Trans. Newcomen Soc., **72** (2000–2001), 91–113

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The Early Development of Structural Pile Foundations in Japan During the Meiji Era 1868–1912

by

Hiroshi ISOHATA, Dr. Eng., Member of JSCE, NKK Corporation, Tokyo.
Tetsukazu KIDA, Dr. Eng., Member of JSCE, Professor, Nihon University, Chiba.

ABSTRACT

Modern technology including pile foundation engineering in Japan developed after the opening of the country brought about by the Meiji Restoration of 1868 under the influence of Western technology. In this paper the development of the early pile foundation engineering has been clarified and examined, covering from conventional wood piles to iron piles through major construction projects in the Meiji era. The development of pile foundation technology was driven by the construction of railways, bridges and port facilities such as jetties and piers that played an important role in the modernization of infrastructures in the Meiji era.

Keyword; *pile, screw pile, foundation, railway, bridge, jetty, lighthouse, seaside pier, modern Japan.*

BACKGROUND AND PURPOSE OF THE STUDY

Japan was opened up to external influence during the Meiji era, which had started from the Restoration in 1868 following the Edo period.

The latter half of the 19th century marked the first era in which engineering technology was widely transferred on a global scale. The flow of the technology from the West to the other world was spurred on by exports of engineering goods and by the dispatch of engineers[1] for various infrastructure construction projects.

The boom in railway construction starting from 1850s brought many British engineers to India and a number of these later found employment other countries such as China, Australia, New Zealand as well as Japan which had just opened its door to foreign countries.

The first railway in Japan commenced construction work in March 1870, as proposed by the British engineer, R. H. Brunton (1841–1901) in March 1869. In the construction work British engineers were involved, including Edmond Morel (1841–1871) and John England (1823–1877), both of whom had been involved in some railway construction projects in southern Australia and Richard. V. Boyle (1822–1908) and Thomas. R. Shervinton (1827–1903) both of whom had worked in India.

The influence of Western engineering had gradually spread through construction projects of railway and many other fields of engineering in Japan

In this study, the development of the early structural pile foundation in the Meiji era is to be set out and considered by examining actual major construction projects in the Meiji era

Development of pile foundation in Japan

Pile foundation as well as direct foundation is the most general construction method for structural foundations and has been used from ancient times. Most of bridge structures before the Meiji era were very simple structures like timber girders that rested on wood-piled bent piers. Wood was the most popular structural material and wood piling was widely used until the middle of the 20th century. Pine, chestnut, cedar, cypress and fir were used for structural piles, pine being the most popular. After the end of the Meiji era the longleaf yellow pine produced in North America, which was longer than Japanese pine, was imported from USA and widely used for piles and columns[2]. Wood piling was generally driven below underwater level as green wood and the supporting force was solely frictional.

The early iron piles were cast or wrought iron pipes or rods with screws, which were imported mainly from England in the Meiji era. The application of iron piles was limited because of the high cost; however they were gradually applied to jetties, piers in ports and substructures of bridges.

Concrete piles with square or hexagonal cross section were first used in Japan in the 1910s. The first large-scale construction work using concrete piles was the construction of the foundation of railway viaducts between the stations of Tokyo and Mansei-bashi from 1915 to 1919. The total number of piles was 9,281, which were 18 to 50 ft. in length with octagonal cross section. The design load of each pile was 30 tons[3]. The first use of concrete pipe pile formed by rolling was in the 1930s. Pre-cast concrete pile with pre-stressed reinforcing steel, firstly used in Sweden in 1939, was introduced in Japan after World War II. It was in 1950s that steel pile was widely used for foundation work in Japan.

In addition to ready-made piles, cast-in-place cased concrete pile methods such as pedestal piling was introduced to Japan in 1915. As regards the method of placing of piles, manual driving or ramming was generally used before and even in the Meiji era. The equipment for placing piles was very simple as shown in Fig.1.

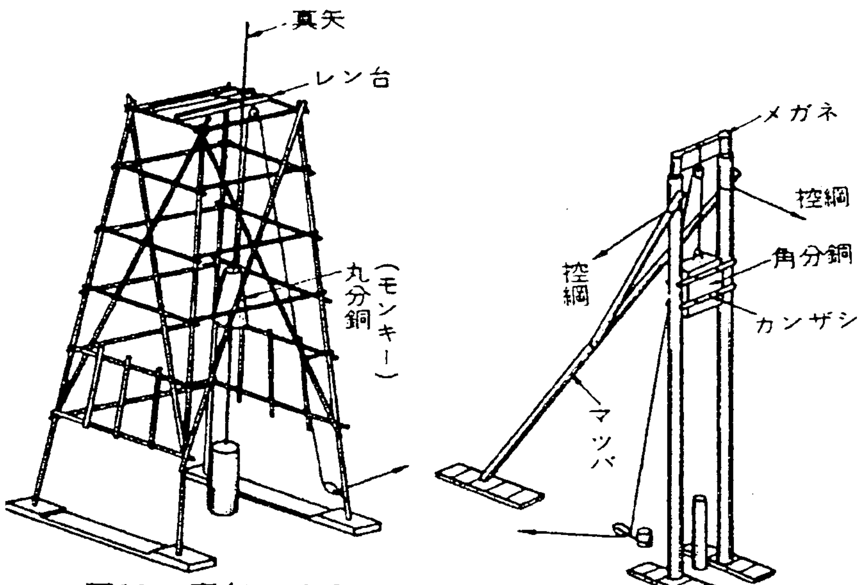

図36　真矢やぐら

図37　二本構

Fig. 1. Early ram drivers

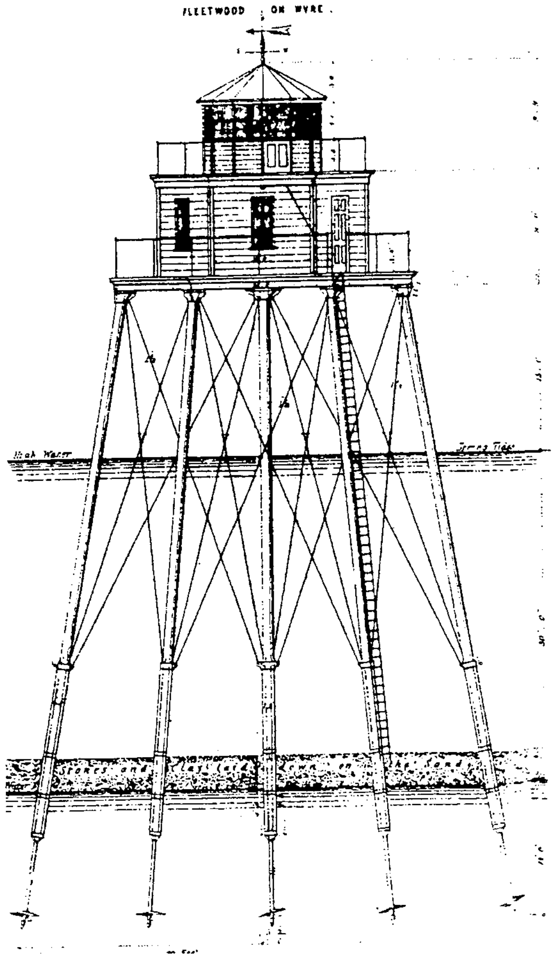

Fig. 2. Lighthouse erected on Mitchell's screw piles, Fleetwood on Wyre, ref.4, plate 2.

It was in Meiji era that steam operated drop-hammers were first used for placing piles in Japan. Single-acting steam hammers were used in 1910s and double-acting steam hammers in 1922. These began to be produced in Japan from 1929. After World War II, in addition to driving, ramming and screwing, the method of placing of piles was diversified and jetting, jacking, boring, pulling down, sand pumping, washing out and vibrating methods were applied according to the conditions at sites.

Development of Iron Pile usage Overseas

The iron pile with screw action was invented and started to be adopted as the foundation of seaside piers and bridge piers from the middle of the 19th century in Great Britain and other Western countries. Screw piles and anchors for mooring were invented and patented by Alexander Michell, Irish engineer, in 1833 and 1847 and screw piling was adopted for the construction of seaside piers and submarine foundations in Brighton, England and in other places[4, 5, 6]. The screw pile was adopted for the construction of ships' moorings, lighthouses and jetties in port and harbours in addition to seaside piers[7]; also screw piling started to be used for the piers of bridges from the 1850s.

Railway construction in India, then a British colony, was an early example of the application of iron pile with screw to bridge piers on a large scale. The construction of the Bombay Baroda & Central India Railway was started in 1854 and the northern half of the railway was opened in

1860. A standardized design of piers for truss girders with spans of 60, 150 and 250 ft. was made, using cast-iron piles of 2ft. 6in. diameter and 9ft. length. In the actual construction work cast iron piles 4 ft. 6 in. in diameter were used[8].

In the construction of pier of the bridge designed by the well-known bridge builder, Alfred Enrico Neville, iron pile with screw was adopted. The design of the Garibaldi Bridge was started in May 1855 and the bridge crossing the river Adige in Berona was open in 1861; this was one of the early examples of application of iron piles with screw to bridge piers. The truss girders were rested on the intermediate piers composed of iron columns on screw piles made in England. The screw was design by Neville in 4ft 6in diameter, but this proved undriveable and smaller substitutes were made in Venice[9].

