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Historical Development of Iron Screw-Pile Foundations: 1836–1900

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Beginning around 1836 screw-pile and screw-cylinder elements were used successfully as helical foundations throughout the world to support a variety of large-scale civil engineering structures. Their development and use is largely attributed to engineers from the UK and the USA. The origins and rise of screw-pile and screw-cylinder foundations are reviewed from an historical perspective focusing on the period from 1836 to 1900. A summary of the use of screw-piles as successful foundations for lighthouses, bridges, and piers as well as their use for other engineering applications is given. A description of the common geometries of screw-piles and screw-cylinders during this period is also presented. The information illustrates that helical foundations have been in use for over 170 years throughout the world and can be considered perhaps the single most important development in geotechnical engineering foundation construction of the mid to late nineteenth century.

KEYWORDS Screw-piles, Piles, Helical-piles, Foundations, Bridges, Piers, Historical, Wrought iron

Introduction

Screw-pile foundations were one of the most globally important engineering advances of the mid to late nineteenth century. They made the construction of lighthouses possible in locations where there would otherwise undoubtedly have been great loss of life and property; they made the construction of bridges possible in locations where they might not have been constructed for another 40 years; they made the construction of ocean-front pleasure piers an industry that would irreversibly change the leisure time of an entire nation. The use of screw-piles as a foundation system was so common during this period that it was not considered a uniquely significant engineering accomplishment at the time to document in any great detail their design and construction on specific projects, other than an occasional passing note. This accounts for the relative lack of detailed technical literature related to their use at this time. While the historical engineering record is somewhat sparse, there is a sufficient

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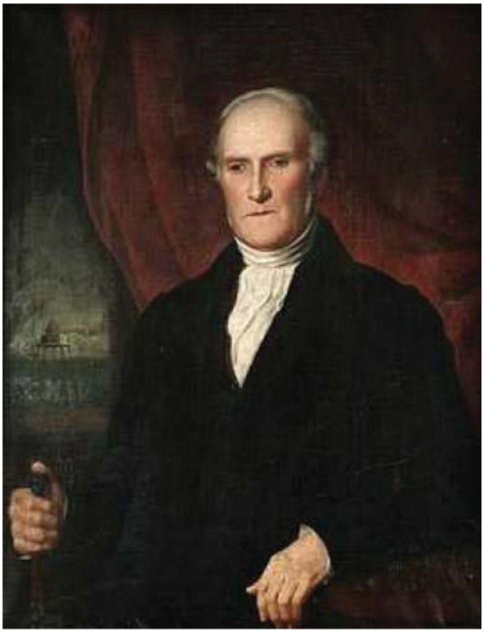

FIGURE 1 Portrait of Alexander Mitchell (1780–1868) Inventor of screw-piles — by Richard Hooke (1823–1887) (from a no-longer-extant website).

amount of collective information to provide a good detail of their application during this period.

Screw-piles were used on large-scale civil engineering works and so they themselves were large scale. It is relatively common to read accounts of projects in which screw-piles with blades ranging from 2.5 to 6 ft in diameter were installed to support a specific structure. This scale of screw-pile required large-scale manufacturing and undoubtedly presented some unique challenges in terms of their handling and installation during a period when most civil construction was performed by hand labour with only the simplest of mechanical advantage. While screw-piles and screw-cylinders had a wide range of applications, by far the largest use was as foundations for the construction of lighthouses, bridges and ocean-front pleasure piers. By comparison, modern screw-piles, although generally smaller in scale than their historic counterparts, are currently being used in many of the same design situations; for support of structures for new construction, for underpinning of existing structures, for tension loading of anchored tower structures and as tiebacks for excavations and slope stabilisation.

Alexander Mitchell and the origin of screw-pile foundations

Most historians agree that screw-pile foundations were introduced as a practical foundation system by Alexander Mitchell (1780–1868), an Irish builder and brick manufacturer. Cox provides an excellent biography of Mitchell and gives us some insight into the man and his work.[1] Mitchell was born in Dublin on 13 April 1780, the eighth son of a family of thirteen. His father, William Mitchell, was Inspector General of Military Barracks in Ireland. In 1787 the family moved to a house on the outskirts of Belfast but when William died in 1790 the family moved again to a cottage about a mile outside the city.

Mitchell's only formal schooling appears to have been about four years spent at the Belfast Academy but his sight, which seemed to be weak from an early age, perhaps as a result of the contraction of smallpox, continued to decline. Before he was 16 his sight was so bad that he could not see to read and by the age of 21 he was totally blind. At the age of 20, using £100 borrowed from his brother George, he began business as a brick manufacturer in an area just east of Ballymacarret. His brickmaking business, which lasted over thirty years, was sufficiently successful that he was able to expand his business into the building of houses and other property development. In 1801 he married Mary Banks, the daughter of a neighbour, and together they had two sons and three daughters.

His business generally prospered as a result both of royalties obtained from screw-piles and screw-moorings and also of contract work, for example in the construction of lighthouses both in the UK and the USA where screw-piles were used as the foundations. His success enabled the family to move around 1839 to a substantial house at 2 Alfred Street on the corner with Little May Street in Belfast, at the time a high-class residential area. A surviving portrait of Mitchell (Figure 1), which probably shows him in his later successful years, presents the picture of the gentleman engineer of the period. Even though he had no formal training in engineering, he apparently described himself as a civil engineer at various times and was elected to Associate Membership of the Institution of Civil Engineers in 1837, very early in the development of his screw-pile foundations. At the time of his election Thomas Telford was president of the ICE.

There is little doubt that the idea for screw-piles was first associated with the problem of safely mooring ships in harbours at the time and seems to have then been applied by Mitchell to the problem of providing good foundations for lighthouses in soft soil in relatively shallow water. Mitchell described the origins of his invention:

> An account of the circumstances which led to the introduction of the screw pile and screw mooring, would possess but little general interest, and is not necessary. It would suffice to observe, that a project, contemplated by the Author, involved the necessity of a much greater holding power than was possessed by any pile, or mooring, then in use; the former being nothing more than a pointed stake of considerable size, easily either depressed in, or extracted from, the ground, and the latter a large mass of stone, or iron, which when submerged became of limited power, and was quite incapable of resisting an upward strain.
>
> The plan which appeared best adapted for obtaining a firm hold of soft ground, or sand, was to insert to a considerable distance beneath the surface, a bar of iron having at its lower extremity a broad plate, or a disc of metal, in a spiral or helical form, on the principle of the screw, in order that it should enter the ground with facility, thrusting aside any obstacles to its decent, without materially disturbing the texture of the strata it passed through, and that it should at the same time offer an extended base, either for resisting downward pressure, or an upward strain.[2]

Figure 2 shows various components of the screw-mooring and screw-pile system devised by Mitchell.

