FORTH CROSSING CHALLENGES AT QUEENSFERRY BEFORE THE RAIL BRIDGE

R.A. PAXTON
Vice Chairman Institution of Civil Engineers' Panel for Historical Engineering Works
Senior Principal Engineer Lothian Regional Council, Highways Dept
Senior Research Fellow Heriot–Watt University

Abstract
In this paper engineering challenges and improvements to crossing the Forth at or near Queensferry from c.208 to 1873 are identified and assessed. Attention is given to the practice of various civil engineers in the work contexts of harbours and ferries, tunnels, and road and railway schemes. More particular consideration ranges from the improvement of ferry landings by Smeaton, Rennie, Stevenson and Telford, to impracticable proposals for tunnels and bridges, and concludes with the railway triple challenge of Sir Thomas Bouch. The subject is necessarily set in a context of the evolution of structural practice and the whole constitutes a history of the Queensferry crossing from a civil engineering standpoint.

1 Harbour and Ferry Improvements

1.1 Introduction

In 1760, although the Queensferry 'Passage Ferry' was the most frequented in Scotland, the bad condition of the loading and landing places, especially at low water, was "not only highly disagreeable and inexpeditious, but even dangerous".(1) As the communications improvements associated with the Industrial Revolution began to gather pace nationally it became essential to improve the ferry. In 1772 a petition was sent to the Forfeited Estates Commissioners from Fife J.P.s and the ferry owners requesting financial aid towards a £980 package of improvements.(2) The name of the engineer, if any, who prepared the plans has not been found. The Commissioners consulted John Smeaton (1724-92), the 'father of civil engineering', who was already making an important contribution to the Scottish infrastructure. In addition to engineering the Forth & Clyde Canal, he had already introduced major improvements to the machinery at Carron Ironworks and built large bridges at Perth and Coldstream.(3) He had also reported on numerous harbours.

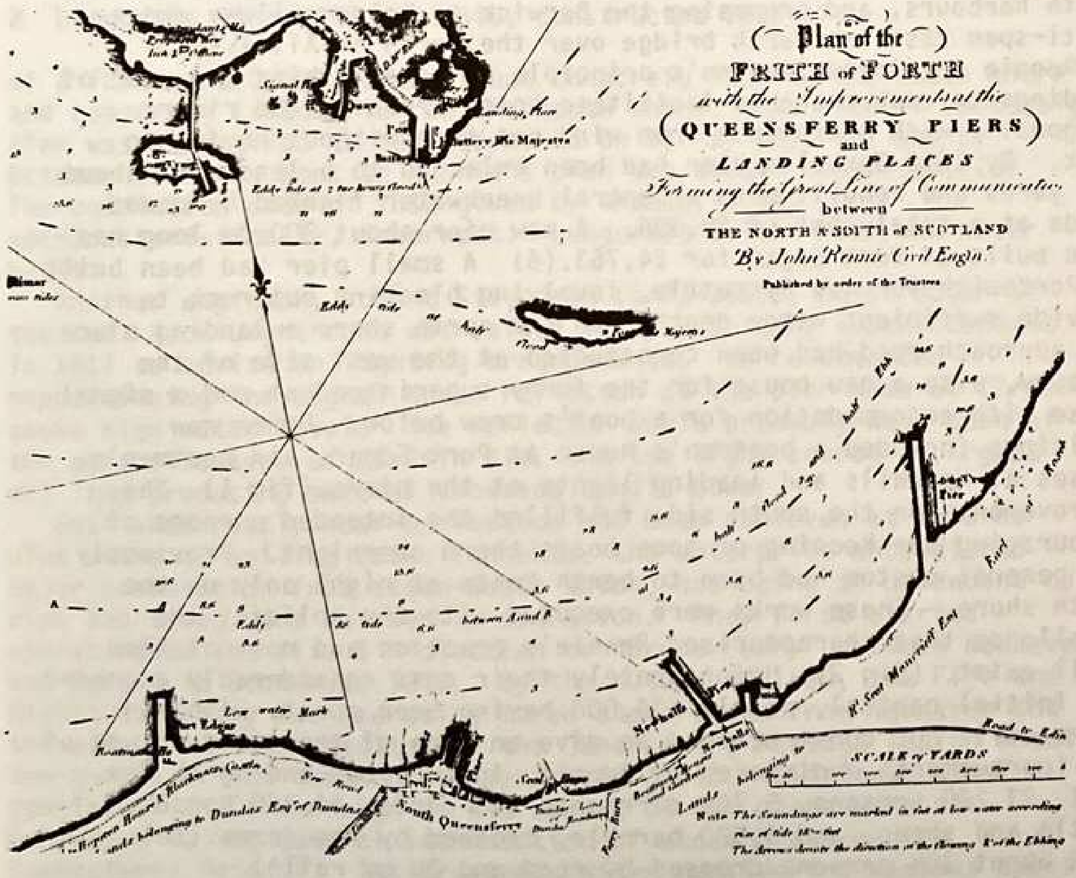
1.2 Smeaton's Report on the Queensferry Landings 1772.(4)

Smeaton considered the principal defect of the ferry to be in its landing places, which being "in a great measure furnished by nature ... require a little assistance from art". He drew particular attention to the lack of low water landings by which "travellers are often detained when the wind is fair and afterwards further detained by the winds coming foul". Then as now the prevailing wind was from the west and there were strong cross currents.

Smeaton recommended having a spread of landings on each shore to enable boats to cross more frequently without tacking, thus saving time. More particularly his recommendations included improving a 96yd length of the Grey Landing (contiguous to Queensferry Harbour) down to low water, to face both east and west. At the West Hall (Hawes) Pier he proposed part facing, part building on and part levelling the rock for 142yd down to a point from 5-6ft above the sand. On the north shore he advocated the extension of Craig End Pier (the town pier) by 53yd and that the East Ness Landing access should be improved by providing a smooth road across the rough rocks. This work was to be done by blasting or by bolting timber to the rock, to take the wheels of carriages in the manner of a rail-road.(4) It would appear that Smeaton's advice, or much of it, was heeded by the applicants and grant-aiding authorities as by July 1777, the Royal Burghs of Scotland had contributed £300(1) and the Forfeited Estates Commissioners £600; the latter on the basis of the ferry forming part of a military road and being the most frequented sea passage in Scotland.(2) In 1775, the Trustees for the Improvement of Fisheries and Manufacturers also contributed to the repair of Newhalls Pier and a landing east of North Ferry.(6)

1.3 Baird's Report on the Improvement of Queensferry Harbour 1817

In the latter part of the 18th century Queensferry Harbour consisted



1 Queensferry landing improvements - Rennie 1809-17

internal-paddle steam-boat which he advocated for use on this ferry,(15) commissioned a paddle steam-boat to the design of their superintendent. The vessel, named the 'Queen Margaret' entered service in October 1821, towing large and small sailing boats in its wake. On the south side at low-water, only Longcraig Pier had sufficient water depth to accommodate the boat and because of the incompatibility of its external side paddles with the pier profile, wheeled traffic could not be handled. In 1821 a fleet of new sailing boats was introduced but the whole operation failed to meet the increasing steam-boat challenge from the 'Broad Ferry' and in 1828 the Trustees consulted Britain's leading civil engineer Thomas Telford (1757-1834) to see what could be done to improve matters.

1.5 Telford's Reports on the Forth Ferries 1828

Telford reported that the probable future revenue of the ferry was incompatible with changing the whole mode of operation from a sailing to a steam-boat system. He advised adopting only improvements which could be accomplished at a justifiable expense, adding, "that such are become indispensibily necessary the rapid improvement of conveyance on all sides is sufficient evidence."(16) Telford's recommendations included an extension of the Signal House (Craig End) Pier into deeper water. This measure was intended to provide a safer wharfage on its eastern side, to protect the extremity of the Battery Pier, and to supply additional accommodation. He commented, that to have extended this pier before the introduction of steam-boats would have obstructed the necessary tacks for sailing boats making passage to the south. On the south side Telford considered it impracticable to obtain a greater low-water depth at Newhall Pier without unwarrantable expense. For low-water use he recommended Longcraig Pier where the water depth was already sufficient, but because this pier was exposed to the prevalent westerly winds and the force of the ebbing tide current, he advised provision of a rubble stone breakwater alongside it at a short distance to the west. Telford left the question of the detail and estimates for these improvements to his Edinburgh civil engineering associate James Jardine (1776-1858).

From a comparison of Rennie's plan and the 1856 O.S. map Signal House pier appears to have been extended. Longcraig breakwater was not built. In 1828 Telford was also consulted about the Fife & Midlothian Lower Ferry. He considered its revenue prospects very good and supportive of nearly £61,000 of improvements including a new pier at Burntisland and a new landing at Newhaven 400 yards out from the existing pier head so as to achieve a 10ft low water depth for steam-boats.(17) This work was not carried out but subsequently major development occurred at Granton and Burntisland harbours.

1.6 Development of Engineering Practice 1770-1830

In structural engineering terms the works referred to so far would have required little in the way of strength calculations, mainly consisting of foundations, gravity masonry walls and timber piles and beams in foundations, and timber and cast iron as struts and tension members. Practices adopted were based on experience or experiment. Piers generally consisted of a pair of masonry walls of a pair of not quite parallel piers curving inwards at their sea-ward ends to form an entrance from the north, with a ferry landing place on the outside of the east pier.(fig 1) The harbour was improved to a design of 1817 by Hugh Baird (1770-1827), engineer to the Union Canal. He advised turning the west pier at a right angle and running it eastwards to a new entrance in the north-east corner of the harbour.(fig 10) This work, which involved rebuilding the head of the east pier adjoining the ferry landing, was carried out and thus the harbour was brought more or less to its present form.(7)

1.4 Major Improvements to the Ferry 1808-17

The ferry improvements completed c.1777, which presumably resulted in two good landings on each shore, sufficed for over two decades, but with increased trade, commerce and travel, a better crossing facility became necessary. In May 1809 an Act(8) was passed vesting the ferry in new Trustees as part of the improvement of the Great North Road from Edinburgh to Perth and beyond, and major development ensued. With a capital of £18,500, after paying off the former owners, the Trustees set to work improving the whole establishment to the plans of the eminent engineer John Rennie (1761-1821). His recent work in the locality had already included Musselburgh Bridge, Bell Rock Lighthouse, Leith, Berwick and St Andrews harbours, recommending improvements at Newhaven, Charlestown, Burntisland and Perth harbours, and proposing the Berwick to Kelso railway and a multi-span cast iron arch bridge over the Forth at Alloa.(9)

Rennie developed Smeaton's principle of establishing a spread of landings on each shore to facilitate boats crossing the river diagonally with assistance from wind and tide without having to tack. By 1812 Newhalls Pier had been enlarged to a length of about 240 yards and rebuilt with a central breakwater flanked by paved roads at a total cost of £8,696. A new pier about 200yds long had been built at Port Edgar for £4,763.(6) A small pier had been built at Portnuick for use by cattle, involving blasting out rock to provide sufficient water depth. On the north shore a landing place and approach road had been constructed at the west side of the Battery, also a new house for the ferry superintendent and a signal house with accommodation for a boat's crew below. Other new buildings included a boatman's house at Port Edgar, six boatmen's houses at Newhalls and leading lights at the piers.(fig 1) The improvements on the south side fulfilled the intended purpose of encouraging the keeping of some boats there overnight. Previously the general custom had been to berth boats at night only on the north shore. These works were executed with the solidity and excellence that characterised Rennie's practice and most of them still exist. (fig 2) Unfortunately their cost considerably exceeded the initial capital, nearly £34,000 having been spent, with two piers still not constructed. To give an idea of the scale of use of the improvements engineered by Rennie, in the year ending 15 May 1811, 83,220 persons, 5,769 carriages and carts, 44,365 horses, cattle and sheep, and 5,520 barrels, crossed by the ferry.(10) (In 1989 about 30m persons crossed by road and 3m by rail!)