Screw piling continued to be used well into the 20th century; in the U.K. steel piles of 3ft diameter with screws of 7ft 6in were used successfully in deep mud in 1950.[10]

In the USA wood was the most popular structural material, not only for piles but also many other structural purposes including bridge superstructures in the 19th century. However, from the turn of the century, steel piling was gradually introduced for the construction of foundations in addition to wood piling. Construction using steel and iron for structural purposes including piling, in the USA, overtook that of Europe; this was supported by the expanding iron and steel industry in USA.[11] Rolled H-shapes for piles started to be produced by Bethlehem Steel and Carnegie Steel in 1908.

STRUCTURAL PILES BEFORE THE MEIJI ERA (–1868)

Most bridges constructed before the Meiji were made of wood and the structural type in widest use was a girder bridge with piled bent piers. "Doboku-Ryo", the Civil Work Department published a book[12] in 1871 to show the conventional timber bridge construction methods which had been used for the Edo era.

According to the drawings and material lists in the book, the pier of a girder bridge was composed of three columns with a diameter of about 30 cm at the tip end supporting a portal with a cross section width of about 35 cm on which girders were rested. The columns were connected

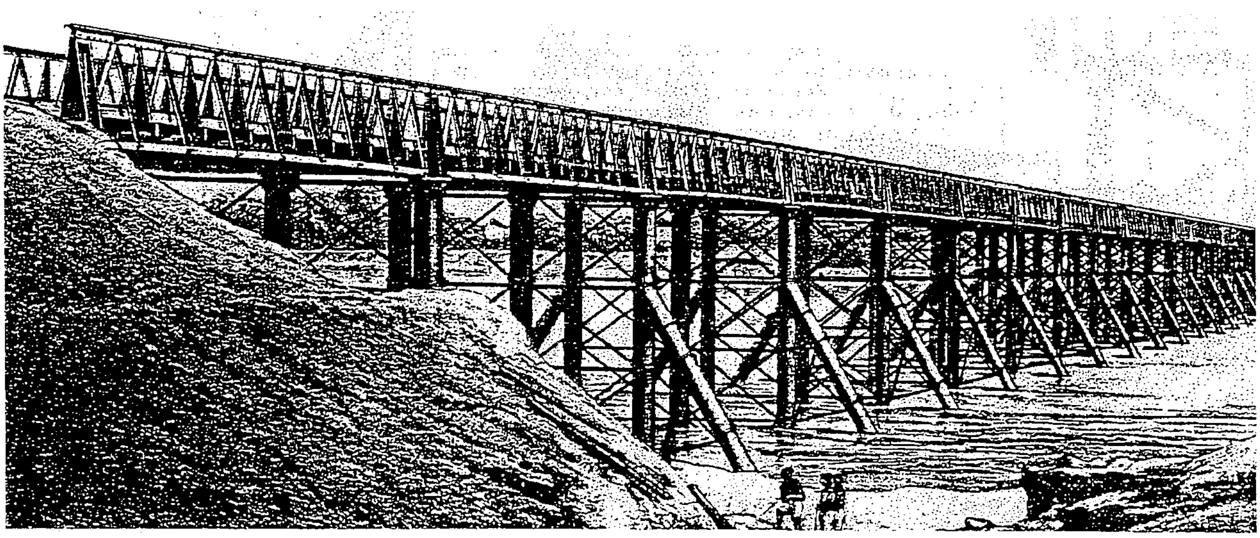

Fig. 3. The Tapti viaduct of bent pile piers with screws, 1860 ref.8, p.85.

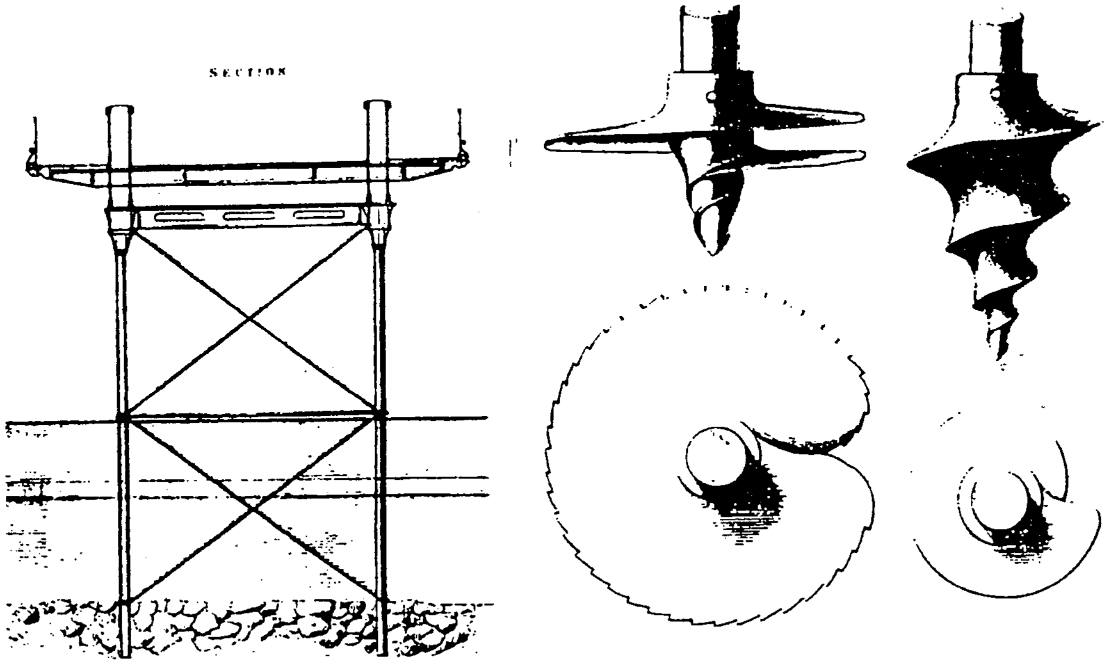

Fig. 4. Ponte Garibaldi, 1861, Neville's last truss bridge with screw piles, ref.9, p.86.

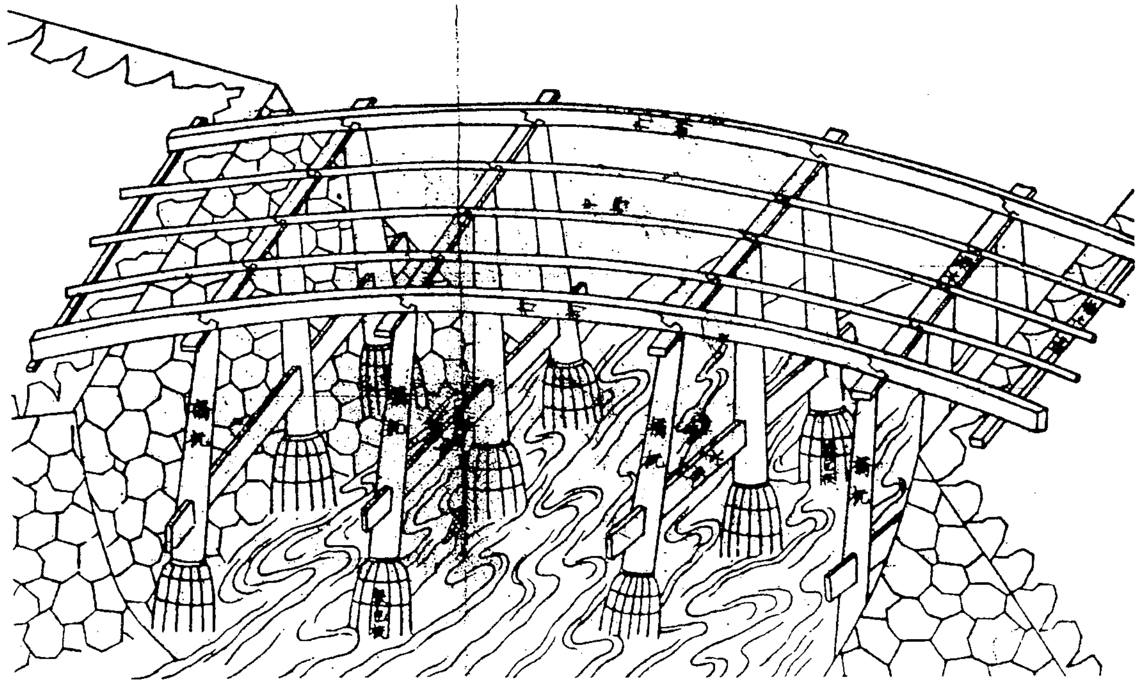

Fig. 5. Conventional timber girder bridge with bent pile piers in the Edo era, ref.12.

Fig. 6. The Fukagawa Mannen-Bashi Bridge in the Edo era, ref.14, p.15.

with intermediate portals with a cross section of about 8 by 20 cm. There were no bracings between columns in most cases. The method employed in placing the pile was not mentioned in this book but it is supposed that boring or driving was adopted. The lower end of the each column was protected by "Netutumi-ita" (root wrapping plate) against scoring.