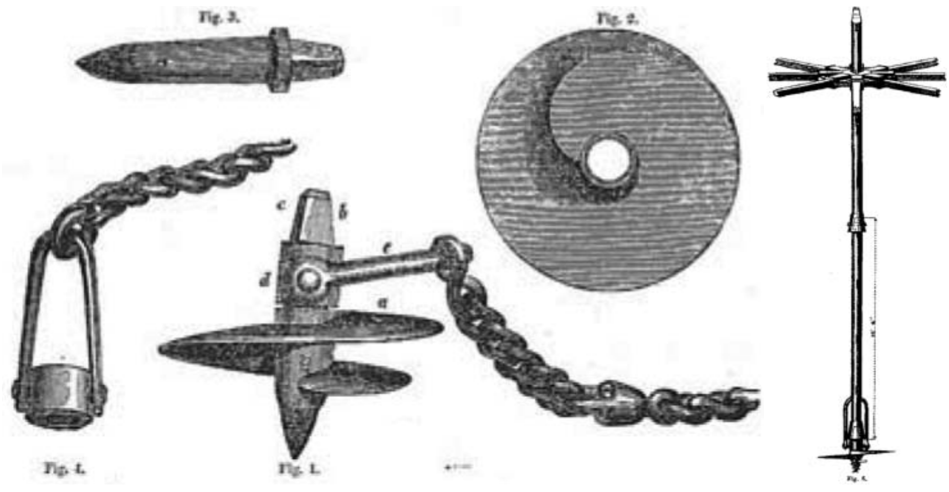

FIGURE 2 Components of screw-mooring and screw-pile system invented by Mitchell (from US Patent No. 3986).

Recognising the potential for his invention, Mitchell applied for a patent in the UK for his invention which was granted as no. 6446 in 1833. An extension of the patent was granted in 1847 and Mitchell also applied for and received a US patent, no. 3986, dated 1 April 1845.

The first professional published account of the installation and application of the screw-mooring was given by Elmes for moorings being constructed for the Port of London:

> This sort of Mooring is constructed, as the name implies, on the principle of the screw, but differing essentially in form from that well-known instrument; for while the spiral thread makes little more than one turn round its shaft, it is at the same time extended to a very broad flange, the hold which it takes of the ground being proportional with its breadth of disc.
>
> Where it is necessary to provide against a very heavy strain, Mr Mitchel [sic] has moorings of 3 ft. 6 in. diameter, and the principle is capable of still further extension.
>
> A mooring of the above diameter presents a resisting surface equal to about ten square feet; whereas the palm of the largest anchor in the British Navy does not exceed half that size; and some estimate of its holding powers may be formed, when it is shown that this broad surface may be screwed to a depth many times greater than that to which the palm of an anchor can ever descend.
>
> The method of laying down the mooring is briefly thus: — A strong mooring chain being so attached to it as to allow the screw to turn freely, without carrying the chain round with it, a powerful iron shaft is then fixed firmly in the upper part of the mooring, which is formed square for that purpose, setting in the same manner as a key to a harp or piano-forte in winding up: it is then lowered by the mooring chain, joint after joint being added to the shaft till the mooring has reached the ground; light levers of 12 ft. in length are then applied to the shaft in the manner of a capstan, when the operation of screwing the mooring into the ground commences.

> Two boats or barges having been moored firmly head and stern close alongside each other, and the upright shaft rising between them about midships, the men place themselves at the bars, and move round from one boat to the other, the two giving them a safe and convenient platform; by a simple contrivance the levers are occasionally shipped outwards, as the screw and shaft sink into the ground.
>
> When the number of men employed can no longer force the screw round, the levers are removed, and the shaft drawn out of the ground, leaving the mooring firmly imbedded [sic] with the chain attached to it; a buoy being shackled to the other end of the chain the work is completed, the time required for the whole operation seldom exceeding a few hours.[3]

Mitchell provided some insight into the mechanics of the bearing power of screw-moorings and screw-piles:

> Whether this broad spiral flange, or 'Ground Screw', as it may be termed, be applied to the foot of a pile to support a superincumbent weight, or be employed as a mooring to resist an upward strain, its holding power entirely depends upon the area of its disc, the nature of the ground into which it is inserted, and the depth to which it is forced beneath the surface.
>
> The proper area of the screw should, in every case, be determined by the nature of the ground in which it is to be placed, and which must be ascertained by previous experiment.[4]

For tension loading, as in the case of screw-moorings, Mitchell suggested that the holding power could be calculated assuming an appropriate failure surface:

> Every description of earth is more or less adhesive, and the greater its tenacity the larger must be the portion disturbed before the mooring can be displaced by any direct force. The mass of the ground thus affected, in the case of the screw-mooring, is in the form of the frustum of a cone, inverted; that is, with its base at the surface, the breadth of the base being in proportion to the tenacity of the ground; this is pressed on by a cylinder of water equal to its diameter, the axis of which is its depth, and the water again bears the weight of a column of air of the diameter of the cylinder.[5]

Remarkably, at a time when the discipline of soil mechanics had yet to be introduced formally to civil engineers, Mitchell's observations suggested the most important factors that influence current design procedures for bearing capacity of a helical or plate ground anchor, i.e., 1) geometry (diameter or area) of the blade; 2) depth of embedment; and 3) soil properties in both the 'nature' of the ground and its strength 'tenacity'. Most of the screw-moorings and screw-piles installed during this period would be considered by modern concepts as 'shallow' installations with depth/ diameter ratios less that about 6. For shallow installations under tension loading, the use of an inverted truncated cone as a failure surface is often used in design.