A new Act(11) was obtained in July 1814 authorising expenditure

2 Longcraig Pier 1990 - Rennie, constructed 1816-17

of a further £20,000 to construct Longcraig Pier on the south shore and Longcraig Island Pier on the north shore. The site of Longcraig Pier was advertised to be determined on 13 May 1816(12) and by October 1817 the work to Rennie's plan was almost completed.(13) The completion date of 1812 given by Graham(7) is, uncharacteristically, incorrect. Longcraig Island Pier was never built.

Another engineer, Robert Stevenson (1772-1850), constructor of the Bell Rock Lighthouse was called in by the ferry superintendent in 1817 to advise on lighting arrangements. He recommended repositioning the signal house reflector at the pier head at 12-15ft above high water level. The reflector would probably have been of the parabolic type of 21-24in dia. and the light source an Argand oil lamp producing several thousand candle-power.

Just when costly near-perfection had been achieved at this ne plus ultra of sailing establishments, the enterprise encountered major competition from steam-boats which, not being so dependent on wind and tide, were quicker in operation. They first started operation on the Fife & Midlothian or 'Broad Ferry' between Newhaven and Dysart in September 1819. By the autumn of 1820, the Fife and Midlothian Ferry was operating three steam-boats from Newhaven and the effect of this resulted in the Queensferry Passage losing about two-thirds of its coach passenger traffic(14). Difficult tidal conditions and the design of and spread of the piers were not conducive to the general introduction of steam-boats on the Queensferry Passage. Its Trustees, after considering various types of paddle steamer, probably including Stevenson's novel 'Dalswinton' internal-paddle steam-boat which he advocated for use on this ferry,(15) commissioned a paddle steam-boat to the design of their superintendent. The vessel, named the 'Queen Margaret' entered service in October 1821, towing large and small sailing boats in its wake. On the south side at low-water, only Longcraig Pier had sufficient water depth to accommodate the boat and because of the incompatibility of its external side paddles with the pier profile, wheeled traffic could not be handled. In 1821 a fleet of new sailing boats was introduced but the whole operation failed to meet the increasing steam-boat challenge from the 'Broad Ferry' and in 1828 the Trustees consulted Britain's leading civil engineer Thomas Telford (1757-1834) to see what could be done to improve matters.

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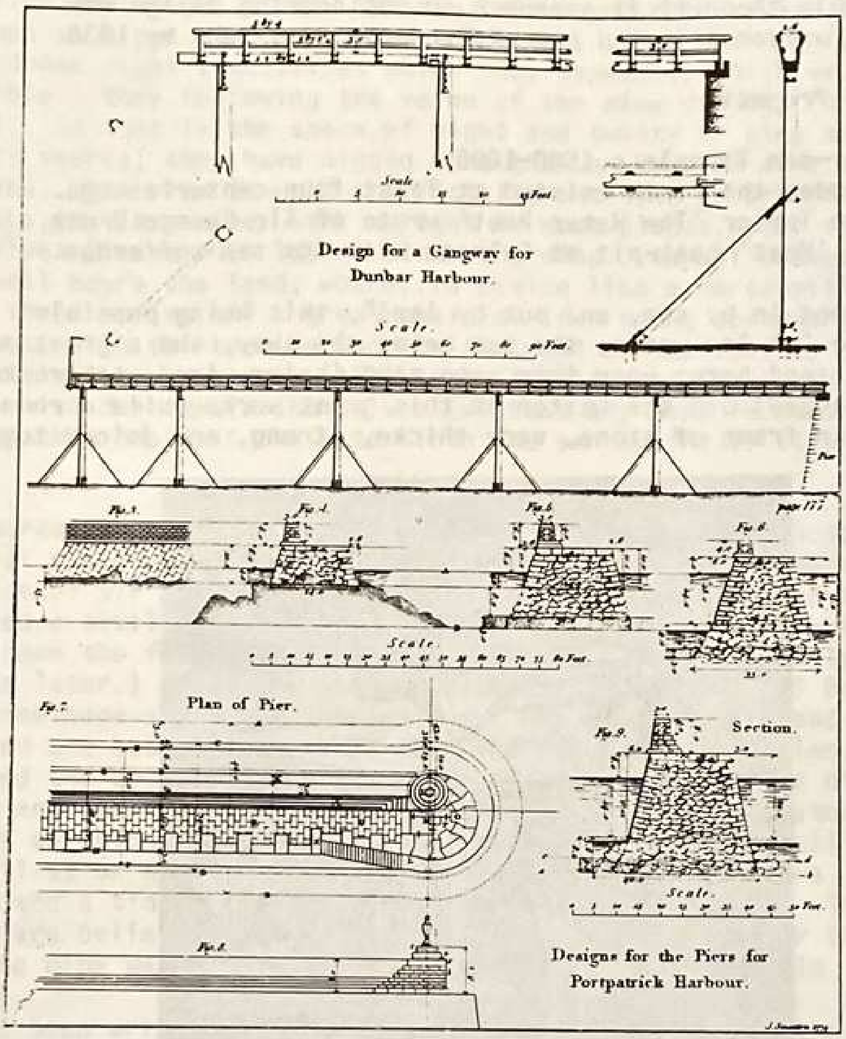
From c.1800, cast iron beams, columns, plates and other castings



3 Typical harbour construction - Smeaton 1770-72

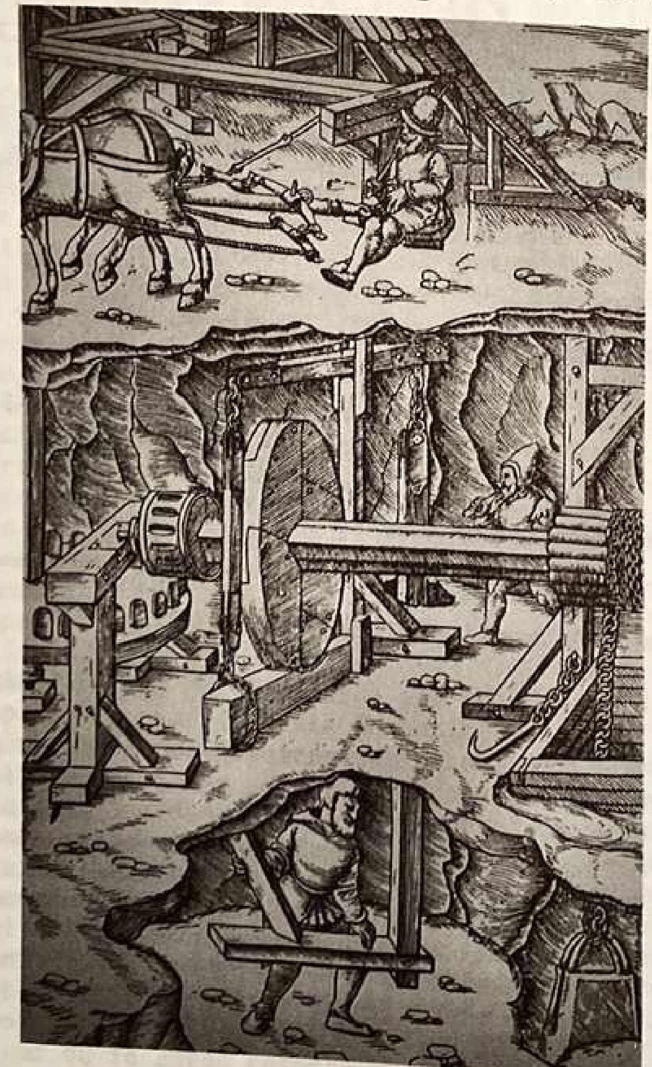
were available. Wrought iron was obtainable up to about 3in dia. cross-section in long lengths and as narrow plates. From c.1800 portable steam-engines were used increasingly for powering pumps, dredgers and other equipment. By 1830, the use of artificial cement, mass concrete in foundations and more effectively preserved timber was developing. The use of steel and reinforced concrete in structures did not begin until the latter part of the century. 'Strength of materials' education for engineers from textbooks, as distinct from 'word of mouth' and experimence, was in its infancy and gathered momentum from c.1817, developing rapidly in the 1820's mainly on a practical and empirical basis. From 1822, Tredgold's textbook on cast iron(18) with its empirically derived safe-load tables was useful to engineers in designing beams of up to 30ft span and columns up to 24ft high. The foundation of the Institution of Civil Engineers as a forum for the exchange of knowledge in 1818 represented a landmark in the development of engineering education. The reliable theoretical approach to engineering design now practised universally had not evolved to any extent by 1830.