Richard H. Brunton, who was the first British engineer hired by the Meiji government and stayed in Japan from 1868 to 1876, said in his book[13] about the conventional bridges as follows

The type of bridge to be seen in Japan in 1870 was, like that of the dwellings already described, of very primitive character. The piers were formed by two trees with the bark on. These were driven into the ground as far as native appliance would allow. The space between these was then spanned by two other tree trunks, selected as having the necessary bend which gives Japanese bridges their arched form.

Timber girder bridge was often adopted as a motif of Ukiyoe painting in the Edo era. Fig.6 shows a Ukiyoe painting of timber girder bridge with two piers at Fukagawa in Edo[14].

WOOD PILE IN THE MEIJI ERA

Shimbashi station and related facilities

The construction of Japan's first railway was commenced on 25 May 1870 at Shiodome area, adjacent to Shimbashi, Tokyo. The transportation service of 18 miles between Shimbashi and Yokohama was started on 13 September 1872. Major structures with pile foundations at Shimbashi

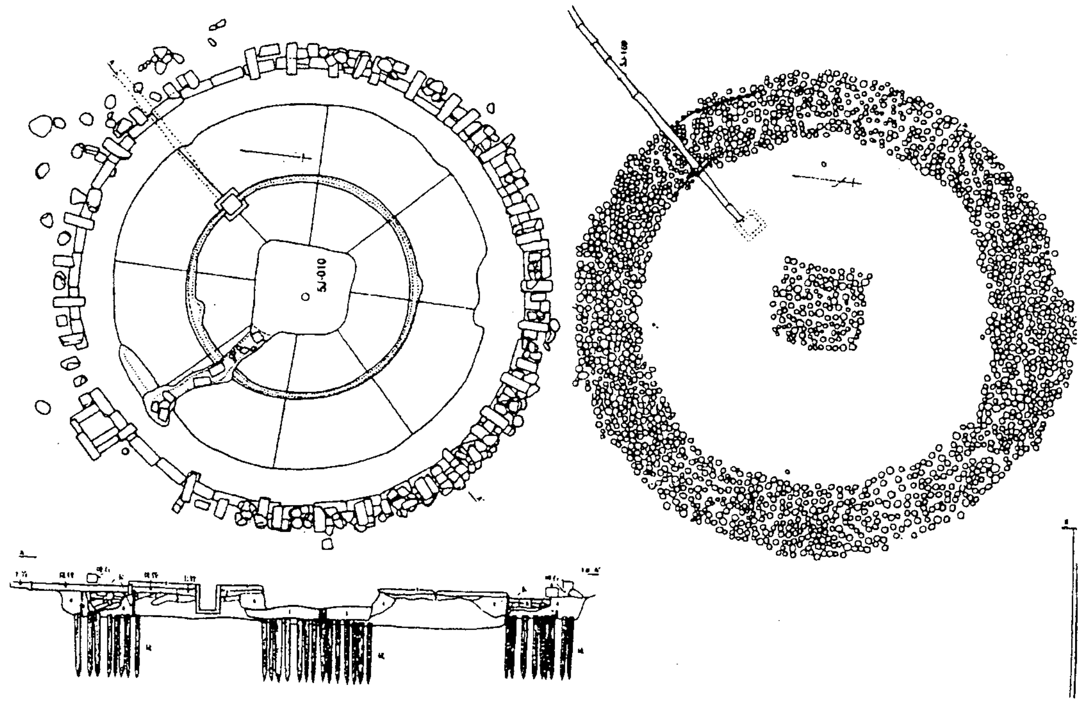

Fig. 7. Arrangement of pile-cluster (right) and base stones for a locomotive turntable, ref.16, p.5.

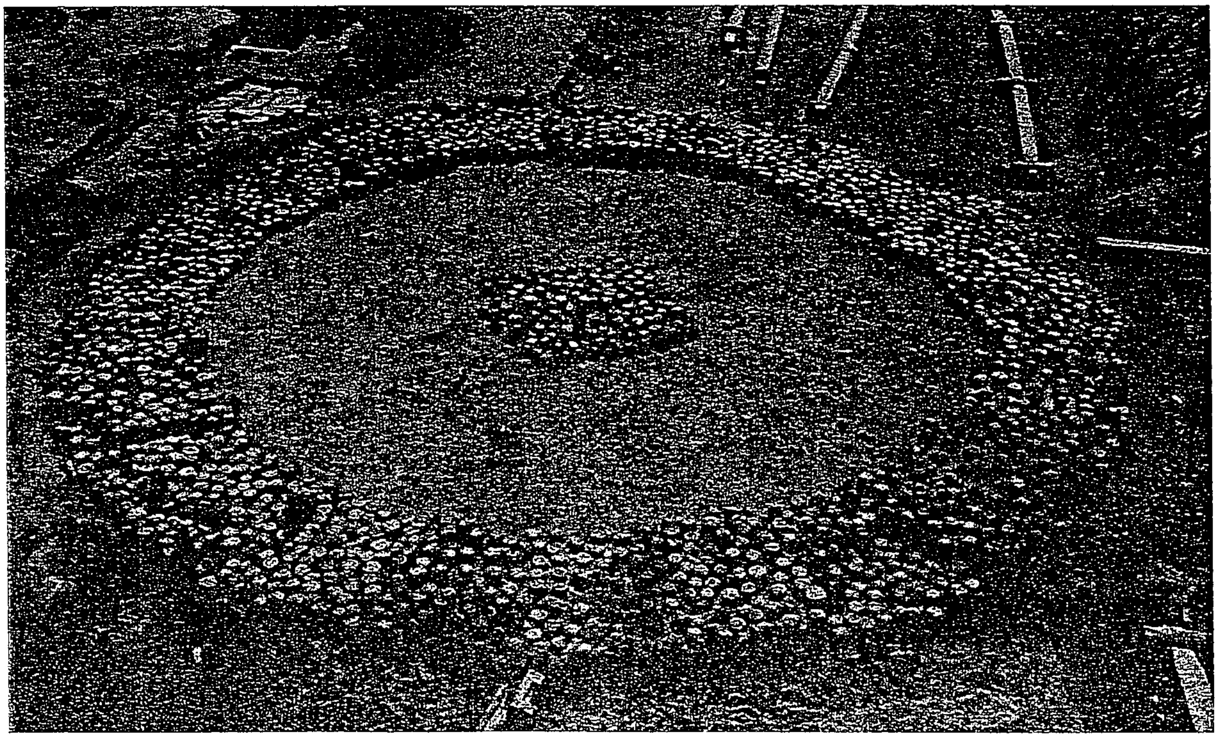

Fig. 8. Excavated pile-cluster for a locomotive turntable,
[Courtesy of Tokyo Metropolitan Government Archaeological Centre]

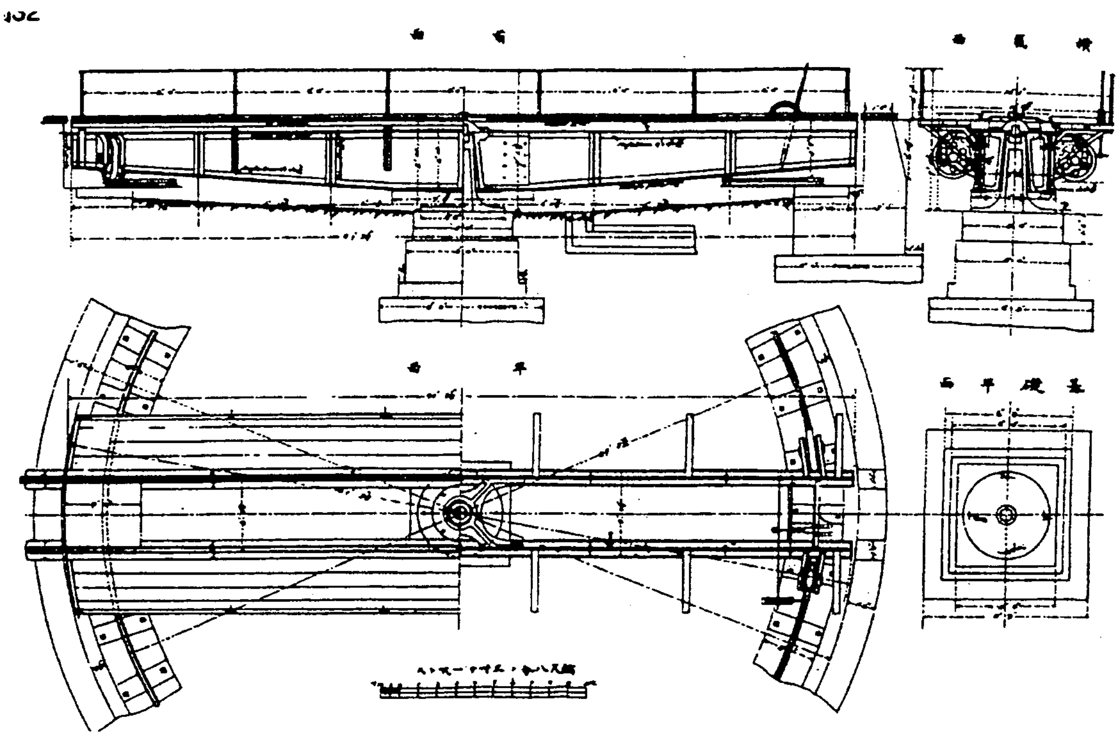

Fig. 9. General view of a locomotive turntable, 1872, ref.16, p.412.