Screw-pile lighthouses

The first application of screw-piles as a foundation was for the Maplin Sands Lighthouse in 1838. There are several accounts of the geometry of this foundation and the lighthouse construction.[6] There was apparently some skepticism regarding the feasibility of the screw-pile foundations and therefore the foundation was left for nearly two years so that the stability could be observed. Meanwhile, the Lighthouse Board elected to construct another structure in Morecambe Bay leading to Port Fleetwood, otherwise known as the Wyre Lighthouse.[7] This structure would actually become the first fully completed structure to be founded on screw-piles. It was only after the Wyre Lighthouse was completed that construction resumed at Maplin Sands to complete that lighthouse. Some details of the site investigation and construction of the screw-pile foundation at Maplin Sands were also given by Redman:

> A deputation of the Elder Brethren of the Trinity House, accompanied by Mr Walker, their Engineer, visited the spot in 1837, for the purpose of surveying the sand, and of ascertaining the best position for a fixed light; various soundings were taken at the time, and the observations were extended to the eastward. . . A boring was made, during this survey, at the south-eastern point of the sand, in order to ascertain its nature and density: this was carried down 27 ft below the surface of the sand, or 26 ft below low water. The sand was compact and hard, so that with an ordinary boring-rod, worked by four men, a depth of 6 ft was penetrated in half an hour, and beneath that depth the facility increased, as the sand appeared to become mingled with silt.
>
> Soon after this preliminary survey, Mr Mitchell, the inventor of the screw moorings, made an application to the Corporation of the Trinity House, that in the erection of the proposed lighthouse on the Maplin Sand, his screws might be used for the foundations; suggesting that the screws should offer considerable bearing-surface, and be fixed upon the ends of wrought-iron piles, which would support the superstructure. This suggestion was favourably received, and in June, 1838, Mr Mitchell received instructions to supply the screw piles, and to consult with Mr Walker as to future measures.
>
> On the twenty-seventh August, Mr Mitchell and his son proceeded to the sand with the piles, which were manufactured of the best Staffordshire iron, 26 ft in length, and 5 inches in diameter; each pile had near its lower end a cast-iron screw, 4 ft in diameter, firmly keyed upon the pile, round which the screw performed one revolution and a quarter; beneath the screws the piles were finished with a large drill, or opening bit. The screws were manufactured at Messrs. Rennie's works, Holland-street, Blackfriars.
>
> The first pile was screwed down on the twenty-eighth August, and all the nine piles were finished on the fifth September, the average work being one pile per day.[8]

Mitchell also gave an account of the work at Maplin Sands:

> In fixing the foundation piles for the Maplin Sands Lighthouse, a raft of 36 ft square was used as a stage, or platform, upon which the men worked, as barges would have been too high from the surface, and it was necessary to ground the raft itself, before the piles could be screwed down to the required depth, their heads being only a short distance above the bank. The raft was constructed of balks of American timber bolted together, leaving an aperture of 2 ft in width from one side to the centre, by which the pile was brought to its position. About forty men, furnished by the Corporation of the Trinity House, were employed on the work: their wages and the cost of the raft amounted to about £300. The contract for the screw-piles, and the Author's professional charges for superintendence, was £900, making the total cost of the foundation for the lighthouse, £1200.[9]

Figure 3 shows a period engraving of workers using a capstan to install a screw-pile from a raft in open water. It appears that the supervisor (perhaps Mitchell?) is standing in the lower right hand corner of the raft. All of the screw-piles for the Maplin Sands Lighthouse were installed vertically.

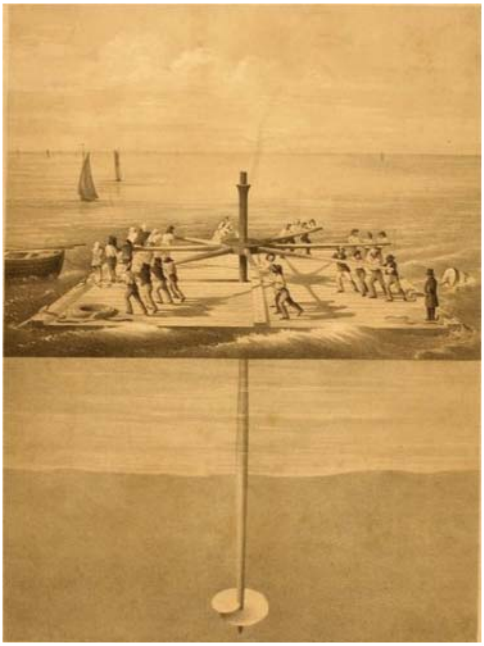

FIGURE 3 Period lithograph showing installation of screw-pile in open sea (from a no-longer-extant website).

One of the most interesting aspects of the work at Maplin Sands performed by Mitchell is given in his account of the field testing that was performed to test the bearing capacity of the screw-piles:

> Before determining the length of the piles and the area of the screws necessary to be employed, a careful examination of the ground was made, and it was proposed to use nine malleable iron piles of 5 inch diameter, and 26 ft in length, with a cast-iron screw of 4 ft diameter, secured to the foot of each. The instrument used in trying the nature of the ground was also employed in testing its holding power. It consisted of a jointed rod 30 ft long, and 1¼ inch in diameter, having at its foot a spiral flange of 6 inch diameter. It was moved round by means of cross levers, keyed upon the boring-rod: and upon these levers, when the screw was turned to the depth of 27 ft, a few boards were laid, forming a platform sufficiently large to support twelve men. A bar was then driven into the bank at some distance, its top being brought to the same level as that of the boring-rod. Twelve men were then placed upon the platform to ascertain if their weight, together with the apparatus, in all about one ton, sufficed to depress the screw. After some time, the men were removed, and the level was again applied: but no sensible depression of the screw could be observed.[10]

According to Mitchell:

> This experiment was made in the presence of Sir John Henry Pelly, the Deputy Master, and some of the Elder Brethren.[11]

The inference from it was, that if a screw of 6 inch in diameter could support one ton, one of 4 ft diameter was capable of supporting at least 64 tons, the comparative area of their surfaces being as the square of their diameters; but this experiment was nothing more than an approximation to the truth, a continuous surface possessing a much greater sustaining power than the same area in detached portions.

In terms of geotechnical engineering practice, both design and geo-construction, the work at Maplin Sands is remarkable and not substantially different from modern geotechnical practice in that we see a Site Investigation to determine ground conditions, Field Testing to obtain site specific performance evaluation of prototype foundations, and Observations during construction of foundation installation. Figure 4 gives an early engraving of the completed Maplin Sands lighthouse.

Based on the successful performance of the screw-piles at Wyre and Maplin sands, Trinity House constructed several other similar screw-piles structures over the next several years, most notably at Belfast Lough, Gunfleet, and Dundalk Bay. Table 1 gives a summary of the specifications used for several lighthouses built between 1838 and 1855 with a comparison of the different foundation elements used. While the screw-piles at Maplin Sands were installed vertically, at most other locations that followed battered screw-piles were used on the perimeter, most likely to provide additional lateral resistance to wave action.

In 1843 screw-piles were used for new lighthouse construction being undertaken in the USA by the US Topographical Bureau, later to become the US Army Corps of Engineers. Captain W. H. Swift was a keen supporter of the use of screw-piles for lighthouses in USA. Swift had visited England to inspect the lighthouses at Maplin

FIGURE 4 Diagram of Maplin Sands Lighthouse (Author's collection).