2 Tunnel Projects

2.1 Under-sea Tunnels c.1580-1805

Tunnels under the Forth existed at least four centuries ago. In 1618, John Taylor 'The Water Poet' wrote of Sir George Bruce of Carnock's 'Moat' coal-pit at Culross with its sea cofferdam entrance:

> "I...went in by sea, and out by land", this being possible because "at low water, the sea being ebd away, and a great part of the sand bare; upon this same sand (being mixed with rockes and cragges) did the master of this great worke build a round circular frame of stone, very thicke, strong, and joined together



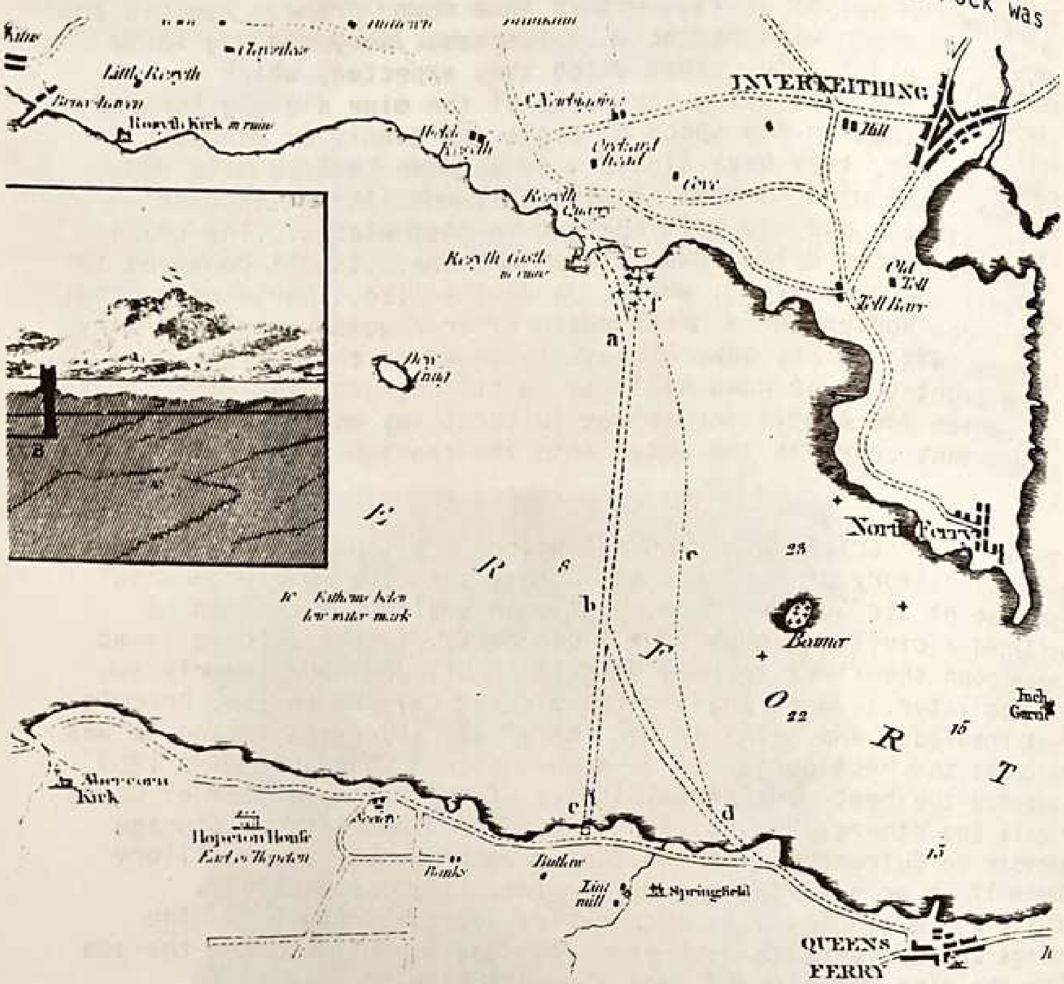
4 Horse-whim and machinery to mine shaft chain - Agricola 1556 with glutinous or bituminous matter so high withall that the sea at the greates flood...can neither dissolve the stones...or yet overflow the height of it. Within this round frame...hee did set workmen to digge with mattockes, pickaxes...They did dig forty feet downe right into...that which they expected, which was sea-cole...they following the veine of the mine did dig forward still: So that in the space of eight and twenty or nine and twenty yeeres, they have digged more then an English mile under the sea...the mine is most artificially cut like an arch or vault...that a man may walk upright in most places...The sea at certaines places doth leake...into the mine...is all conveyed to one well neere the land; where...a device like a horse-mill, that with three horses and a great chain of iron going downeward many fathoms, with thirty-sixe buckets fastened to the chaine, of which eighteene goe down still to be filled, and eighteene ascend up...which doe emptie themselves (without any mans labour) into a trough that conveyes the water into the sea againe..."(19) (fig 4)

The works described are of outstanding significance in Scotland's industrial history and provide an insight into the entrepreneurial enterprise of Sir George Bruce, gentleman coal-owner who can be considered a civil engineer in all but name. (Smeaton is believed to have been the first to call himself 'civil engineer' nearly two centuries later.) When leasing the mine at Culross in 1575 Bruce's "great knowledge and skill in machinery" was acknowledged and he was considered the best person to re-open the then abandoned mine.(20) He adopted the best continental 'state of the art' practice of Georg Agricola and others.(21) By 1595 Bruce had constructed a storage reservoir on Culross Muir to guarantee water supply to a colliery water-mill at or near the horse-gin site. He also erected a windmill and a tide-mill as alternative power sources.(22) The workings are believed to have extended some two miles under the sea before the mine was flooded over the cofferdam in a storm in 1625.(23)

It has been written that a proposal for a tunnel under the Forth at Inchgarvie was mooted about 1790,(24) but it was not taken seriously, possibly because of the impracticability of mining through whinstone. Fifteen years later a proposal for a tunnel 1½ miles to the west did receive wide consideration.(25) The engineering case for it was supported by successful under-sea tunnelling precedents at the Culross, Bo'ness and Whitehaven mines, and operational canal tunnels at Harecastle and Sapperton. By 1805, the Bo'ness workings had extended about a mile under the Forth at depths from 20-80 fathoms. The Valleyfield under-sea workings of Sir Robert Preston at Culross were so dry that they could be drained "by a boy with a bucket".(27) At Whitehaven the workings were at a depth of from 80 to 150 fathoms under the sea with access via white-walled tunnels on a 1 in 6 gradient.

2.2 Forth Tunnel Proposals 1805-7

In November 1805 a William Vazie, possibly a mining engineer, sought the opinion of a leading Edinburgh mining engineer John Grieve as to whether a tunnel under the Forth from Rosyth Castle to the opposite shore was practicable. Grieve thought that it was, as the rock was



5 Forth Tunnel plan 1806. Inset : Moated shaft - looking west

likely to be passable freestone, but called for this to be confirmed by borings all along the tunnel line. On the basis of a maximum water depth of 11 fathoms (66ft) from a chart, Grieve suggested a maximum depth for the tunnel sole of 30 fathoms (180ft). He proposed twin 15ft wide arched tunnels with a central drain level beneath. The tunnels were to have had 500yd entry sections parallel to each shore with gradients of 1 in 25 so as to achieve 50ft of cover before turning under the sea. From these turnings the main tunnels would have descended for 1800 yards from each side at a gradient of 1 in 45 meeting mid-way at the maximum depth. For drainage Grieve proposed constructing two moated engine pits over 200ft deep at each low water mark. At the bottom of the pits steam-engines and pumps were to have been installed. He estimated the cost of the tunnel at £160,000-£170,000 with a four year construction period.

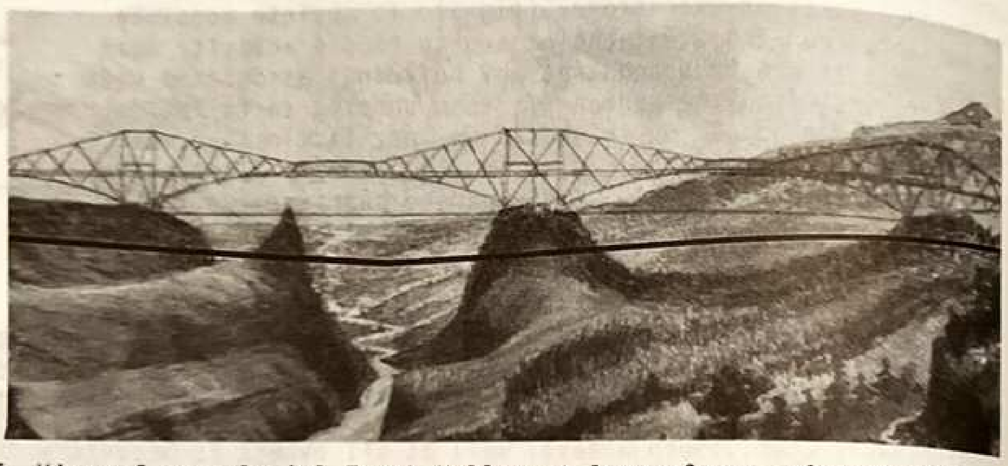
In summer 1806 Vazie and his associate Taylor reported in similar vein after a site visit with Grieve. Some alterations were suggested to meet objections from the Earl of Hopetoun. The proposed tunnel entrance on the south was moved westwards to within a few hundred yards of Queensferry.(fig 5) To obviate possible smoke nuisance from the steam-engine and to reduce activity near Hopetoun House it was proposed that any buildings associated with the project, including the permanent steam pumping installation, were to be located on the north shore. A busy little town was envisaged at Rosyth "with the Castle in its bosom". Alternative cross-sections were given both with separate carriageways for 'comers' and 'goers'. More thought had been given to passing under the deep part of the river.

> "If the boring should in any manner of way leave the investigation incomplete...it may become necessary to advance...with caution...by putting down pits at low water mark...to the necessary depth and cutting a communication by a level between them...Such a level will at all events be necessary as a drain...for drawing the water from the tunnel...Will require to have placed...the engines necessary for the great work...no new or additional expense...an expenditure would be incurred, including engines, from 12 to 15000 £..."(25)

The proposal was also supported by the civil engineer Robert Bald (c.1778-1861), who considered it highly prudent to make soundings and borings as a preparatory step. The Scots Magazine was "happy to see that this undertaking is in a great state of forwardness and that a number of noblemen and gentlemen of the first respectability have organised themselves into a regular body for the purpose of carrying it into effect".(26) In March 1807 a Dr Millar and Vazie republished an enlarged illustrated edition of the various reports with an economic case.(27) The tunnel was not started, probably more for economic reasons than doubts about its engineering practicability.