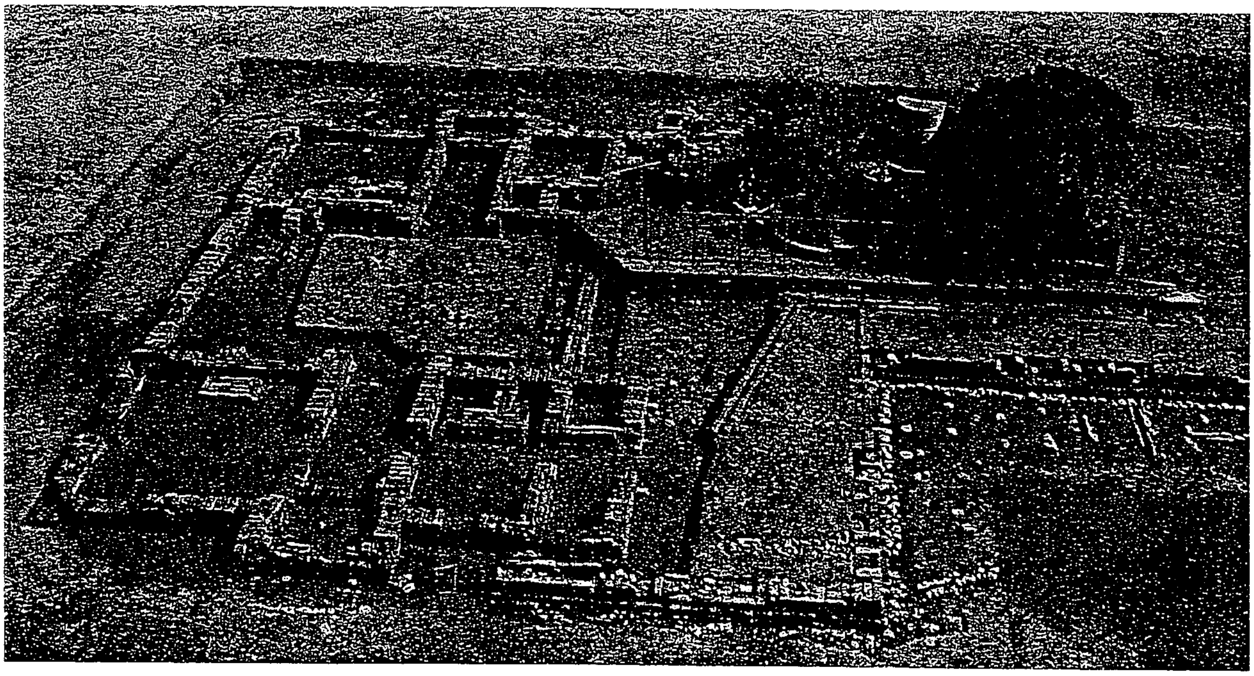

Fig. 10. Excavated foundation of Shimbashi station building and the platform, ref.17, p.22.
[Courtesy of Tokyo Metropolitan Government Archaeological Centre]

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station were the station building, platform, locomotive and wagon turntables, engine house, coal-bunker, houses for engineers, storage houses and so on. These have been excavated for examination at Shiodome Ruin[15] by the research[16, 17] of the Tokyo Metropolitan Government Archaeological Centre from 1992 to 93.

For the construction of the foundations of the locomotive turntable, 1,828 pine wood piles with a length of about 2 m. were driven as a cluster. The turntable was in the shape of circle with a diameter of 12.5 m. and the piles were driven at the centre part and outer edge where the concentrated load of locomotive was supported.

The building of Shimbashi station designed by American architect, R. P. Bridens, was completed on the 30 April 1872. The station building was in service for 50 years until it was destroyed by the Kanto Great Earthquake which occurred on 1 September 1923. The foundation of the building was pine wood pile with a length of 3.6 m. A pair of piles was driven at intervals of 30 to 50 cm for the foundations of the building and 1,000 piles were used in total.

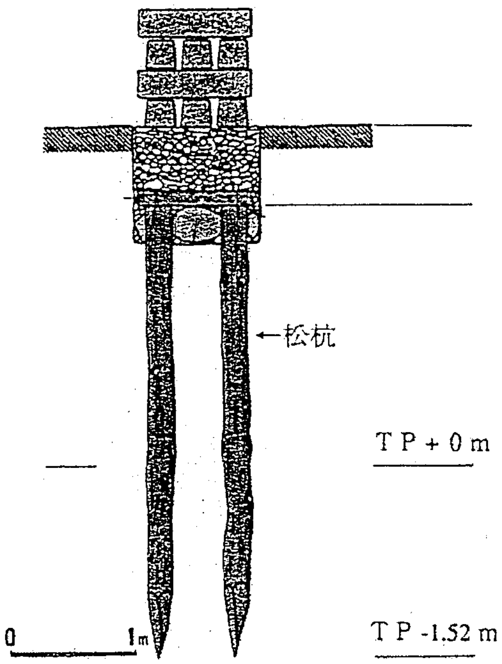

Fig. 11. Foundation of Shimbashi station and piles. ref.17, p.21.

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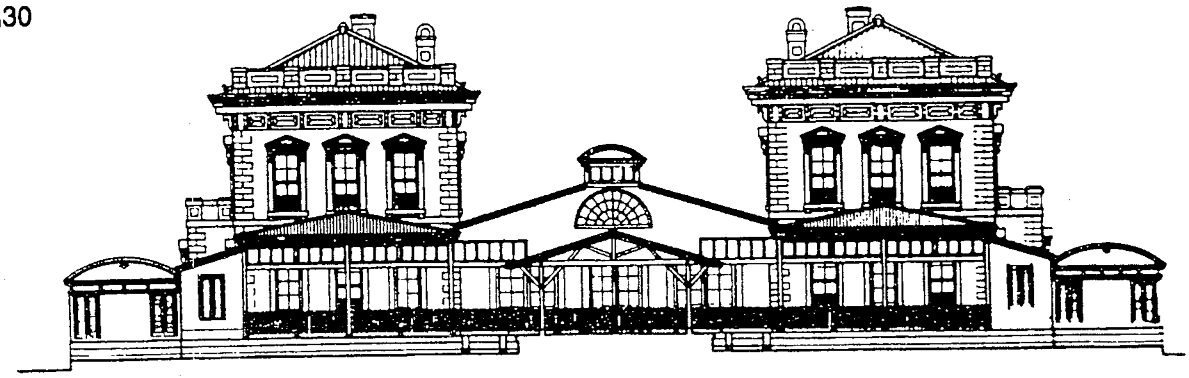

Fig. 12. General view of the Shimbashi station building, 1872, ref.16, p.412.

Wood pile for bridge substructure

Wood was still the most popular material for the construction of bridges through the Meiji era. Table 1 shows the number of bridges by materials at the beginning of 20 century. The type of timber bridge substructure most widely used was bent piling.

Table 1

Number of bridges by materials[18]

Year	Iron	Masonry	Timber	Others	Total
1902	85 (0.03%)	53,478 (18.7%)	232,227 (81.2%)	362 (0.1%)	286,152 (100%)
1907	114 (0.04%)	61,816 (20.4%)	240,868 (79.4%)	554 (0.2)	303,352 (100%)
1912	315 (0.10%)	67,935 (21.1%)	252,596 (78.6%)	623 (0.2%)	321,469 (100%)

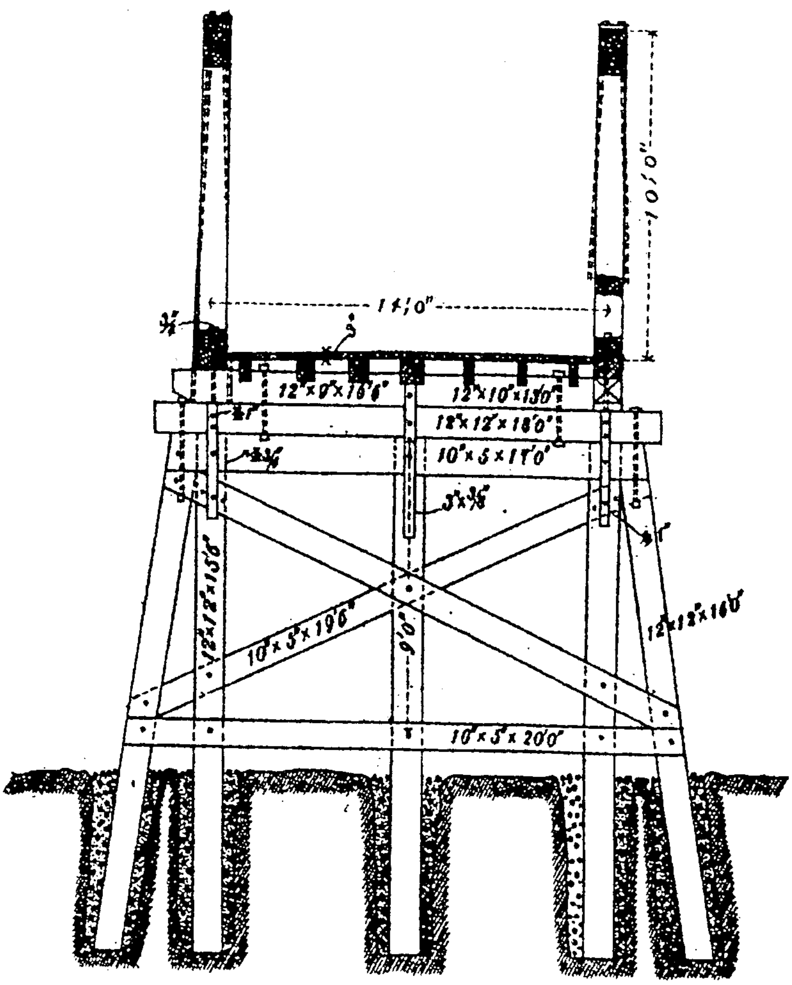

Fig. 13. The Shinpu Bridge, Gunma, c.1891, ref.19.