TABLE 1

SUMMARY OF EARLY SCREW-PILE LIGHTHOUSE FOUNDATIONS, 1838–1855

Year	Location	No. of screw-piles	Diameter of helix (ft)	Diameter of shaft (inch)	Depth below mudline (ft)	Soil conditions
1838	Maplin Sands	9	4	5	15	Sand
1839	Fleetwood-on-Wyre	7	3	5	10	Marl
1844	Belfast Lough, Carrikfergus Bay, Holywood Bank	9	3.5	5	16	Coarse sand and gravel over blue clay
1852	Gunfleet off Harwich	9	2.5 - sand 3 - clay 4 - very soft soil	N/A	N/A	Sand

Sands and Wyre and recounted his impressions giving his recommendation to use screw-piles at Brandywine Shoals in Delaware Bay in a letter to the US Committee on Commerce, dated 10 February 1842:

> During a visit to England, last year, I made it my particular business to examine the screw-pile light. One is placed upon the Maplin Sands, in the mouth of the Thames, 60 miles below London, and in a situation where, of course, it is exposed to the heavy gales of the North Sea; it has been erected between two and three years. . . The second light is on the west coast of England, at the mouth of the Wyre, in Lancashire. This light was erected under the direction of Captain Denham, R.N., about two years since. I visited it in May last, and examined particularly all its parts. Captain D. was kind enough to communicate to me many interesting details connected with its construction; the whole work, from the beginning to the end, was entirely successful.[12]

The actual construction of the Brandywine Shoals lighthouse was undertaken by General Hartman Bache, assisted by a young Lieutenant George G. Meade. Details of the diameter of the helices and depth of embedment are not currently available, but it is likely that they did not differ substantially from similar structures that Swift had seen in England. The success of the screw-pile lighthouse at Brandywine Shoals led the way for the topographic engineers to build other structures along the eastern coast and as far south as Florida and the Gulf of Mexico. Meade was assigned to construct a series of lighthouses from New Jersey to Florida. While a number of these structures were built on land and were constructed as tall masonry structures, two of the lighthouses in Florida at Sand Key and at Sombrero Key were constructed by Meade using screw piles.

During the period from 1861 to 1880, at least sixty lighthouses were constructed along the eastern coast, and the gulf coast of the USA using screw piles as foundation system. For open sea lighthouses, the screw pile foundation allowed rapid construction, provided bearing support for compression, uplift and lateral loading and still allowed the waves to move freely through the latticework of the foundation. The most common use of screw-piles as lighthouse foundations in the USA, however, was for shallow-water sheltered locations where little or no ice formed.

Ocean front piers

While construction of screw-pile lighthouses was perhaps in the forefront of his screw-pile work, Mitchell's success with screw-moorings and screw-piles allowed him to expand his contracting activities into other areas and develop other applications for screw-piles. This work was initiated even while lighthouse construction was still being performed. One of the earliest structures to be built was the pier extension at Courtown, Wexford. The construction of this pier in 1847 would set the stage and successfully demonstrate that screw-piles could be used to support large ocean front piers with great speed, efficiency and cost savings. This would be a concept taken up by several of the great pier builders right through the end of the nineteenth century. In addition, this project would demonstrate a new method of screw-pile installation specifically suited to this type of work. Mitchell gave an account of the work at Courtown:

> In the summer of 1847, the screw-pile was subject to a new trial, in the construction of a pier, or jetty, near the village of Courtown, about twelve miles south of Arklow, on an open and exposed part of the coast of Wexford. On its commencement, a startling difficulty presented itself. Barges, or strongly constructed rafts, had been previously found sufficiently steady to act as stages for the workmen, when screwing down either piles or moorings; but the coast at Courtown being unprotected nearly from north to south, with an open sea of 70 miles in front, a surf of great height and force beats almost without intermission upon the shore, preventing the use of any floating body in the construction of the works. As a steady footing for the men is to a certain extent essential, it became indispensable that the screwing down of the piles should be effected from the work itself. The method of construction that was adopted was very cheap and simple. The piles were to be placed 17 ft apart, in a direct line outwards; a projecting stage was therefore rigged, extending that distance forwards, with the other end resting upon and temporarily attached to the solid part of the pier. The screw-pile was then run forward upon rollers, lifted by tackle, and placed vertically in the situation it was intended to occupy. A wheel, 32 ft in diameter, formed of capstan-bars lashed together at their ends, with a deeply grooved end to each, was keyed upon the body of the pile, and an endless rope-band was passed around it, and held in tension round a smaller grooved pulley, fixed about 150 ft back towards the shore. These preparations being made, a number of men hauling upon the endless band gave a rotary motion to the large wheel, and screwed the pile down to its place with great ease. The same operation was repeated for the next pile laterally, — the cross-beams were laid on, the overhanging platform was pushed forward, and two more piles were inserted. During this time the cross-braces were applied, and the permanent platform was finished.
>
> The works were by this means conducted with such facility and regularity, that, in spite of rough weather, one bay of 17 ft in advance was generally completed in a day.[13]

The use of Mitchell's endless rope provided a practical solution of being able to construct a pier sequentially, from the land outward into the open sea. The wheel allowed the workers to stand on the completed portion of the pier as construction progressed. This allowed both a safer work area and a much shorter construction period. Figure 5 shows a period engraving giving plan and profile views of the screw-pile work in progress at Courtown. At the bottom of the page it is indicated that the plan was presented by 'The Screw Pile Company' presumably set up to operate under

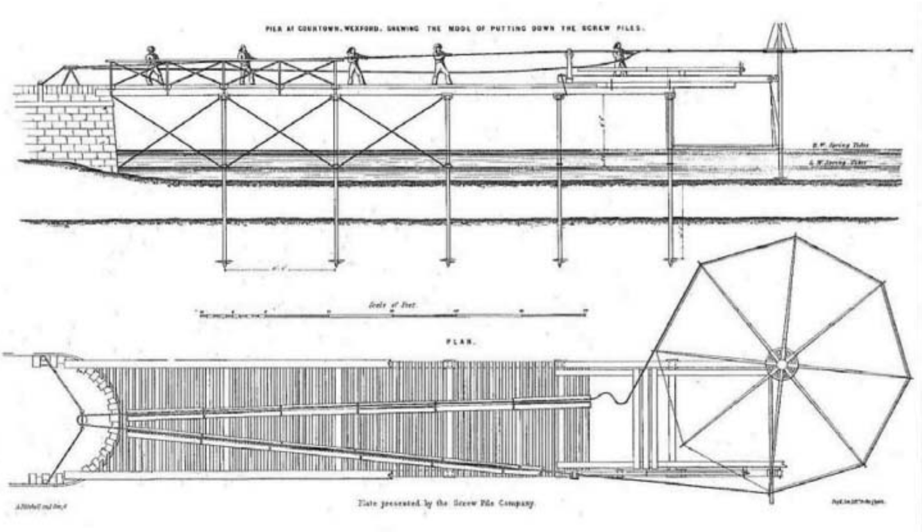

FIGURE 5 Diagram showing construction of Courtown Pier (from Mitchell[13]).