2.3 Assessment

It is fortunate for the promoters that the project did not proceed, as the ground under the deep part of the river would have proved very different from that which they imagined. The mining experts of the day expected the freestone to extend from shore to shore, a concept which was proved as late as 1964 several miles west when the Kinneil and Valleyfield mines were joined, but at a depth of about 1800ft.(28) At the depth of 180ft proposed for the Queensferry Tunnel, the miners would have encountered a deep channel in the bed of the river filled with sand and silt. H.M.Cadell of Grange, the Scottish geologist drew attention to this subject in 1913(23) and provided a dramatic sketch of his impression of the pre-glacial Forth valley, complete with mammoth and Forth Bridge.(fig 6) Although Cadell's concept of deeply buried pre-glacial river channels is no longer considered tenable,(29) there is no doubt that a channel containing a considerable depth of sand and silt does exist, whatever its origin, and his sketch serves to illustrate the difficulty the tunnellers would have had to contend with. The question now is whether the tunnel could have been constructed in such material in 1807. A review of contemporary experience indicates the answer.



6 View of pre-glacial Forth Valley at Queensferry - Cadell 1913
NOTE: The approximate tunnel line has been added by the author

From 1796-98 an engineer Ralph Dodd proposed a tunnel under the Tyne between North and South Shields.(30) Although this tunnel did not proceed, it was the precursor of his ambitious scheme for a 16ft dia. road tunnel under the Thames from Gravesend to Tilbury which did start.(31) Difficulties with groundwater in the preparatory operation of sinking a shaft for this tunnel in sandy material proved so great that the entire capital for the project was consumed without even achieving the shaft and in 1803 the project was abandoned. Undaunted by this set-back, a Cornish mining engineer, Robert Vazie (it is not known whether he was related to the William Vazie previously referred to) commenced work on a tunnel under the Thames at Limehouse in 1805. Difficulties experienced in sinking a 13ft diameter shaft through gravel and quicksand again proved so great that operations were suspended. Rennie and another leading engineer William Chapman were consulted but could not agree on a course of action. Work eventually recommenced under the direction of Richard Trevithick, notable Cornish mining engineer (and 'father of the locomotive'), on a 5ft pilot driftway ultimately intended to form a drain under the tunnel. A 30hp steam engine was used to pump out water. For a time good progress was made until, when nearing the far side of the river, sand and water frequently burst into the driftway and in 1808 work stopped. In March 1809 a premium was offered to any person furnishing a plan enabling the tunnel to be completed. At least 53 plans were received and examined by the eminent engineers Dr Charles Hutton and William Jessop who, after due consideration, concluded that "an underground tunnel which would be useful to the public and beneficial to the adventurers is impracticable". The problem had confounded the experts. Many thousands of pounds had been irretrievably lost and not a single brick of the tunnel had been laid.(32-34)

There can be no doubt that the proposed Forth Tunnel involving a substantial length of construction in river-bed silt and sand was beyond the technology of its time. A considerably deeper tunnel with the same gradients and passing under the soft material would have been ruled out on cost grounds. It would however be an option to consider for a new crossing of the Forth today.

3 Road Bridge Schemes

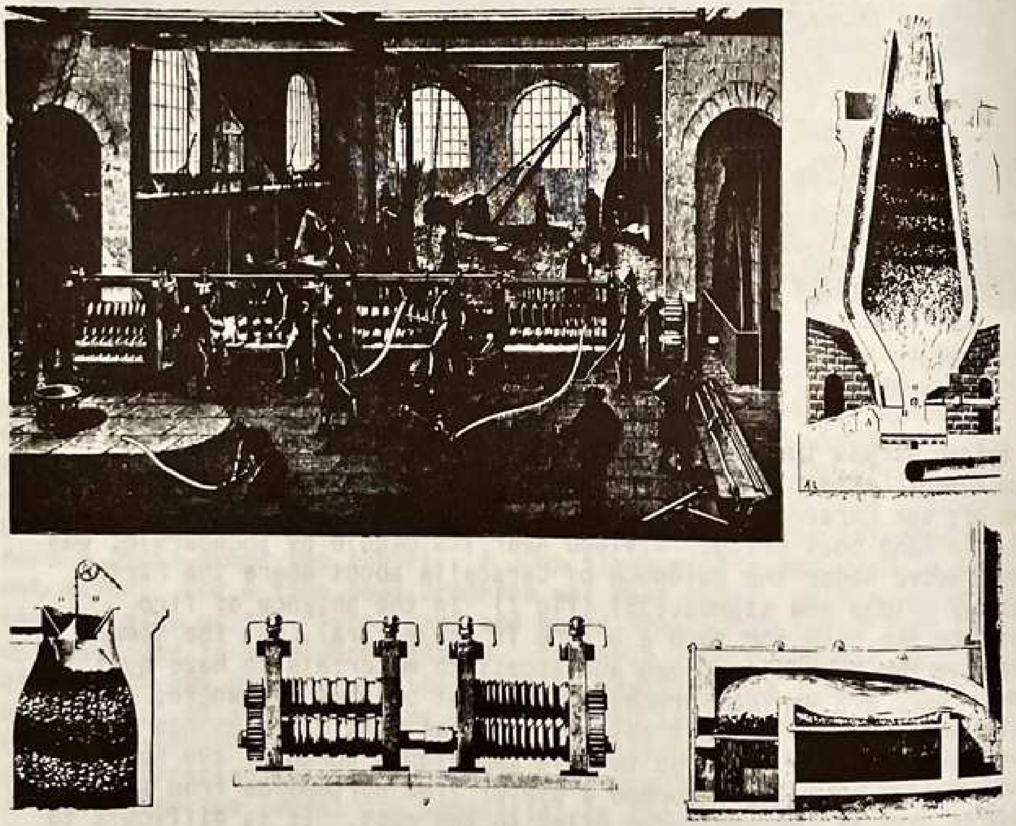
3.1 Possible Roman Campaign Boat Bridge

7 Possible Roman campaign boat bridge, Queensferry c.208. Drawn by D Cameron with advice on details from Dr G. Maxwell & author

A bridge across the Forth at Queensferry was probably considered by the Romans, possibly c.208 during the campaigns of Emperor Severus and his son Caracalla. One romanist has recently suggested that a 1¼ mile long boat bridge, divided near its middle by Inchgarvie, was constructed under the guidance of Caracalla about where the Forth Railway Bridge now stands.(35) (fig 7) In the absence of firm evidence the case for such a bridge is conjectural, but the Romans did have the technology, men and access to materials to have built one. There are various precedents of boat bridges elsewhere, some being depicted on Trajan's column. Several tens of thousands of Roman soldiers are believed to have campaigned north of the Forth and a bridge would have formed a useful link northwards from the Severan base at Cramond three miles to the east. It is difficult to imagine a boat bridge surviving winter storms; possibly assembling it was a seasonal operation. The provision, positioning and securing of some 500 boats would have been a major task. Would the Romans have given such a project the necessary priority over a ferrying operation?

3.2 Developments 1740-1817

A bridge may have been suggested as early as 1740(24) or 1758(36) but no details have come to hand. As the materials then available for construction were essentially timber and stone with limitations in use on bridge spans of about 100ft and a maximum foundation depth of about 10-15ft under shallow water, a bridge in deep water would have been impracticable. In 1772 Smeaton thought that it would be worth spending up to £100,000 (perhaps equivalent to £50m today) to bridge the Forth at Queensferry, but considered a bridge unachievable.(4) The considerably increased production of good quality wrought iron that followed implementation of Henry Cort's (1740-1800) inventions in iron manufacture after 1783 gave engineers scope for constructing bridges with tension members. Before Cort's improvements a tilt hammer working by water-power produced one ton of bars of doubtful quality in 12 hours. His rolling mill, absorbing approximately the same power, produced 15 tons of uniformly high quality iron in the same time. At a final stage, the iron was passed through grooved rollers producing uniform sections of various dimensions.(37) (fig 8) (38) The wrought iron link-bar

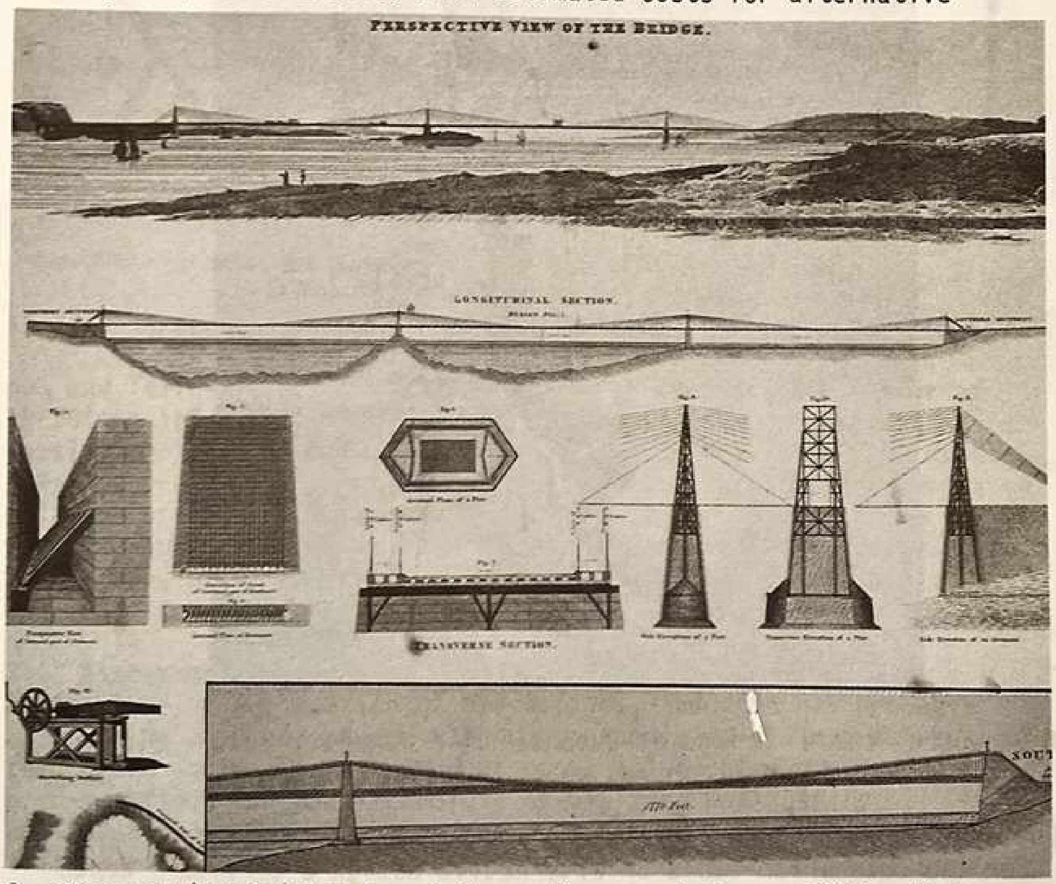


8 Iron making c.1850 - Rolling mill, blast and puddling furnaces

suspension bridge was adopted in North America from 1800.(39) Telford designed a bridge centering supported by inclined iron stays for crossing Menai Strait in 1811. By the summer of 1817 Scotland led Europe in having four iron tension footbridges erected. Their spans ranged from 110ft-261ft.(40) From 1814-17 Telford and Capt Samuel Brown (1774-1852) were taking the first steps in developing the long-span suspension bridge for carriage traffic based on experiments in connection with the Runcorn Bridge project.(41) At the end of 1817 the first practical 'strength of materials' textbook having any bearing at the subject was published and that was mainly about timber.(42)