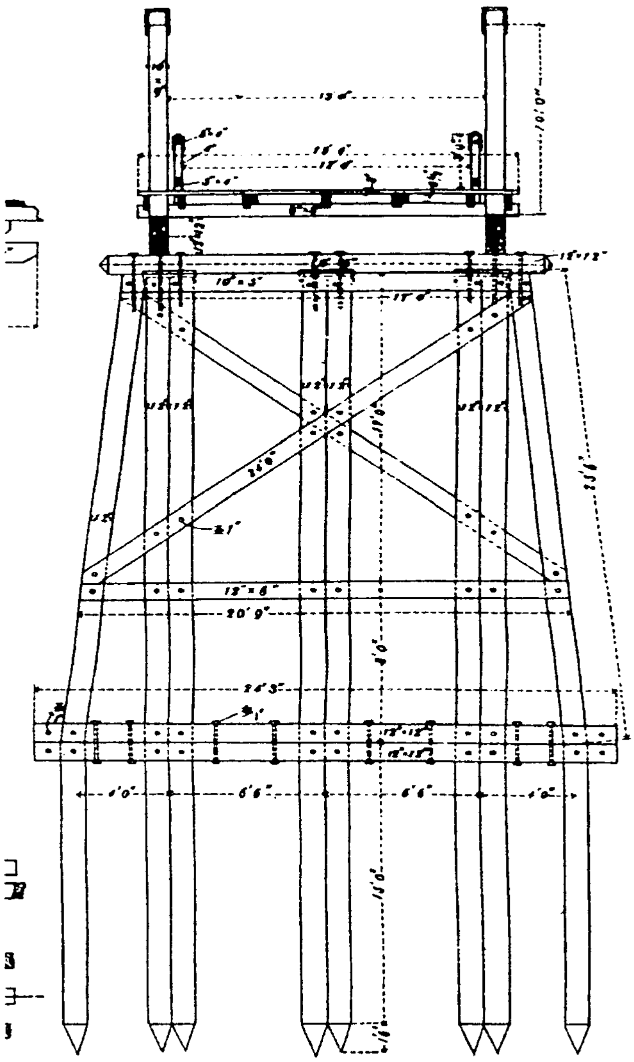

Fig. 14. The Imajuku Bridge, Gunma, c.1891, ref.19.

The Japanese engineer A. Nozawa designed and constructed several timber bridges in the Gunma prefecture between 1891 and 92. The piers of these bridges were piled bent piers, piles were driven or bored into the ground[19]. For driving, the toe of the pile was sharpened and a cast or forged iron shoe was attached on to prevent tearing[20]. Fig.13 shows a piled bent pier on which a truss girder rested. The pier was composed of three vertical piles and two diagonal piles with cross section of 12 by 12 in. placed into the ground by boring. The piles were connected with each other by portals at the top and just above the ground and diagonal bracing also connected to the piles. Fig.14 shows another example of a piled bent pier. Piles were driven into the ground and connected to each other by portals and bracings. These two examples were similar to the conventional bridge substructures in the Edo era from the viewpoint of material, however they differed from the conventional ones as regards structural design. These two bridges designed by the Japanese engineer clearly show the influence of European engineering, which had been built up over 25 years since the beginning of the Meiji era.

Table 2

Chronological list of structural foundations with iron piling.

Year	Major works
1868	*(The Meiji Restoration)*
1870	Koraibashi Bridge, Osaka (Cast iron pile with screw)
1872	First railway completed, Shimbasi -Yokohama (Wood pile-cluster, wood piled bent pier etc. No iron piles)
1873	Ajigawa Bridge, Osaka (Cast iron pile with screw)
1874	Mukogawa Railway bridge and other three bridges (Wrought iron pile with screw)
1875	Haneda Lighthouse, Tokyo (Wrought iron pile with screw)
1876	Naniwa Bridge, Osaka (Cast iron pile with screw)
1876	Kobe Railway Pier (Wrought iron pile with screw)
1876	Rokugougawa Railway bridge (Cast iron cylinder)
1884	Onohama Railway pier, Kobe (Wrought iron pile with screw)
1887	Nagaragawa Bridge (Cast iron pile with screw)
1892 - 94	Yokohama Great Pier (Cast iron pile with screw)
1902 - 03	Osaka Port Pier (Steel pile with screw)
1906 - 17	Yokohama Great Pier, Second phase
1910s	*(First Concrete pile)*

(Edited by authors)

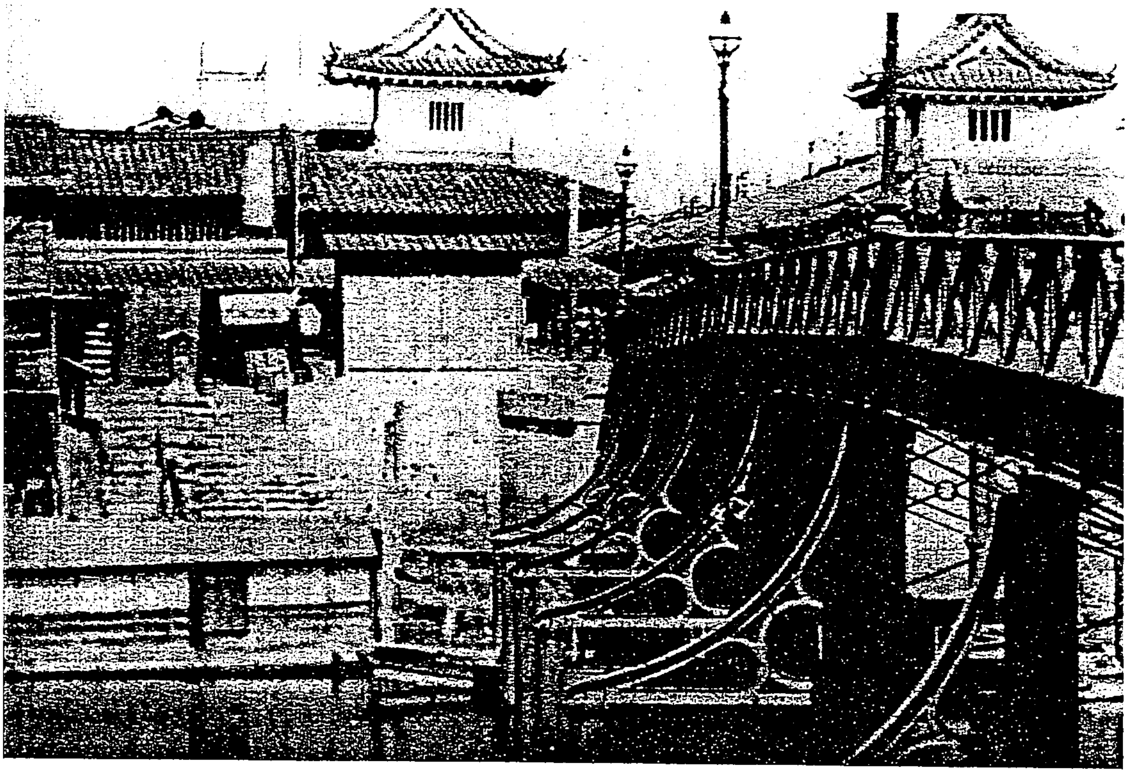

Fig. 15. The Koraibashi Bridge, Osaka, 1870, ref.14, p.27.

IRON PILING

Iron has excellent properties as a structural material. The use of the iron pile is an important factor that shows the trend of the development of modern pile foundation technology even though their use was limited because of the expense. Iron was never used for structural purposes, including piles, in the Edo era and all the materials and the related technology were introduced from Europe. Table 2 shows chronologically early major construction works with iron pile foundation.

The Koraibashi Bridge, Osaka, 1870

The early application of iron piling to bridge substructure was the Koraiba-bashi Bridge completed in 1870 in Osaka. The pile was cast iron pipe with screw of diameter 1 ft. and 29 ft. in average length. Four piles were screwed into the riverbed for each pier that gave a wide base to support two plate girders with 30 ft. span. The bridge had eight spans in total and the roadway was 18 ft. wide. This bridge was fabricated by Andrew Handyside and Co. in England and exported to Japan. The weight of the cast iron for the pier was 39.3 tons and the total weight of iron used for this bridge was 90.5 tons[21].

The contract for the importation of this bridge engendered some conflict. This conflict was the first example, followed by a lot of similar conflicts, caused by the differences of custom and the way of business in Japan which was meeting foreign countries for the first time since the beginning of the 17th century. (See ref.40.)