that name by Mitchell. A similar note is indicated at the bottom of the plate showing the Maplin lighthouse given in Redman's paper.[14]

Mitchell also described the overall scope of the project at Courtown and the geometry of the screw-piles used:

> The new part of the Courtown jetty is 260 ft in length beyond the solid stone part of the old jetty. The main roadway is 18 ft 6 in. wide with a line of railway laid upon each side, leaving a space for passengers in the centre between the lines. It is terminated by a cross-head or platform, 54 ft long by 36 ft wide, with a landing stage at each end, which can be raised or depressed, to suit the convenience of the vessels loading or discharging... The bottom into which the piles were inserted consisted of an average depth of about 8 ft of sand and gravel, upon a firm blue clay. Screws of 2 ft diameter were therefore sufficient, with wrought-iron piles, of 5 inches diameter, inserted in the ground to a depth varying between 11 ft and 15 ft.[15]

In effect, the pier construction at Courtown not only served as a model demonstration of the feasibility of using screw-piles to support on ocean front pier, but the pier is effectively a bridge so that that the most natural extension of this work would be the use of screw-piles in bridge construction, as will be discussed.

A flurry of construction activity associated with work on ocean front piers started not long after the success at Courtown and was led largely by arguably one of the most famous pier builders during this period, Eugenius Birch (1818–1884). However, before most of the pier construction was to take place around the English coast, Mitchell undertook to build a substantial pier at Madras, India in 1859. F. Johnson, who was an agent for Mitchell, described the work:

> The Madras Pier, designed by Messrs. Saunders and Mitchell, was commenced in the latter part of the year 1859 by Mr F. Johnson, their successor, and is now nearly completed. This pier is 1080 ft. in length, and its width 40 ft. 6 in. It terminates in a

> cross-head 160 ft long by 40 ft. 6 in. wide. The piles are of solid wrought-iron, the screws of which are inserted to a depth varying from 11 ft. to 19 ft. 6 in. in the ground. The pier extends about 40 ft beyond the water line of surf.[16]

Eugenius Birch's first use of screw-piles was at Margate Jetty on the eastern shore in 1853 (Figure 6). Since Mitchell had received only a seven-year extension of his 1833 patent in 1847, by the time Birch began construction at Margate it is likely that the patent had run out and there would have been no royalties to pay to Mitchell. This meant that any engineer could incorporate the use of screw-piles for his projects without requiring Mitchell's involvement. Birch would use screw-piles at several other locations, including Blackpool North, Deal, West Pier at Brighton, Aberystwyth and others. The design of most of these piers was very similar with the use of both vertical and battered screw-piles.

The use of screw-piles for pier/wharf foundations also found its way to the US and other parts of the world during this period. In the US one of the most notable structures supported on screw-piles was the government pier built in 1871 at Lewes, Delaware, described by Stierle:

> There are altogether 297 piles, placed in 81 cross-rows, 21 ft apart from center to center, and measured along the axis of the pier. The piles in each row stand 10 ft 6 inches apart from center to center. Fifty-four rows of piles, those under the narrow part of the pier, have 3 piles each and the 27 rows supporting the pier head have 5 piles in each row... From the first to the forty-ninth row, the diameter of the pile is 5¼ inches; the length increasing, more or less, from 16 to 25 ft. For the next five rows, from the fiftieth to the fifty-fourth inclusive, the diameter is 5¾ inches; the length as the water is now getting deeper, rapidly increasing from 25 ft to 29 ft 6 inches. The next row, the fifty-fifth, is the

FIGURE 6 Period postcard of Margate Jetty built on screw-piles (Author's collection).

> first row of the pier-head. In this and the two following rows, the fifty-sixth and fifty-seventh, the diameter of the piles is 6¾ inches; their length, for the rows named, being respectively, 31, 32½ and 33½ ft.[17]

Figure 7 shows a diagram of a portion of the Lewes pier. All of the screw-piles were installed vertically and had a blade diameter of 2 ft 6 in.

Another notable screw-pile pier was built in the USA at Fort Monroe, Virginia in 1888. Open screw-cylinders were installed and then wooden piles were driven through the open cylinder to a depth several feet below the blade. Duncklee described the geometry of the screw-cylinders:

> The lower section, which rests on and encases the wooden bearing pile, is 8 ft long and 13 inches in interior diameter, the iron being 1 inch in thickness... About 1 foot above the lower end of this section of pile are two screw-pile blades, with a maximum diameter of 32 inches. The blades are 2.5 inches thick at the junction with the cylindrical pile, this thickness diminishing to three-eights of an inch at the edge of the blade.[18]

Screw-pile piers were also built in many other parts of the world, including India, South America, Europe and the United States. Table 2 gives a partial list of known screw-pile piers built around the world during this period. There is limited detailed information on the geometry of the screw-piles used at many of these pier locations, although it appears that most screw blades were in the range of 2.5 to 4 ft in diameter.

It may be that Eugenius Birch recognised the potential for using screw-piles for ocean front piers from his work in India around 1845–1847 where he and his brother John Bannis Birch worked on the East Indian Railway from Calcutta to Delhi, and may have seen screw-piles being installed in that country for bridge foundations.[19]

Bridge foundations

It is not surprising that both screw-piles and screw-cylinders became commonly used as bridge foundations following some of the success with pier construction. I. K. Brunel may have been the first to consider the use of screw-cylinders specifically for bridge foundations. Mitchell wrote:

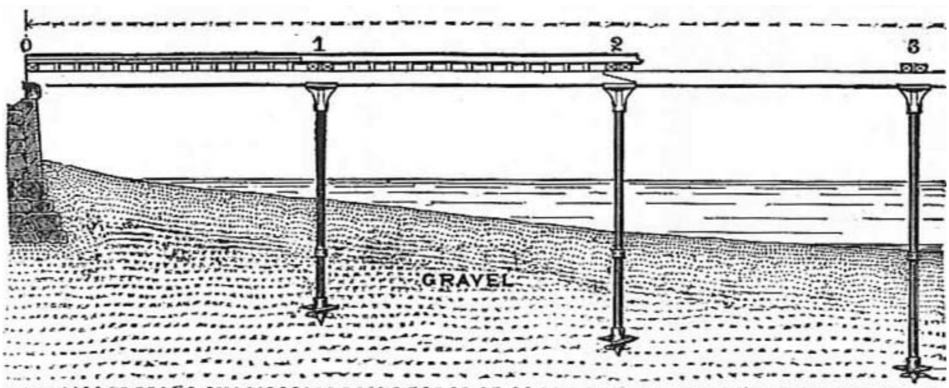

FIGURE 7 Diagram of Lewes, Delaware Pier on screw-piles (from Stierle[17]).