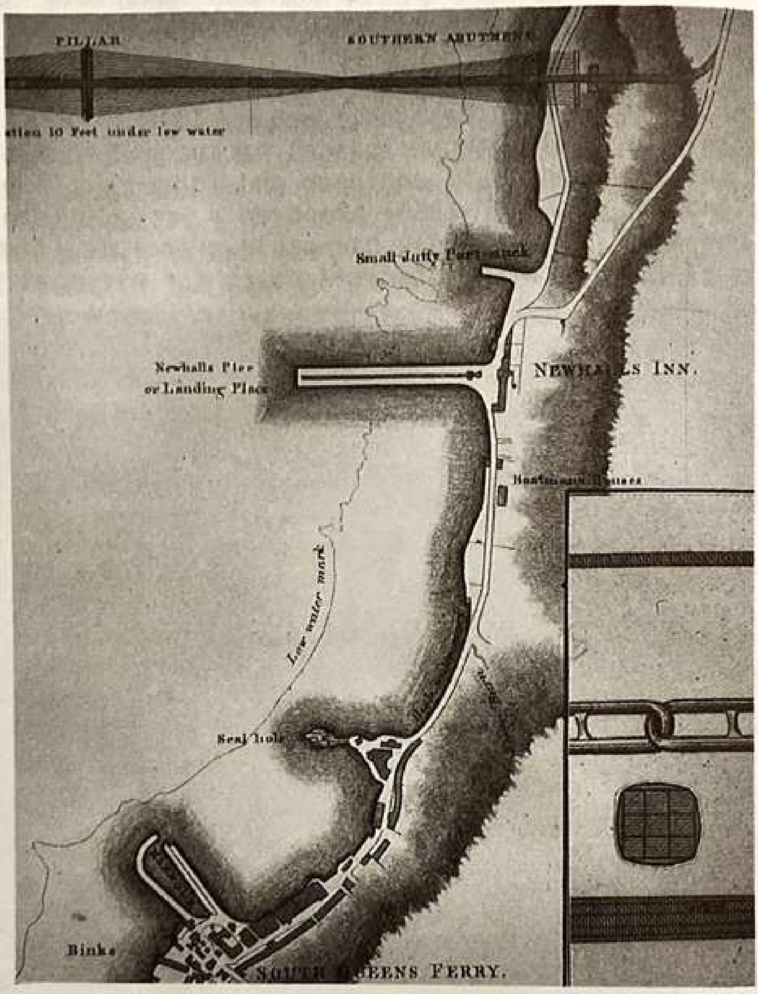
3.3 Anderson's 'Chain Bridge' Designs, January 1818.(43)

It was against this primitive technological background that an Edinburgh land surveyor and civil engineer and former pupil of Jardine, James Anderson (c.1790-1856) proposed a wrought iron bridge on either the rod-stay or catenarian bar-cable principle.(fig 9) He envisaged spans of 2000ft, with estimated costs for alternative



9 Proposed 'chain' bridge at Queensferry - Anderson 1818 - Note stay design and ironwork stretching machine. Inset and cross-section - Catenary cable design

heights of 90ft and 110ft above the river of from £144,000-£205,000. The site was to have been within about 300yds of the present rail bridge.(fig 10) The headroom for shipping was to have been 90ft or 110ft and the deck 33ft wide with a 25ft carriageway. In the rod-stay design the pairs of rods terminated at the outside of the deck at 100ft (or 50ft) intervals and at the other end fanned out laterally across the tower top to counteract "the effects of wind and any undulating or vibratory motion". The stays were to have had cross-sectional areas proportional to the strain induced. The pair of stays from the tower tops to mid-span would have a declination of

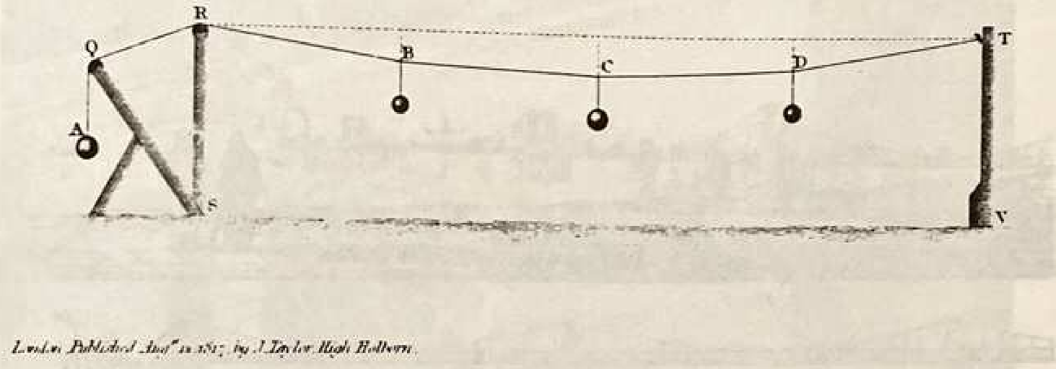


10 Proposed 'chain' bridge at Queensferry - Anderson 1818 - Plan at south side. Inset chain and cable details

100ft in 1000ft or just less than 6°.

For the catenarian cable or alternative design a curvature depth of one-thirtieth of the chord line (66ft 4in) was proposed. Twelve 3in nominal diameter cables were envisaged, each consisting of nine 5/8in square bars and 4 facing segments, the whole bound round with wire.(fig 10) For this proposal the iron stays of the first design were retained to inhibit deck undulation. In both designs masonry piers were proposed with cast iron tower frames above the roadway. The timber deck was to have rested on 20 (or for the stay design 40) principal bar members or 'basis chains' 1 x 1½in deep extending nearly 6000ft between abutments and tensioned to a sag of 20ft in 2000ft. The abutments and towers were to have been constructed first, over which were to have been stretched a temporary catenarian footway along which the stays which were to meet at mid-span would have been conducted. The middle bearer with two 'basis chains' was then to have been hoisted up from boats and the stay ends connected.

The cables and bars were to have been stretched into position using a machine capable of exerting 65tons from 1cwt applied to the handle, and terminate at a cast iron anchor beam on each side of the bridge. These anchors were to have been positioned 150ft behind each abutment face and 100ft below the roadway, stability being provided by a superincumbent mass of masonry of these dimensions 40ft wide and weighing nearly 23,000tons. Anderson based his proposed ironwork on simple experimental results,(fig 11) both his



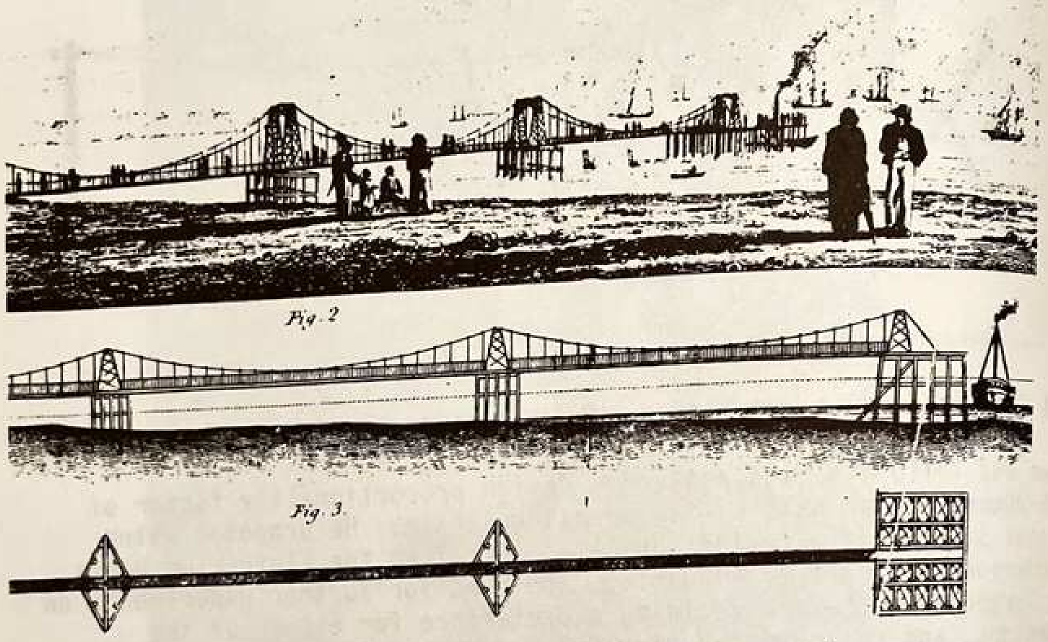
11 Iron strength testing arrangement by Anderson (after Telford)(42)

own and Telford's, and assumed a design proportionality factor of 15-20tons in^2 or half of its breaking strain. He proposed using local stone and 'excellent quality' lime from the Elgin Lime Works. Anderson particularly emphasised the need for further experiments on a larger scale before deciding a preference for either of the designs, and reserved the right to modify and improve them.(43) He sent a copy of his designs to Telford(44) who almost certainly regarded them as over-ambitious.

