heartach
Lighthouse
erected 1869-72
D & T Stevenson



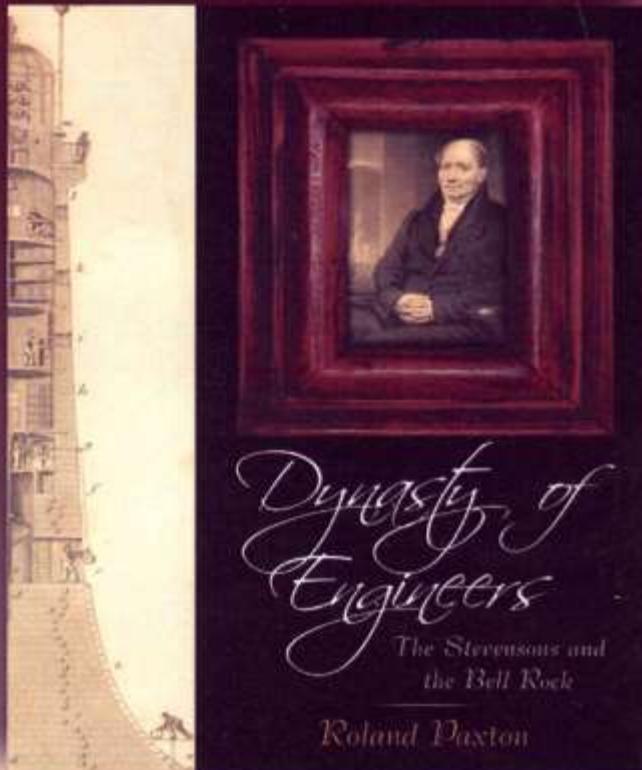


Stevenson's Carr Rock Beacon about 40 ft high, erected 1817, was destroyed in a storm shortly after completion. Modern analysis at Heriot-Watt University indicates that for a 5-year storm event, 5 m high waves would have exerted an overturning moment at the failure plane of nearly twice the restoring moment of the tower weight on four occasions within an hour, the probable failure cause. i.e. The 180 ton weight of tower was insufficient to resist a wave impact of about 200 tons acting on the basis of North Sea research about 2.5m above the failure plane





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Roland Paxton

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