TABLE 2

PARTIAL LIST OF SCREW-PILE PIERS

Pier (Designer/Builder)	Date	Style	Geometry	Reference
Margate, Kent (E. Birch/ Bastow of Hartlepool)	1853	N/A	N/A	*ILN* (21 May 1853), p. 397
Glenelg, South Australia	1856	N/A	Cylinder – 8 inch, blade – 2 ft, pitch – 6 inch	*CEAJ* 19 (1856), p. 69
Blackpool (E. Birch/R. Laidlaw & Son)	1863	N/A	N/A	*ILN* (30 May 1863), p. 598 *CEAJ* 26 (1863), p. 162
Deal, Kent (E. Birch/R. Laidlaw & Son; J. E. Dowson)	1864	N/A	N/A	*ILN* (19 November 1864), p. 520 C. Bainbridge, *Pavilions of the Sea* (Robert Hale, London, 1986)
Lytham, Lancs (E. Birch/ R. Laidlaw & Sons)	1865	N/A	N/A	*ILN* (29 April 1865), p. 415
Aberystwyth, Wales (E. Birch)	1865	N/A	N/A	*ILN* (21 October 1865), p. 384
Teignmouth, S. Devon (J. W. Wilson/ J. E. Dowson)	1867	N/A	N/A	C. Bainbridge, *Pavilions of the Sea* (Robert Hale, London, 1986)
Clevedon, Somerset (R. Ward & J. W.Grover/ Hamilton, Windsor Ironworks)	1868	SP	Shaft – 5 inch, blade – 2 ft	*ILN* (10 April 1869), p. 369 *ICE* 32, (1871), pp. 130–36
New Brighton, Liverpool (J. Brunlees)	1868	SC	Cylinder – 12 inch, blade – 2 ft 6 inch	*ICE* 28 (1869), pp. 217–25
New Ferry, Liverpool (J. Brunlees)	1868	SC	Cylinder – 12 inch, blade – 2 ft 6 inch	*ICE* 28 (1869), pp. 217–25
Eastbourne, Sussex (E. Birch/J. E. Dowson)	1870	N/A	N/A	C. Bainbridge, *Pavilions of the Sea* (Robert Hale, London, 1986)
Mazagon Pier, Bombay, India	c. 1870	N/A	N/A	E. Matheson, *Works in Iron* (E. & F. Spon, London, 1873)
Punto Avenas, Costa Rica	c. 1870	SP	Shaft – 4 inch and 5 inch, blade – 2 ft 3 inch	Matheson, as immediately above
Hastings, Sussex (E. Birch/ R. Laidlaw & Sons)	1872	N/A	N/A	*ILN* (1872)
Milford Haven, Wales (Davey)	1874	SP	Shaft – 5 and 6 inch, blade 2 ft 3 inch	*Transactions of the Society of Engineers* (1874), pp. 89–111
Portsmouth Harbour Pier and Railway Station, Hants	1875	SC	Cylinder – 18 inch, blade – 4 ft, pitch – 8 inch	H.R. Reynolds, *Practical Problems in Foundations* (Crosby Lockwood & Son, London, 1960)
Birkenhead	1877	SC	Cylinder – 1 ft 7 inch, blade – 2 ft 7 inch, pitch – 8 inch + spiral tip piles	*ICE* 50 (1877), pp. 164–68
Huelva – Rio Tinto Railway, Spain	1878	SC	Cylinder – 16 inch, blade – 5 ft, pitch – 6 inch	*ILN* 53 (1878), pp. 130–63; *Scientific American Suppt.* 124 (18 May 1878), p. 1971
Bournemouth, Hants (E. Birch)	1880	N/A	N/A	*ILN* (28 August 1880), p. 204

TABLE 2

CONTINUED

Skegness, Lincolnshire (Clark & Pickwell)	1881	N/A	N/A	C. Bainbridge, *Pavilions of the Sea* (Robert Hale, London, 1986)
St Leonards-on-Sea, Sussex, England	1888	SC	Cylinder - 12 inch, blade - 2 ft 6 inch, 3 ft, pitch - 6 inch	*Scientific American Supplement* 651 (23 June 1888), pp. 10391–10393
Koto Nou, Gulf of Benin, Africa	1892	SP	Shaft - 5⅜ inch	*Engineering News* (6 October 1892), p. 320
Blankenberg, Belgium	1895	SP	Shaft - 11.7 inch, blade - 3.93 ft, pitch - 5.3 inch	*Engineering News* 33 (6 June 1895), p. 360
Bangor, Wales	1896	N/A	N/A	C. Bainbridge, *Pavilions of the Sea* (Robert Hale, London, 1986)

NOTE: SP, screw-pile; SC, screw-cylinder

> Mr Brunel has recently caused a very interesting and conclusive experiment tried, near the proposed site of the bridge for carrying the South Wales railway across the river Wye, at Chepstow. A cast-iron cylinder, 3 ft in diameter externally, 1½ inch in thickness, cast in lengths of 10 ft each, with internal socket and joggle joints, secured with pins and run with lead, was armed at the extreme bottom with a sharp wrought-iron hoop, and a little above it was a helical flanch projecting 12 inches all round from body of the cylinder, around which it made an entire revolution, with a pitch of 7 inches. By means of capstan-bars worked by manual labour, and by strong winches, this cylinder was screwed into the ground, near the bank of the river, but out of the influence of the tide, to a depth of 58 ft, in 48 hours and 14 minutes, through stiff clay and sand down to the marl rock. In descending to that depth the cylinder made 142 revolutions, and the average rate of sinking per revolution very nearly accorded with the pitch of the screw.[20]

One of the earliest designs for a screw-pile bridge was presented by Brunlees for a railway drawbridge over the Leven estuary near Ulverstone for the Ulverstone and Lancaster Railway.[21] Screw-piles with blade diameters of 2 to 3 ft with shafts of about 10 inches in diameter were proposed to support the span and were to be founded in sand. By 1870, a number of successful bridge projects had been completed using screw-piles or screw-cylinders.