3.4 Assessment

At the time of publication of his designs, Anderson was probably approaching 30 years of age with more experience of land surveying than civil engineering. His designs as illustrated were undoubtedly over-ambitious for the technology of his time and justify Westhofen's comment that the proposed structure was "so light indeed that on a dull day it would hardly have been visible and after a heavy gale probably no longer to be seen on a clear day either".(45) Basically the cross-sectional areas of the iron cables and bars were much too small for the elevations adopted which, with tower heights of 67ft and 100ft above the roadway, were too flat. Unacceptably high levels of stress would have been induced in the ironwork. Anderson seems to have been unaware that as wrought iron was stretched, it deformed permanently beyond a stress of between 9.5 and 11.5tons in^2.(46) The stress in the cables of his catenarian design would have exceeded these figures under their self weight alone. His design stress was three to four times greater than the 5 tons in^2 safe design stress which gained general acceptance later. The provision against deck oscillation was also almost certainly inadequate but at least he had made some allowance. Even at that time Telford regarded 1000ft as a maximum span for suspension bridges, modifying this to 800ft after 1825 when he had experienced the deck oscillation phenomenon at Menai and 600ft in the case of Clifton Gorge. It was not until 1931, with the completion of George Washington Bridge, that a 2000ft span was reached and surpassed.

The nearest Anderson seems to have come to suspension bridge construction was the successful renewal in 1830 of the timber sea-ward abutment of Trinity Chain Pier erected by Capt Samuel Brown for steam-boat use in 1821.(47,48)(fig 12) This was a difficult and



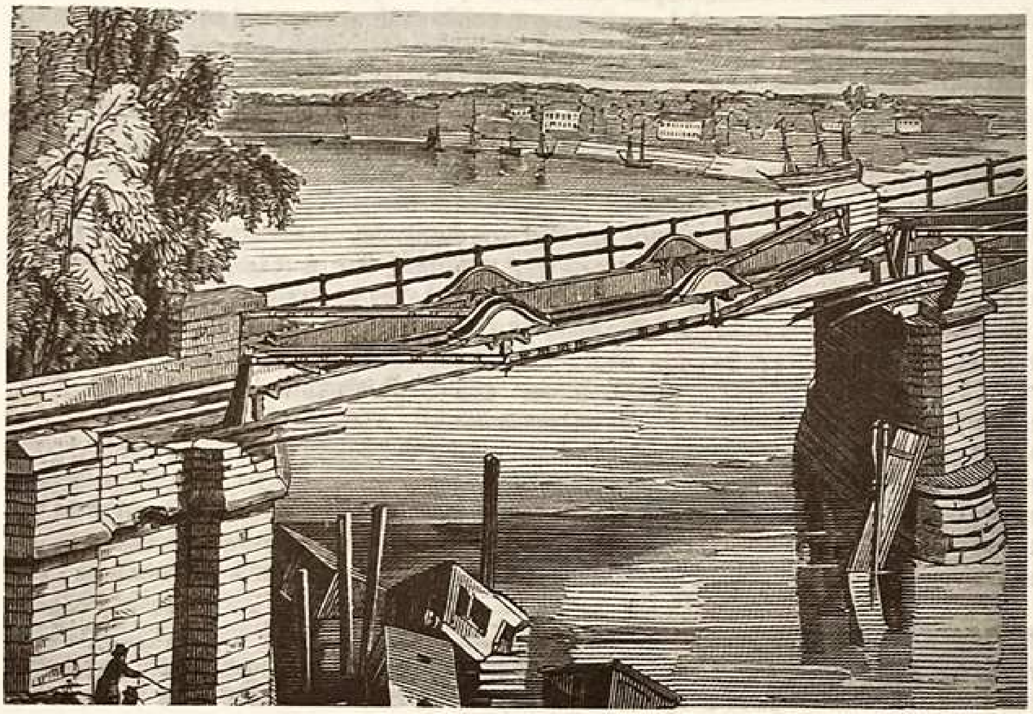
12 Trinity Pier, Newhaven - Sea-ward abutment 1821 (48)

hazardous operation involving the replacement of many sea-worm ravaged piles whilst at the same time preserving the tension supporting the structure.

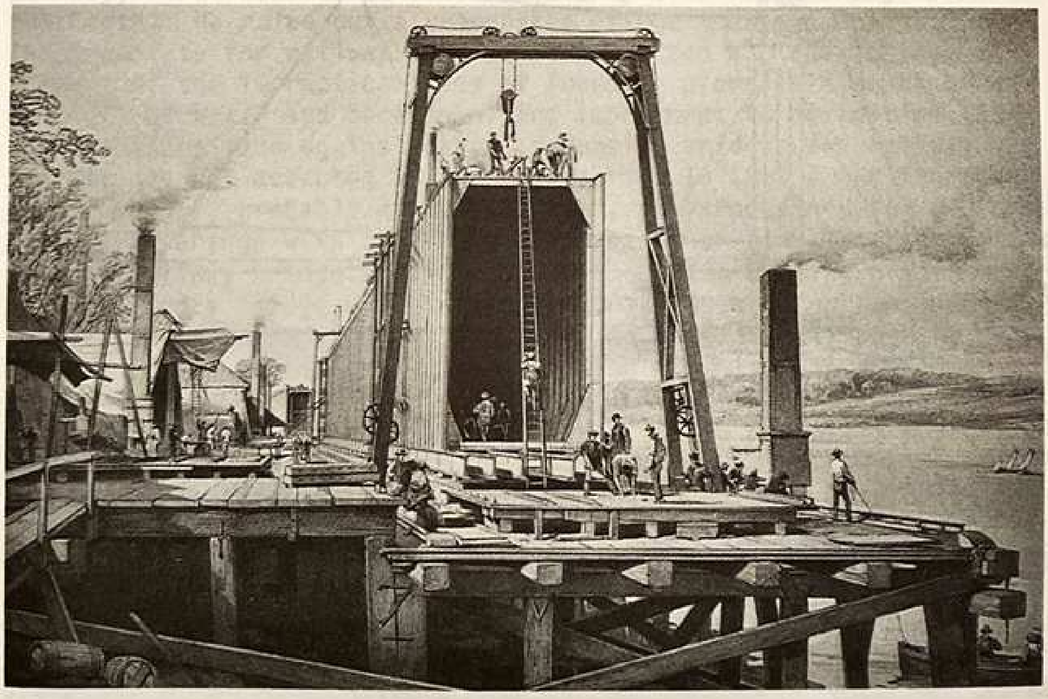
It is doubtful whether Anderson would have promoted his designs at all if he had not been encouraged by Telford's Runcorn Bridge project with its 1000ft central span.(49,50) Unfortunately for him, Telford's development of the long-span suspension bridge had not yet matured and been translated into the elegant and long-lasting Menai Bridge, a process which took a further five years to evolve at the frontiers of technology. In consequence, Anderson adopted and even compounded undesirable features from the 1814 Runcorn Bridge design which Telford later abandoned e.g. the cable form, catenarian cables of too flat curvature under as well as over the road-way and a design stress that was too high.(51)

In conclusion, Anderson deserves some credit for correctly foreseeing rock-founded cable-stayed or suspension bridges as the means of achieving large spans. The proposal seems to have helped his practice to flourish. From 1836-46 Anderson was an F.R.S.E.

4 Railway Bridges



13 Dee Bridge, Chester 1847 - Combined iron girder 100ft span (52)



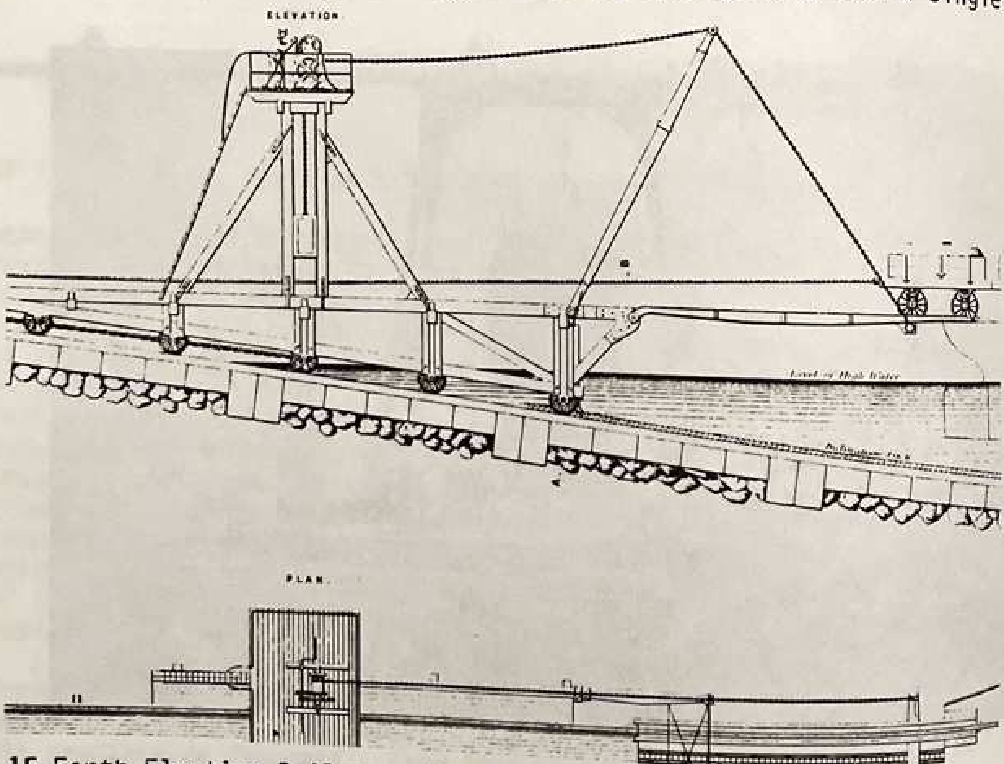
14 Britannia Bridge, Menai Strait - Construction of tube 1848 (53)

4.1 Introduction

From 1830-50 most iron bridges on railways were of the cast iron arch or beam types or combinations of cast and wrought iron, the latter contributing additional tensile support, with spans rarely exceeding 100ft.(fig 13) A number of failures involving cast iron beams had occurred and from the mid-century wrought iron replaced cast iron in general use for beams . The wrought iron plate girder, precursor of the steel 'I' beam, developed c.1846. A railway suspension bridge had been erected at Stockton in 1830. It was under-designed and proved hopelessly inadequate, two waggons causing a deflection of 18in, and after being propped for a time it was replaced by a cast iron bridge in 1842.(41) This experience discouraged engineers from adopting suspension bridges for railways. The Britannia Tubular Bridge with its 460ft spans over the Menai Strait constructed from 1846-50 under the superintendence of Stephenson and Fairbairn represented a major step forward in the evolution of the wrought iron girder bridge.(53)(fig 14) Crossing the Forth and Tay was a bigger challenge and an interim solution was adopted by Sir Thomas Bouch (1822-80). By 1850 he had designed and successfully installed the world's first floating railway between Granton and Burntisland.