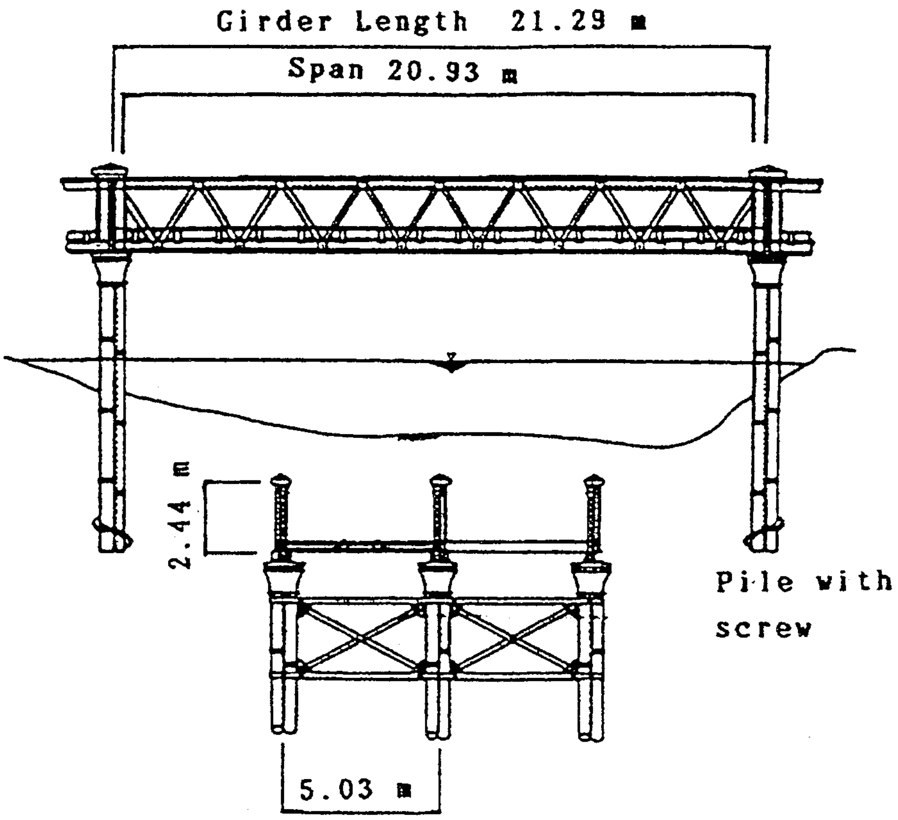

Fig. 16. Mukogawa Railway Bridge, Osaka, 1874, ref.22, plate. 18.

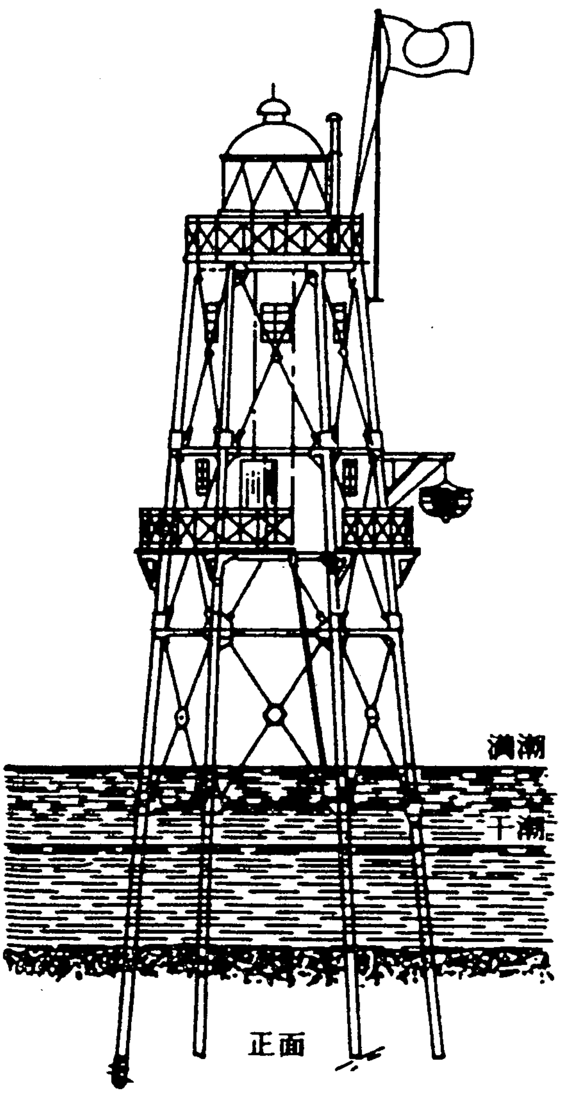

Fig. 17. Haneda Light House, Tokyo, 1875; ref.25, p.21.

Mukogawa Railway Bridge, Osaka, 1874

The first iron railway truss bridge was constructed with other three river crossing bridges between Osaka and Kobe in 1874. The Mukogawa Railway Bridge was one of them. The superstructure of the bridge was a wrought iron truss girder with a span of 70ft. For the substructure of the bridge, wrought iron pipe pile of a diameter of 2 ft. 6in. with screw was used. The pier was bent piling composed of two piles with an average length of 20 ft[22, 23].

William Pole, Consulting Engineer in England, was in charge of design and all the ironwork was manufactured by Darlington Iron Works Co. and exported to Japan. Theodore Shann, hired British engineer, was in charge of the construction.

Haneda Lighthouse, Tokyo, 1875[24, 25]

The Haneda lighthouse was the first lighthouse constructed on iron piles with screws. The construction work began in March 1874 and was completed one year after. The lighthouse was 55 ft. high and eight piles were screwed diagonally into the ground.

The design was by the famous lighthouse builders Charles & David Stevenson, who were Consulting Engineers to the Japanese Lighthouse Department,[26] and was fabricated in England for export to Japan. The lighthouse was constructed by the Lighthouse Department, Yokohama, headed by R. Brunton.

Kobe Railway Pier, 1876[27]

At the end of Kobe station yard, a wrought iron pile pier was run out into the sea. This pier was the first railway pier in Japan. Kobe station was opened on 30 April 1874 when the railway service between Kobe and Osaka started. At that time some facilities in the station yard had not been completed and it was on 27 June 1876 that the railway pier was opened. The pier was 450 ft. long and 40 ft. in width; wide enough for four lines of track. The pile was wrought iron pipe with a diameter of 12.5 in. and the screw was made of cast iron with a diameter of 5 ft. After the pier was completed, imported materials for the construction of railway extension work was landed directly from ships to the railway trucks. This pier was removed in 1967 when the adjacent shipyard was expanded and a new repair dock was constructed by Kawasaki Heavy Industry Co[28].

Another pier was constructed as a private sector in November 1884 in Kobe. The Onohama Iron Pier was 149.8 m. long and 12.8 m. wide for three lines of track.

Rokugogawa Railway Bridge, Tokyo-Kanagawa, 1876

In the first railway construction between Shimbashi and Yokohama all the bridge piers were constructed by bent wood piling. The life of these structures was quite short and some of the piers suffered damage caused by rotting of the materials and scoring of the columns. All the bridges were rebuilt and this work was completed on 27 November 1876. Among the bridges the Rokugogawa Railway bridge over the river Rokugougawa was the longest. The new bridge was constructed just upstream of the old bridge and the piers were constructed by the well foundation method using bricks and iron[29].

The brick well was of 12 ft. outer diameter and the cast iron cylinder was 8 ft. outer diameter. One pier was composed of a pair of brick wells or cylinders and after they were placed concrete was poured into the inside. This work was based on the design of William Pole in England and Vicars Boyle in Japan, and the ironwork, 410 tons in total, was manufactured by Hamilton Windsor Ironworks Company Limited.

Nagaragawa Railway Bridge, Gifu, 1887[30]

The Nagaragawa Railway Bridge over the river Nagaragawa located between Giju and Hozumi on the line of Tokaido was opened on 21 January 1887. The bridge had a length of 1,493 ft. with five spans of 200 ft. in the centre and two spans of 100 ft. at either sides. The superstructures were standardized wrought iron truss girder bridges. The foundation of the abutments and piers were cast iron piles with screws.