By far the largest construction works using screw-piles as foundations for bridges was for railway construction in India, in particular for the Bombay, Baroda and Central Railway. The construction of the works, including the use of screw-piles was described by Kennedy:

> The piers are composed of hollow cylindrical cast-iron piles, of 1-inch thickness of metal and 2 ft. 6 in. outside diameter, cast in 9-ft lengths weighting 1½ tons each. They are of two principle [sic] patterns for the portions of the piles above and below the ground. Those above the ground have flanges outside for bolting them together by twelve 1-inch bolts; while those underground have the flanges inside bolted together by ten 1-inch bolts, and are flush on the outside... they are large enough inside to leave room for a man getting in to bolt the several lengths together properly in the process of erecting. The

> foundation is obtained by one of Mitchell's screws at the bottom of each pile, of 4 ft. 6 in. diameter, which finds its own foundation without the expense of cofferdams or any other artificial preparation of the ground... To obtain the requisite strength of foundation, the greatest length of pile used has been 45 ft below the ground and 72 ft above.[22]

Installation of the screw-cylinders was described as follows:

> The use of animal power was adopted in screwing down the piles at the great Nerbudda bridge, where a large part of the river bed is uncovered at low water, and it is only in such situations that animal power has been made available direct by means of a long lever. The general practice has been, where the foundations are not always under water, to hoist the piles into the proper position by shear legs, and hold them in this position by guides whilst they are screwed into the ground by a crab winch acting on the end of the lever; but where the ground is always covered with water a staging has been erected on timber piles surrounding the site of the pier. Latterly the principle of floating rafts has been successfully adopted instead of fixed staging.[23]

A summary of the project indicates that screw-cylinder bridges were used to span 32 rivers, giving a total of 25,160 ft of bridge span, consisting of 409 individual spans, all supported on screw-cylinders.[24] The screw-cylinders were manufactured in England by Horseley Iron Co., Tipton, and Victoria Iron Co., Derby, and shipped to India.

In his book on the use of iron for bridge and roof construction, Matheson described a number of bridges that had used screw-cylinders for bridges.[25] Matheson was employed by the iron fabricator Andrew Handyside & Co. of Derby who built a large number of iron structures. All of these bridges were placed on large diameter screw-cylinders which had become more common, no doubt to provide increased lateral resistance to river currents. Table 3 gives a listing of some projects involving the use of screw-piles or screw-cylinders for bridges up to about 1875.

After about 1875 and continuing to the end of the century, many other bridge works were completed around the world using screw-piles or screw-cylinders for foundations. A number of these projects are summarised in Table 4. Even after the turn of the century, screw-piles continued to be used for bridge foundations up until about 1920. After about 1875 some advances were also made in screw-pile technology by modifying the geometry of the screw blade or by adding additional blades along the shaft in effect to produce a multi-helix screw-pile or by modifying the configuration of the lead screw blade to improve the ease of installation.

Other applications

Throughout this period, screw-piles and screw-cylinders were also used in other civil engineering construction applications besides foundations for new structures such as underpinning of sinking buildings and as anchors.

Underpinning

Duckman described the use of screw-cylinders to underpin the Town Hall at Great Yarmouth, England, which had been completed in 1882. By 1886 the west side of the structure has settled more than 12½ in. at the ends as compared with the east side.

TABLE 3

SCREW-PILES USED FOR BRIDGE FOUNDATIONS TO 1875

Bridge	Date	Style	Foundation geometry	Reference
Chey-Air Bridge, Madras Railway	c. 1865	SP	Shaft - 5 inch	*ICE* 24 (1865), pp. 184–95
Adige River Bridge, Verona, Italy	1866	SP	Shaft - 8 inch, blade - 2 ft 9 inch, pitch - 12 inch	*CEAJ* 30 (1 April 1867), pp. 105–07
Midland Railway over Avon River, Bristol, England	1869	SC	Cylinder - 2ft 6 inch, blade - 4 ft 9 inch	*CEAJ* 18 (1855), p. 33; *Scientific American* 20, (3 April 1869)
Brazil	c.1868	SC	Cylinder - 12 inch, blade - 2 ft 6 inch	*ICE* 27 (1868), pp. 275–319
Eau Brink Viaduct, Lynn	c. 1868	SC	Cylinder - 18 inch, blade - 3 ft 3 inch	*ICE* 27 (1868), pp. 275–319
Stour River Viaduct, Christchurch	N/A	SC	Cylinder - 13½ inch, blade - 2 ft 6 inch, pitch - 3 inch	*ICE* 29 (1870), pp. 403–10
Cambrian Railway Viaducts	c. 1870	SC	Cylinder - 10 and 14 inch, blade - 3 ft	*ICE* 32 (1871), pp. 137–70
Osaka, Japan	N/A	SC	Cylinder 12 inch	E. Matheson, *Works in Iron* (E. & F. Spon, London, 1873)
Buenos Aires, Argentina	N/A	SC	Cylinder - 18 inch, blade - 3 ft 6 inch	Matheson, as immediately above
Derwent River, Derby, England	N/A	SC	Cylinder - 24 inch, blade - 4 ft 3 inch	Matheson, as immediately above
Wye River, Whitney, Herefordshire, England	N/A	SC	N/A	Matheson, as immediately above
Avon River, Tiverton, England	N/A	SC	Cylinder - 30 inch, blade - 4 ft 3 inch	Matheson, as immediately above
Avon River	N/A	SC	Cylinder - 4 ft 9 inch	Matheson, as immediately above

NOTE: SP, screw-pile; SC, screw-cylinder

The structure was set on shallow foundations and founded on about 5 ft of 'made ground' overlying about 17 ft of 'ooze' (silty clay) which was underlain by gravel. Screw-cylinders with blade diameters of 2½ and 3 ft, shaft diameters of 1½ and 2 ft and a pitch of 6 inch were screwed into the gravel on both the inside and outside of the walls. New girders were placed on top of the screw-cylinders and the girders were encased in concrete to support the existing footings. This application is not substantially different than many modern applications of screw-piles.[26]

Anchors

Several applications of screw-piles to support tension or uplift loads were presented apart from those previously used for lighthouses. For example, Feld indicated that A. Goodwyn, of the Royal Engineers, used small screw-piles 7 ft long consisting of a 1 inch rod to which was attached an 1/8 in thick screw of sheet iron 5½ inch in diameter with a pitch of 2 inch to hold brushwood to provide shore protection.[27]