4.2 The Granton-Burntisland 'Floating Railway' 1850

The ferry vessel was a specially designed end-loading paddle-steamer called 'Leviathan' built by Robert Napier & Co. The 389-ton vessel had a speed of 5 knots and commenced operation in February 1850. It could carry up to 34 goods waggons and the average time for a single



15 Forth Floating Railway - Bouch 1850 - Granton slip-way trip, including loading and unloading an average of 21 waggons, was 56 minutes.(54) The waggon transference arrangement on each shore consisted of a slip-way travelling platform with horizontal top, at the end of which were four movable wrought iron girders that were lowered onto the end of the ferry boat when the platform was in position. The platform was moved up and down the slip-way by means of a 30hp. stationary steam engine which was also used for hauling the trains. The movable girders were operated manually from two powerful crab-winches above the platform.(fig 15)(55) In the early 1860s Bouch proposed a similar system at Queensferry to accommodate passenger trains, but he allowed his preference for a bridge to override this concept which, by comparison, he considered inefficient. The Granton to Burntisland ferry continued to operate until the Forth Bridge was opened in 1890.

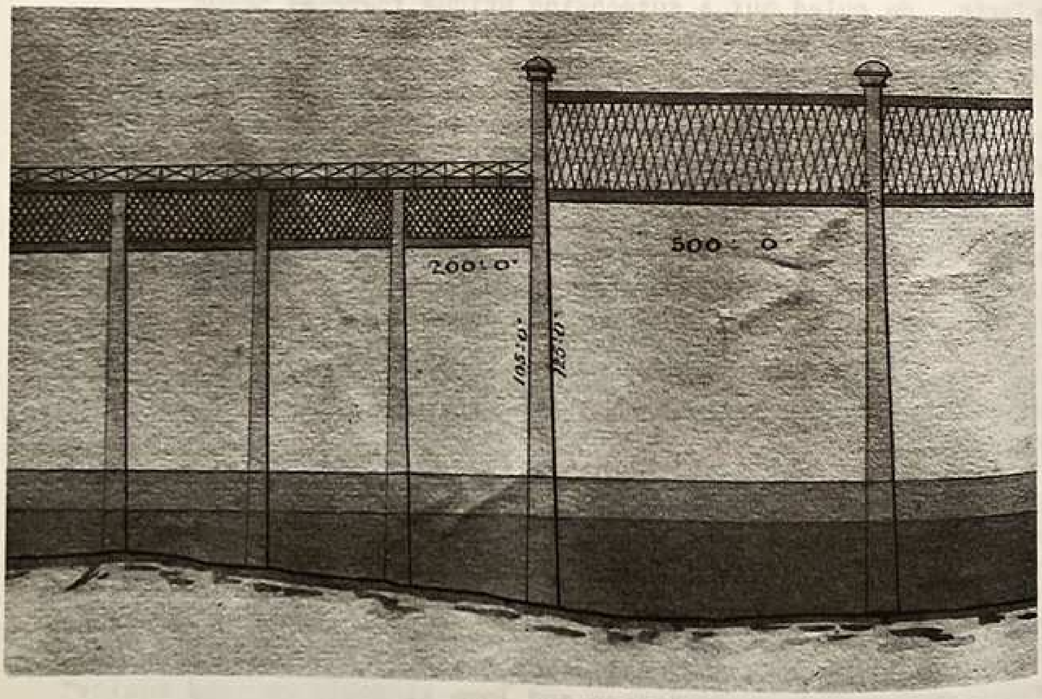
Bouch credited Thomas Grainger (1794-1852), his predecessor as Engineer to the Edinburgh, Perth and Dundee Railway, with the original idea of floating trains across the Forth. Grainger proposed to use hydraulic cranes to transfer trains between shore and the ferry vessel. Bouch thought that this operation would be too slow. Another engineer J. F. Bateman (1810-89) claimed that he had originated the floating train concept with a proposal for Queensferry in 1845 when he was Engineer to the Edinburgh & Perth Railway. He had proposed installing stationary steam engines at the top of 1 in 12 ramps on each shore, trains being hauled over tail-pieces between the vessel and ramp.(55)

4.3 The Proposed Forth Bridge at Charlestown 1862-66

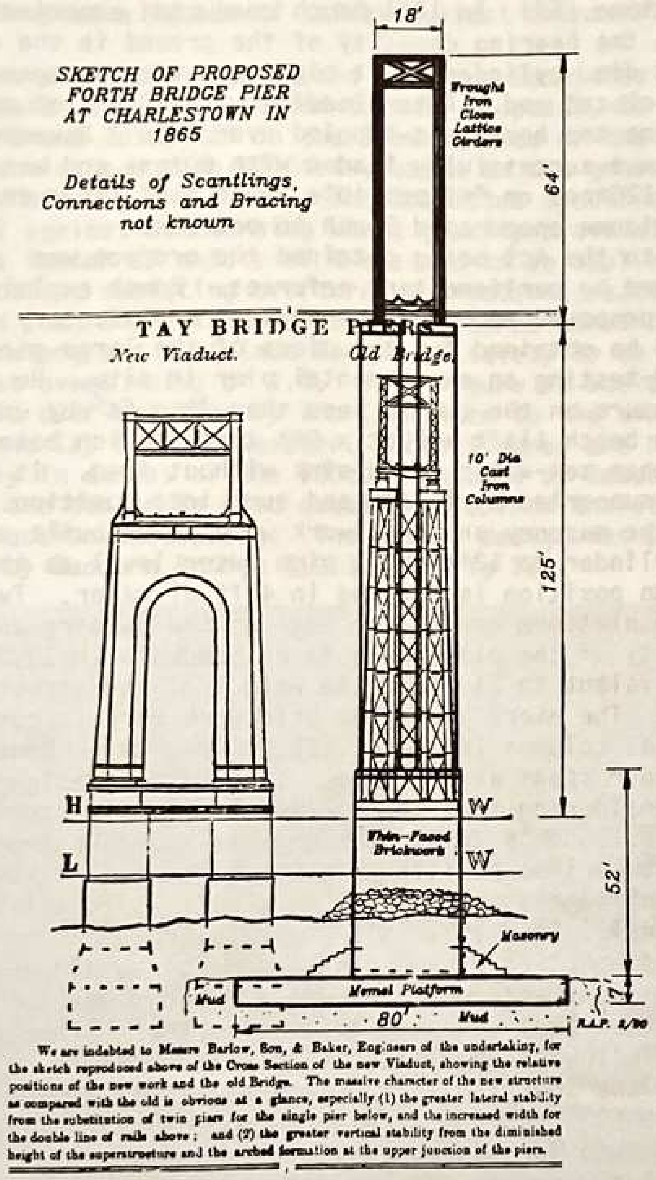
Bouch, now Engineer of the North British and Edinburgh & Glasgow Railway, first considered the Queensferry site for a bridge across the Forth. He ruled out a suspension bridge there as being inappropriate for railway traffic and rejected a girder bridge on account of the impracticability of founding piers in a depth of up to 240ft of water and because of the impediment to navigation.(56) The predisposition against using suspension bridges for railway traffic was not accepted by all engineers. In 1864 a 'Mr Thorntan of Edinburgh', probably Robert Thornton, prepared plans for a suspension bridge with three 2000ft spans at or near the site of the present railway bridge.(57) In 1862, a Charles Dowling published a proposal for a bridge with two continuous wrought iron tubes 5810ft long in seven 800ft spans at about the same site. Although he considered the tubes just self supporting at this span, he proposed adding suspension chains or cables, including some diagonals, to inhibit lateral movement.(58) Neither of these proposals was adopted.

In 1862 the Westminster consultant engineers G.R. Stephenson (1819-1905) and J.F. Tone(59) produced an outline report for consideration by the North British Railway directors on the means by which it might be possible to 'pass' the River Forth. Stephenson, nephew of the famous Robert Stephenson, had already had the experience of constructing a major iron bridge over the Nile and had assisted his uncle with the multi-span box girder bridge over the St Lawrence at Montreal. Stephenson and Tone strongly advised against the railway ferry concept which they considered inefficient. They also advised against the construction of a bridge across the Forth at Queensferry, considering a suspension bridge with minimum spans of 1300ft to be impracticable for railway traffic, and cited the speed limit of 3mph on the American engineer J.A. Roebling's 800ft span Niagara Bridge (1855-92). Stephenson and Tone recommended construction of an iron girder bridge across the Forth between Blackness Castle and Charlestown at an estimated cost of £500,000 and envisaged a completion time of three years.(59)

Bouch seems to have accepted or to have come to the same conclusions as Stephenson and Tone and in 1863-64 was working on designs for a single-track girder bridge across the Forth near Charlestown. One design in 1864 was for a 3979yd viaduct rising to 100ft in height for two 290ft navigation spans. From the south the spans were: 19 x 40ft; 42 x 40ft; 24 x 207ft; 2 x 290ft; 4 x 207ft; 44 x 40ft; and 4 x 40ft.(60) Another design had spans ranging from 100ft to two 600ft spans over the navigation channel.(56) The proposed main spans were larger than those of Britannia Bridge and Brunel's Saltash Bridge (1859) with its 455ft spans. The Company prevailed on Bouch to reduce the large spans and the design for the 'Bridge of Forth' in the 1865 Bill was a 3887yd viaduct with 62 wrought iron close-lattice girder spans, rising to 125ft clearance for four 500ft navigation spans. From the south end the spans were: 14 x 100ft; 6 x 150ft; 6 x 175ft; 15 x 200ft; 4 x 500ft; 2 x 200ft; 4 x 173ft; 4 x 150ft and 7 x 100ft.(61)(fig 16) The 500ft span girders, each 64ft deep and weighing 1170 tons, were to have been fabricated on land, floated to site on pontoons and elevated into position by means of hydraulic jacks. The bridge was estimated to cost £476,000 excluding the railway and contingencies. If it had



16 Proposed Forth Bridge, Charlestown - Bouch 1865 (61)



17 Proposed Forth Bridge, Charlestown - Bouch 1865. Drawn on 1881 section showing old and present Tay Bridges for comparison(68)

been built it would have been the longest and largest railway bridge in the world.