This bridge was designed by the hired British engineer C.A.W. Pownall (1849 -?) and fabricated by Patentshaft Ltd, in England. For the foundation of the abutments two cast iron pipe piles with a diameter of 3 ft. 3 in. and 1 1/8 in. thick were used. For the pier of 100 ft. spans four cast

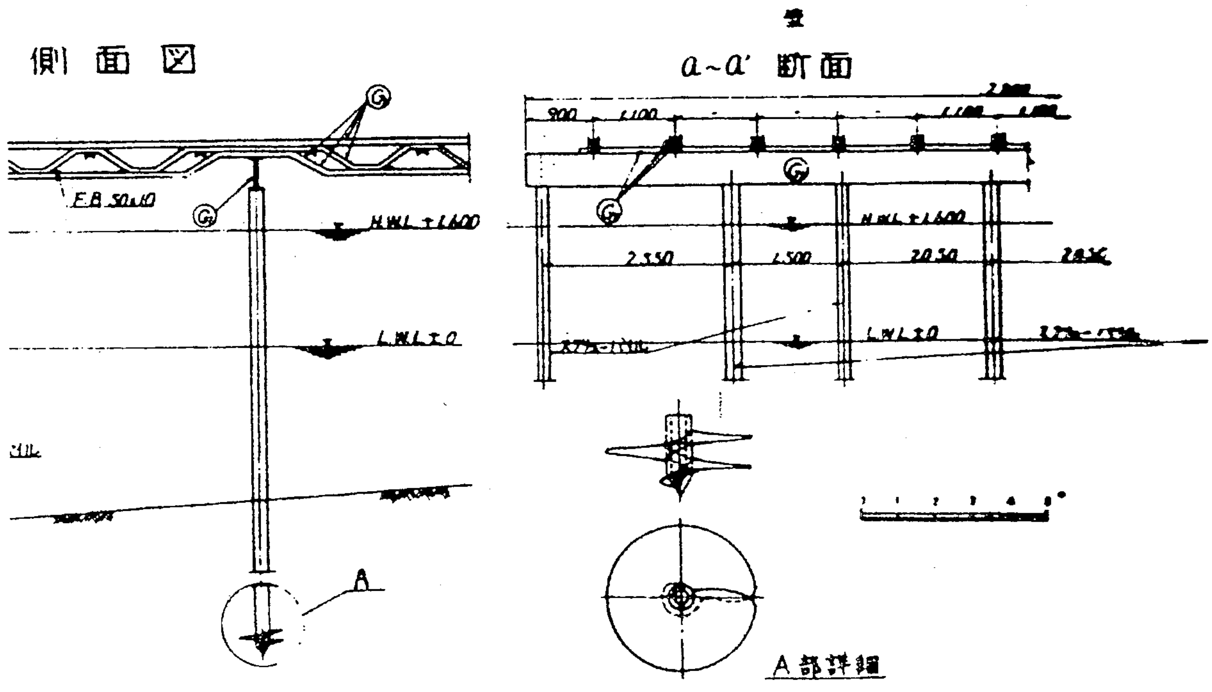

Fig. 18. Kobe Railway Pier, 1876, ref.27, plate 23.

Fig. 19. The Nagaragawa Railway Bridge, Damaged Piers of cast iron columns, Gifu, 1891, ref.30.

iron piles with a diameter of 2 ft. 6 in. and 1 in. thick were used and for the pier of 200 ft. span, five piles of the same section were used. The cast iron pipes were jointed by inside flanges to get the required length of columns. After they were screwed into the ground or riverbed concrete was poured into the inside of the piles. The columns were connected to each other by T-shaped portals and diagonal bracings of wrought iron rods. The piers of the bridge were destroyed by the earthquake on 28 October 1891[31]. The piers supporting the 200 ft. spans of central part of the bridge completely collapsed. The columns of the piers were broken by strong horizontal forces or ground movement and the ends of girders fall to the ground. Most of the collapsed columns were broken immediately above or below the flange joints near the ground level.

The substructure of this bridge was reconstructed by brick well methods and reopened for service one year after. The bent piling pier method was not selected for the construction of bridge substructures after this disaster.

Yokohama Great Pier, 1894[32, 33]

From the beginning of the Meiji era the export and import of goods by marine transportation was increasing rapidly and expansion of the port facilities of Yokohama harbor was envisaged. The construction of Yokohama port was the first substantial port construction work with iron piles in Japan. The first design of the Yokohama port was made by R.H Brunton in 1873 and later the Dutch engineer C.J. van Doorn (1837–1906) and the British Royal Army engineer, H. S. Palmer (1838–1893) submitted designs. Palmer's design was adopted for the actual construction work[34].

The main parts of the construction of the port were the breakwater and pier in which more than 500 iron piles with screws were used and took up 20 % of the total cost of the construction.

The pier was composed of three main sections. Those were a bridge section at the coast, the intermediate section and offshore section. The lengths of the sections were, respectively, 50 ft. of bridge section, 345 ft. of the intermediate section and 1,500 ft. of offshore section; the total length of the pier was 1,895 ft. The bridge was placed to retain boat transportation along the coast. The width of the pier was 39 ft. in the intermediate part and 62 ft. 6 in. in the offshore section where ships anchored

The abutment of the bridge on land was masonry and the pier on the other side was bent piling composed of 3 iron columns of diameter 24 in. and of lengths from 42 ft. 9 in. to 30 ft. 1 in. with screw in the tip. The three piles were connected by diagonal bracings. The girder was 50 ft. wrought iron Howe truss and cedar wood was used for the deck. The arrangement of piles in the intermediate section was 22 rows at intervals of 15 ft. and each row was composed of three piles. The lengths of piles were from 47 ft. 6 in. to 54 ft. In the offshore section each row was composed of five piles and there were 101 rows in total. The lengths of piles were from 54 ft. to 63 ft.

The piles in the intermediate section and offshore section were common and the design was standardized. Each pier was composed of four kinds of standardized parts. Part A was used for the highest part of the column, which had a connection with a crossbeam. The second was part B with flange joints at both ends. The lowest was part D with dowel joints at both ends, upper end for part C and lower end for the screw. Part C connected with part B by a flange joint and with part D by a dowel joint. The length of parts A, B and D was 9 ft. and the length of part C varied according to the depth at the site to adjust the total length of the column. The material of the pile was cast iron and both ends of each part were finished by machine processing. The screw with a diameter of 5 ft. was connected with part D by a dowel joint and fastened by a wedge pin. The columns were connected to each other by T shaped portals and rod bracings[35].

Prior to the pile foundation work the examination of the ground bearing capacity was carried out. It was started in August 1890 at Kanagawa town near the site where there were similar ground conditions. A temporary pier was constructed with iron piles supplied by Phoenix Cast Iron Company in England.

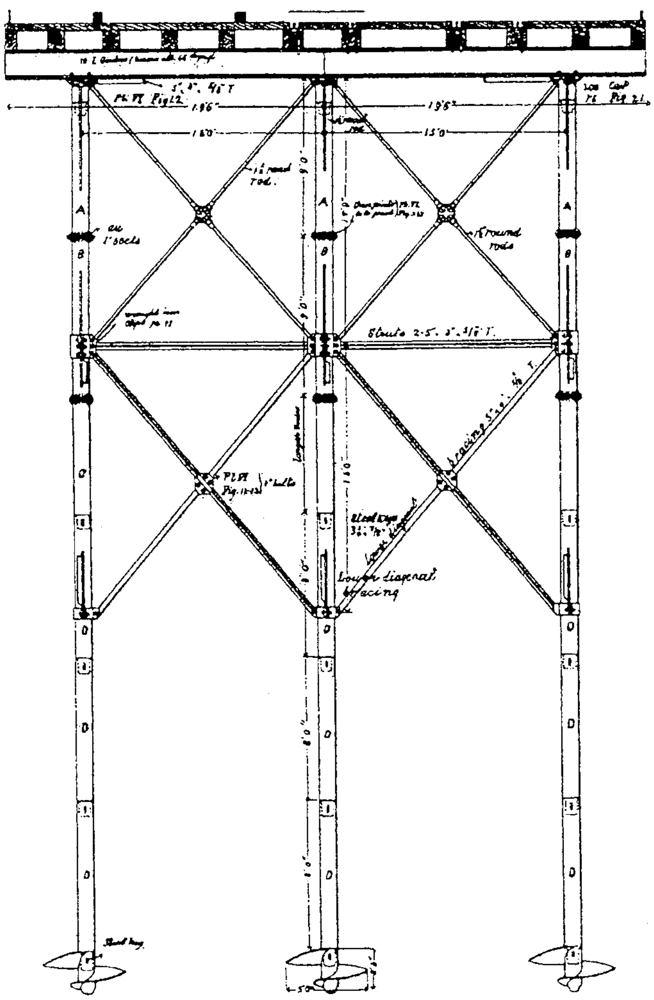

Fig. 20. Yokohama Great Pier, 1894, Iron Pier Cross Section, ref.34, plate II.

Irth (?) trading firm was awarded the contract of the supply of the iron pier and Barrow Field Iron works in Glasgow was in charge of the fabrication. The first members for the iron pier arrived in October 1892 and the construction work was started in 12 November 1892[36]. The pier was completed on 21 March 1894 including the railway truck work on the pier. After the completion of the work the pier was expanded from 1906 to 1917 as required by increased transportation. However the Kanto Great Earthquake destroyed the pier on 1 September 1923. According to the report on the earthquake disaster[37] the piles were broken with brittle fracture near the joints close to the seabed level, which was caused by the nature of cast iron. The concrete columns used in the expansion work had relatively small damage compared with iron piles.

Osaka Port Pier, 1903[38, 39]

Osaka Port Pier was constructed following the Yokohama Great Pier. In the construction work of the pier, steel piles were adopted for the first time in Japan.

The total length of the pier was 1,500 ft. and the width was 75 ft with wood deck on which were two track ways and one crane track. The pile was steel rolled round bar of a diameter of 6 in. and connected in three 20 ft. long parts. The average length screwed into the seabed was 24 ft. Both ends of the steel round bar were forged in hexagonal cross section, which were joined by coupling with the adjacent part or with the screw.