TABLE 4

PARTIAL LIST OF BRIDGE PROJECTS USING SCREW-PILES 1875–1900

Bridge	Date	Style	Foundation geometry	Reference
South Australia	c. 1878	SC	Cylinder - 12 inch	*ICE* 56 (1878), pp. 24–38
Mobile River Bridge, Mobile, Alabama	1885	SP	Shaft - 6 inch, blade - 4 ft, shaft 8 inch, blade - 6 ft	*Engineering News and American Contract Journal* (4 April 1885), pp. 210–13; W.M. Patton, A Practical Treatise on Foundations, (John Wiley, New York, 1900)
Wumme River Bridge, Bremen, Germany	1890	N/A	Blade - 32 inch	*The Engineering and Building Record* (5 April 1890), pp. 280–81
India	1892	SP	Shaft - 9¼ inch, blade - 3 ft 6 inch	*Engineering News* (4 Aug. 1892), p. 116
Koenigsberg, Germany	1895	SC	Cylinder - 2.56 ft, blade - 4.92 ft, pitch 10.8 inch	*Engineering News* (26 May 1892), p. 532
Drawbridge over Dee River, Queensferry, Wales	1900	SP	Shaft - 6 inch, blade - 3 ft	*ICE* 138 (1898), pp. 344–49; *Engineering News* 43, no. 3 (1900), pp. 46–48
Swing Bridge, River Weaver, Northwich, England	N/A	SC	Cylinder - 2 ft 6 inch, blade - 4 ft 6 inch, pitch - 10 inch	*Engineering News* (20 Sept 1900), pp. 190–91

NOTE: SP, screw-pile; SC, screw-cylinder

Bateman and Revy suggested that screw-piles could be used to anchor cast iron tunnel sections for their design of an immersed tube Channel Tunnel between France and England.[28] A similar plan for an immersed tube tunnel was described in *The Manufacturer and Builder* and attributed to Mr P. J. Bishop.[29]

Installation methods

Methods used for installation of screw-piles experienced a progression and a shift from hand installation using a capstan or wheel to the use of animal power to rotate the capstan and later the use of steam[30] and hydraulic power.[31] The expanding use of screw-cylinders for bridge foundations during this time undoubtedly required higher installation torque as resistance built up along the perimeter of the cylinder. The use of both steam and hydraulic power presented themselves as possibilities to reduce the workforce, increase efficiency of the work and obtain higher torque but towards the latter part of the nineteenth century other methods were developed to provide higher torque for both more rapid and deeper installations.

Screw pile geometry

In addition to the widespread use of screw-piles, which had a slender shaft (either solid or hollow) and develops its primary capacity from the helical plate, screw-cylinders having a large cylindrical hollow shaft with a relatively small helical screw section were also developed and used extensively during this period. Most large

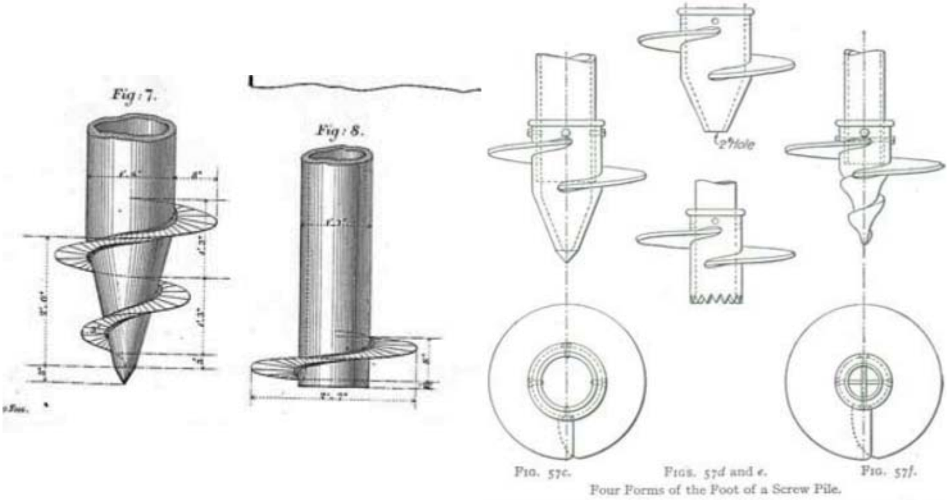

FIGURE 8 Variations in screw-pile helix geometries (from Matheson[25]).

diameter screw-cylinders were used in bridge construction to provide additional lateral resistance to currents. The helical blade of a screw-cylinder was used to facilitate the installation of the cylindrical shaft making the pile a combination end bearing and shaft resistance foundation element, but more importantly, the larger diameter shaft provided a larger resistance to lateral forces in comparison to its screw-pile counterpart.

The geometry of screw-piles and screw-cylinders developed alongside the growing applications and specific diameters of shafts and blades were manufactured for specific projects to meet the nature of the subsurface conditions and the anticipated loads. Based on the wide range of sizes used during this time, it appears that manufacturers had little difficulties in meeting the design requirements. After about 1875, the largest variation that developed was in the shape of the lead helix for screw-piles, which experienced considerably modification to meet different ground conditions in an attempt to make installation easier, as illustrated in Figure 8. The addition of extra helices along the shaft to create a multi-helix screw-pile or screw-cylinder became more common in the latter part of the nineteenth century.

Summary

Screw-pile and screw-cylinder foundations were perhaps the most important foundation development of the nineteenth century. Their use throughout the world allowed a great number of large-scale structures to be built at a time when other available alternative foundation methods would not have been as successful. Some of these structures are still standing which is a testament to the materials and workmanship used. The decline in their use was most likely related to the mechanisation of the construction industry and the development of other deep foundation methods, including pneumatic caissons, open-hole cylinders, bored piles, and many other proprietary foundation systems that became popular at the beginning of the twentieth century.

It would not be until the 1950s when a slow return to the use of screw-piles, largely as ground anchors, would be seen. In the past two decades that rebirth has seen a steady increase in growth in many civil construction applications. It is interesting to note that historically, the use of screw-piles and screw-cylinders was described in some detail in nearly every available civil engineering book related to foundation engineering up through the 1920s. Today, although they have regained a significant portion of their popularity for a variety of applications, there is scarcely a single university level foundation engineering textbook that gives little more than a passing mention of screw-piles, screw-cylinders, or helical ground anchors.

Screw-piles possessed a number of advantages over other types of available deep foundations; they were relatively easy to install with hand labour; the component parts were readily available; installation was relatively rapid; they developed bearing capacity shortly after installation; the size and length could be varied to suit the ground conditions; and they were most probably economically competitive. In fact, these are among the same advantages that modern screw-piles possess, which makes them just as viable as a foundation system now as they were in the nineteenth century.

Notes

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3 J. Elmes, 'Description of Mr Mitchell's Patent Screw Moorings', *CEAJ* 1 (1837–1838), p. 22.

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5 Mitchell, 'On Submarine Foundations' (1849).

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