The promoters were concerned about the difficulty of achieving adequate foundations for the great girder piers in soft ground. Of the many borings made on Bouch's behalf by Jessie Wylie (whose subsequent borings for the Tay Bridge indicated a non-existent rock shelf almost right across river and involved Bouch in considerable design changes and delay)(62) many easily penetrated through soft silt for more than 120ft. One bore even went to 231ft without reaching the bottom.(23) From several hundred borings there was not a single bit of stone.(56) In 1864 Bouch conducted experiments on site to determine the bearing capacity of the ground in the river bed using two 6ft dia. cylinders 48ft high, one with an open end and the other with a closed end. After loading with 60tons of pig iron one cylinder became top heavy and toppled over. On 7 November 1864 another cylinder was successfully loaded with 80tons and was expected to take 120tons or "if possible 5tons ft^2" later that day.(64) This outcome encouraged Bouch to proceed.

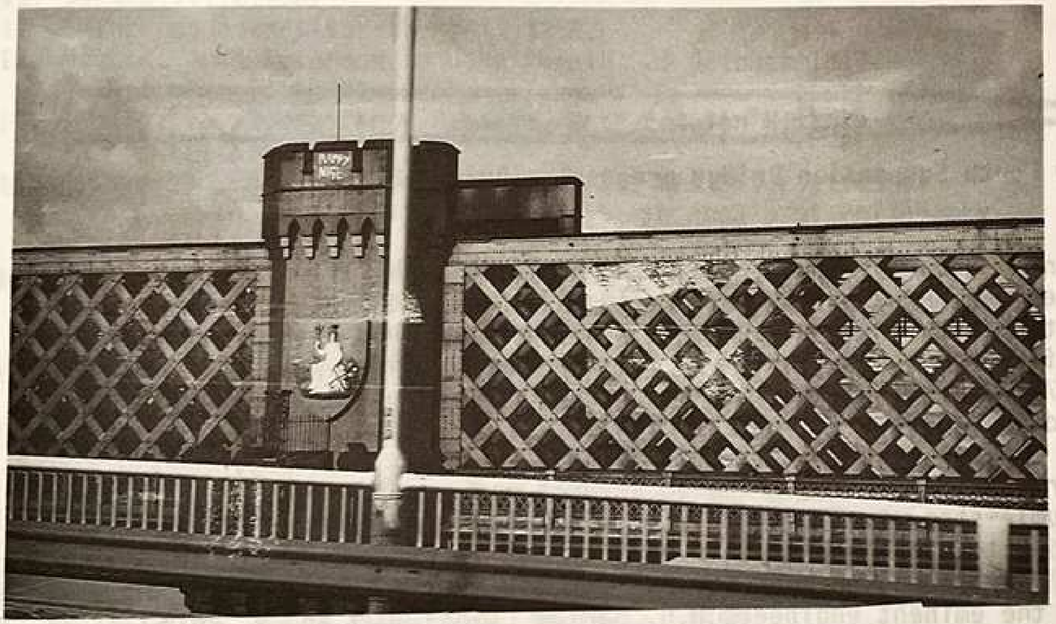
In 1865 prior to the Act being obtained the project was thoroughly examined by parliamentary referees. Bouch explained in evidence that he proposed to determine whether satisfactory foundations could be obtained for the piers of the large girders by building and load-testing an experimental pier in situ. He proposed reducing the pressure on the mud to less than ¾ton ft^2 by use of a platform of green beech 114ft x 80ft x 9ft thick, which being slightly denser than sea-water would sink without load. It was to be towed to site supported by floats and sunk into position. On top of the platform the masonry and brickwork were to be built up within a wrought iron cylinder to 12ft above high water level as the platform sank into position in the mud in 40ft of water. Twelve 8ft dia. tubes on the platform around the edge of the masonry and also the interior cavity of the piers were to be loaded with 10,000 tons of pig iron, equivalent to 2½ times the weight of the structure plus a standing train. The piers above the brickwork were to consist of a pair of 10ft dia. columns 1in thick.(56,63)(fig 17). Bouch envisaged the girder spans as continuous but had not designed them on this basis, considering this an additional safety factor.

On 14 June 1866, Bouch's trial platform was launched from Burntisland and towed into position off Charlestown. It was smaller than previously envisaged, now being 80ft x 60ft x 7ft thick and constructed of memel (pine).(63) Six weeks later, when the preparations for submersion of the platform were rapidly approaching completion, the Company abandoned the project for financial reasons. It is understood that they expected to lose northern 'through traffic' revenue following an amalgamation between their Caledonian Railway rival and the Scottish North Eastern Railway, which took place on 10 August 1866.(65-66) The workmen were paid off and the raft was towed back to Burntisland. The experiment had cost the North British Railway Company £34,390.(67)

4.4 Assessment of the Charlestown Bridge Proposal of 1865-6

The abandonment of the bridge was almost certainly fortunate, not only on account of the questionable nature of its structural continuity and foundations in 'mud' (60) but also because of its probable instability in strong wind. In cross-section, the bridge with its 64ft tall girders 125ft above the river would have been too narrow for its height.(fig 17). Although the proposal did survive searching parliamentary scrutiny, the wind problem was not properly appreciated at that time. Bouch envisaged a wind load of 180tons on a 500ft span, weighing 1170tons, based on a pressure of 30lbs ft^2, from which it seems reasonable to assume a lattice girder elevation consisting of 58% holes and 42% iron on the basis that the wind pressure was applied to the nett area of iron. Bouch would probably also have adopted a factor of safety against overturning.

If the rules drawn up by the Board of Trade Committee after the Tay Bridge disaster (69) had applied to this proposal, ie 56lbs ft^2 on the windward and 28lbs ft^2 on the leeward side of the girder, the wind load would have been 1200tons, based on the gross area of the girder, discounting the holes. The Committee specified a factor of safety of 2 against overturning where gravity provided the restoring force and a factor of safety of 4 was was to be applied to holding down connections resisting overturning. Modern practice would give give a wind load of 580tonnes, more than three times the figure that Bouch estimated, and a minimum factor of safety to be applied to this against overturning of 1.4. This figure is indicative of the considerable over-reaction by the Committee to the wind question following the Tay Bridge disaster. Both figures are however, considerably in excess of the 180tons assumed by Bouch. With hindsight, the design is also questionable from the standpoint of post construction settlement. The girder design was probably influenced by Runcorn Bridge (1863)(63)(fig 18).

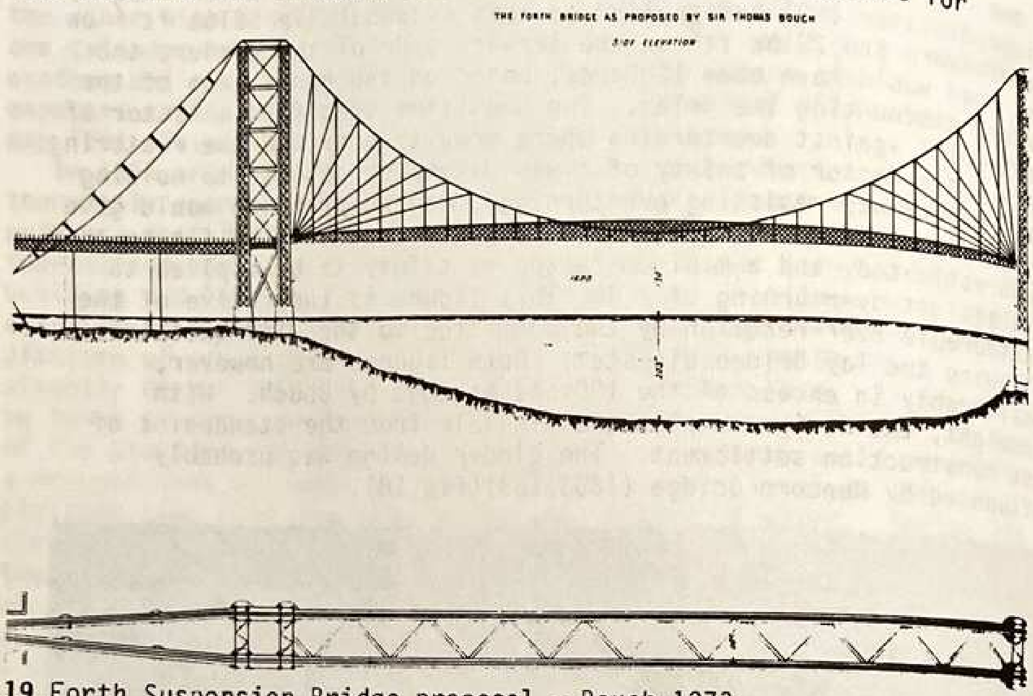


18 Runcorn Bridge today - constructed 1863-68

Bouch's design cannot necessarily be assumed to have suffered a similar fate to that which befell the Tay Bridge thirteen years later. Its piers were more robust than the latter. The design might have been abandoned or modified as a result of the experiment. Without details of the scantlings, connection arrangements and bracings it is not possible to comment with certainty as to how the different elements of the design would have fared with time. By comparison with the present Tay Bridge, with its iron caissons sunk at least 20ft into the sandy silt, widely straddled piers, and designed to the post-disaster wind pressure code, there is no doubt which design is to be preferred.

4.5 The Forth Railway Suspension Bridge Project 1871-80

The pressure for bridging the Forth and Tay did not subside for



19 Forth Suspension Bridge proposal - Bouch 1873

long. Under new management, the North British Railway Company took over the ferry at Queensferry in 1867. In 1868 the railway from Ratho Junction to Queensferry was completed thus establishing a rail-ferry link with Fife. This link was further developed in 1877-78 with the construction at Queensferry of a 900ft timber jetty and a 1,300ft whinstone breakwater.

In 1871 Bouch, it is said perhaps influenced by Anderson's earlier scheme(67), prepared several designs (45) and proposed a double-span steel suspension bridge with heavily stiffened deck and 1,600ft spans more or less on the line of the present bridge.(fig 19) After having been carefully examined and favourably reported on by the eminent engineers W.H. Barlow (1812-1902) and W. Pole (1814-1900),(70) the bridge received its authorising Act in August 1873. Work was slow to start and it was not until 30 September 1878 that the foundation stone of a brick pier was laid at Inchgarvie. Towards the close of 1879 William Arrol (1839-1913) was hard at work on preparations for the steelwork when the Tay Bridge fell. By the following summer Bouch's design had been abandoned, and all that survives on site is the base and a score or so courses of brickwork of Inchgarvie pier, now supporting a beacon.

Bouch was probably influenced to change his mind and adopt a suspension bridge by the success of Roebling's Cincinatti-Covington road suspension bridge. This bridge of 1075ft span was completed in 1866 and is still in use.(71) Bouch's bridge might have lasted too, but few engineers would doubt the superiority of its successor.

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