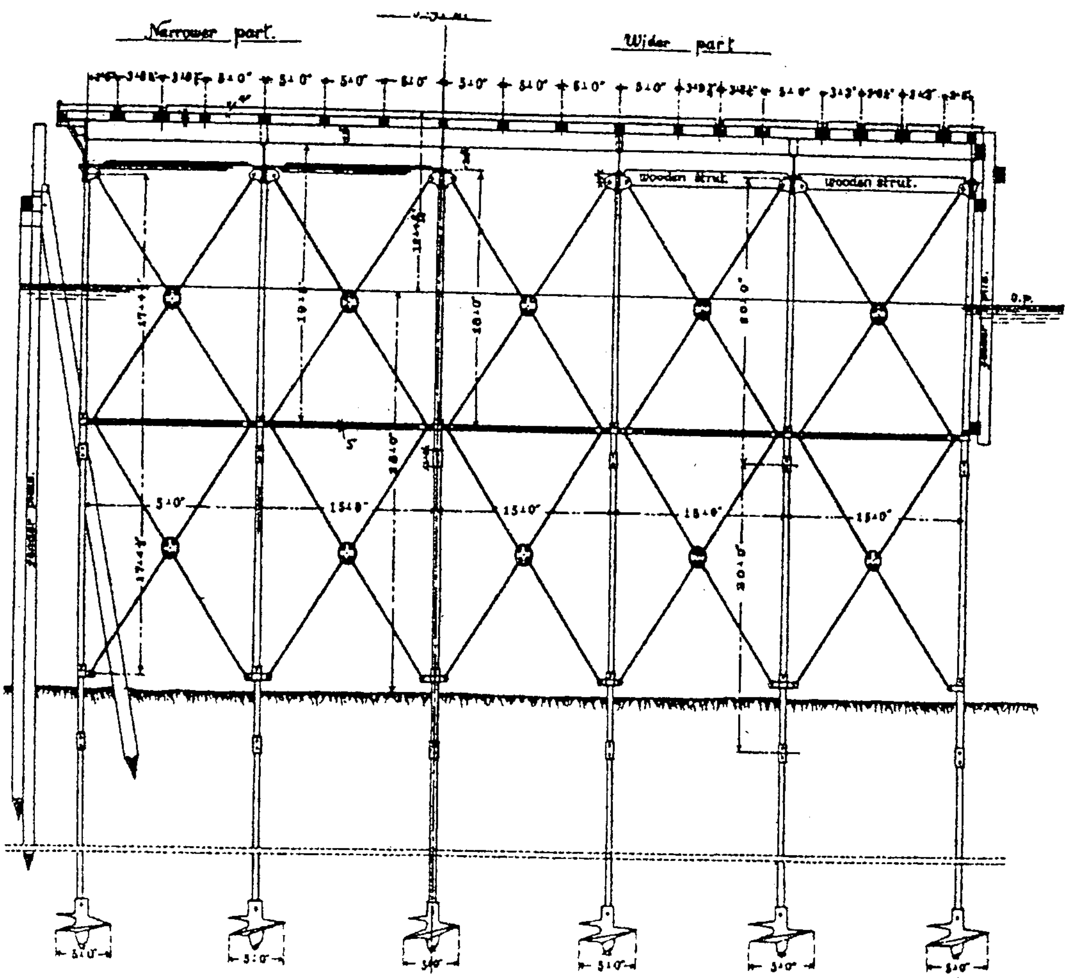

Fig. 21. Osaka Port Pier, 1903, ref.38, plate 2.

The pile was screwed into the seabed by turning the wheel attached to the top of the pile. Small boats were anchored around the pile and workers turned the turning wheel by walking around on the staging on the boats. The screwing of the piles was started in March 1902 and all of 678 piles were finished to place by January 1903. According to the record on the work, the maximum number of piles placed a month was 107 during summer time.

Prior to the pile placing work the bearing force of the pile was examined on site. 12 piles were used for testing and concrete block and rails were loaded on the piles. The test load starting from 26 tons was increased to 64 tons and the bearing force of the ground was estimated at 1.6 tons per square ft. at a depth of 23 ft. below the seabed.

4,134 tons of steel and 88 tons of bolts and nuts were manufactured by Johnson & Rafrin (?) in Pittsburgh, USA and imported through Hunter trading firm of Nagasaki.

From the end of nineteen-century to the beginning of twentieth-century the exporting country for iron products including pile to Japan moved from Britain to USA. The Japanese manufacturer, Locomotive Manufacturing Co. Ltd., manufactured 1,013 tons of cast iron coupling for the connection pieces of steel round bar. Pinewood for the deck of the pier was imported from USA.

CONCLUSION

Wood was the major material for structural piling through the Meiji era as it had been in the Edo era. Wood was easy to procure and process for structural material. Wood was produced in Japan and from the end of the Meiji era American pinewood lumber started to be imported for pile foundations to support heavier and bigger superstructures. Though wood was still the major material for structural piling, the method, the specification and the design for structural piling were changing during the Meiji era under the influence of European technology.

Structural piles of the railway related facilities in Shimbashi Station had never been experienced in the Edo era. The pile-cluster of the locomotive turntable was the first substantial structural pile foundation in Japan. The solid structural piled bent piers like the bridge substructures in Gunma had never constructed before in Japan

On the other hand, the introduction of iron piling that had never been used before marked apparent features of the modernization of pile foundation technology. The application of the iron pile was limited since the cost of imported iron pile was much greater than wood pile. However, application of iron for pile foundation was an important factor, which showed the progress of the development of structural pile foundation technology.

Iron pile has a strength of more than 10 times compared with that of wood and it is possible to manufacture in specific shapes and dimensions. For construction with iron piling, related industrial technologies were required such as processing by machines, handling equipment and design technology.

In the construction of the Osaka Port Pier, steel piling was used for the first time and cast iron parts were manufactured in Japan. The first domestic supply of the iron for piles was supported by the development of the iron industry as the background, in which Yawata Iron Works, the first national iron works started operation in 1901.

In western Japan iron piling had been applied to the foundations of railway bridge substructures since the beginning of the Meiji era. Wrought iron pipe piles with screw were applied to the four railway bridge substructures including the Mukogawa Railway Bridge in 1870's.

The application of iron piling to railway bridges was decided by local site conditions. As many ready-made materials as possible were used to avoid problems due to unknown conditions at site and unknown workmanship of unskilled local labors. At that time surveying techniques had not been established and it was not easy to procure equipment for surveying in Japan. It was quite natural that British engineers in charge of the construction of the railway bridges preferred to use as many ready-made materials as possible to shorten the construction period at the site where there were unknown and unfamiliar conditions for them. This situation was supposed to be similar in the construction work in other countries such as India at that time.

With the growth of the domestic supply of bricks, cement and other related materials and equipment for the construction of foundations, the well foundation method became a practical alternative to bent pile foundation. The bent pile pier method became one reserved for foundations needed when the construction was carried out in a short period. In case of the re-construction of the Rokugougawa Railway bridge foundation, the cast iron cylinder method was applied as well as the brick well method. The design consideration for the application of cast iron cylinder was the same as that in cast iron pile mentioned above. The re-construction became necessary after a short period because scoring of piles or rotting of wood materials had already damaged the existing bridge in service.

The earthquake was one of the important factors which affected the development of the foundation technology in Japan. The structures in the Edo period like traditional timber towers in temples had a structural nature to absorb the energy of earthquake by dovetail joints with slight flexibility due to the nature of cedar wood. Horizontal forces on wood structures due to earthquake were relatively small compared with the iron structures in the Meiji era because of the light dead load. Cast iron columns jointed by flanges were strong enough for vertical compression; however once they were affected by dynamic forces or horizontal forces due to earthquake they became quite insufficient structures. Especially the joins of the piles became fatal weak points to suffer brittle fracture. The typical example was the Nagaragawa Railway Bridge destroyed by the earthquake in 1891, from which a lot of lessons were learned. After this earthquake disaster, cast iron bent pile piers were seldom used and the brick well method or direct foundation became the general method for railway bridge substructures.

The brick well foundations were firstly adopted on a large scale for the substructure of the Arakawa Railway Bridge on which construction work started from April 1883. The diameter of the well was 12 ft. and the wall thickness was 2 ft. and it was placed to a depth of about 50 ft.[40].

By contrast, bent iron pile was developed as general method for offshore or marine construction works. Because of the regulations for construction on the sea, the alternative method was limited and bent pile using prefabricated piles was superior in meeting the regulations. The basic idea of this method is still efficient at present and early experience of the bent iron pile pier was followed by many other pier constructions, which still use the present steel pile methods.

Pile foundation technology was developed by the strong influence of western engineering, especially from Britain, for the execution of actual construction work. Many British engineers were involved in the construction works and the Japanese accumulated their experience and learned through the works. Materials and equipment for construction that had been imported from Europe were gradually superseded by domestic products. All these processes were magnificent examples of technology transfer for structural pile foundation as well as in other fields of engineering.

British engineers' contribution to the development of the pile foundation in Japan should be specially mentioned. Railway Departments or other organizations of Japanese government hired a lot of British engineers for the construction of railways, ports roads, bridges and many other civil works. They carried out the construction works with the support of industry and engineers in Britain.

It should be recognized that the technology transfer was transfer of the systems as well and they were accompanied unavoidably by numerous conflicts caused by the differences of customs, systems, ways of engineering judgment etc[41]. The process to overcome these conflicts was also in