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IMMERSED TUNNEL TECHNOLOGY: A BRIEF HISTORY OF ITS DEVELOPMENT

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Summary: The first tunnel made of segments, which were sunken and then merged under water, was built in 1896. It was a passage for conducting sewerage under Boston Harbor. The first tunnel for passenger traffic was constructed ten years later, also in the United States. Since then more than one hundred immersed tunnels of different size and length have been built worldwide. But the rise of "build-and-sink" technology is much older than that. Before the Boston Harbor tunnel was built the method has been theoretically elaborated in numerous patents and subsequent proposals. After that practically verified and perfected to the present form. Today's "build-and-sink" technology allows constructing floating immersed tunnels, buried in a sub aqueous trench or simply laid on the bottom. The case of immersed technology is shown as an example of a technique, which was invented ahead of its time.

Key words: immersed tunnel, sunken tunnel, subaquanous tunneling

1. INTRODUCTION

In 1854 Charles Dickens, in his weekly journal "Household Words" wrote: "...Of all bores, one of the strangest, if it ever come to anything, will be the purposed tunnel or tube to be laid along the bed of a river or sea, or at any rate to be immersed in the water of the river or sea – not like the Thames Tunnel".
We are not quite sure which of the proposed tubes he referred to. At the time there were several proposals of tunneling The Thames, and some of them suggested laying the tubes on the river bed. When Dickens wrote his words, the famous Thames Tunnel had been in use for some ten years, and underwater drilling was not an established practice yet. In fact boring in hard rock seemed to be so natural; the miners had been practicing it for centuries, but drilling in soft soil, like under The Thames, was something different. Marc Brunel, probably the most celebrated engineer of all times, found a solution; it was a protective shield that was pushed forward by hydraulic jacks. Brunel used to say that he was inspired by a worm making holes in the planks of wooden ships in the London docks. Those worms used to line their tunnels with an excretion hardening in

time and thus forming a kind of stiff shield. If the immersed tunnel technology was to be based on an example from nature, there should be a creature making such shield in pieces ashore, sinking them and then joining underwater.

2. IMMERSED TUNNELING NOW AND THEN

Today the immersed tunnels are composed of prefabricated sections or segments placed usually in trenches that have been dredged in a riverbed or sea bottom. In practice the sections are constructed at some distance from the tunnel location, most often in dry docks. Each segment is made watertight with temporary bulkheads on both ends and then floated into position over the trench, lowered into place, and joined together under water. The temporary bulkheads are removed and the trench is backfilled with earth to protect the tubes.

In common understanding the history of immersed tunneling began in 1910, with the construction of a two-track railroad tunnel across the Detroit River between the United States and Canada. But the rise of "build-and-sink" technology is much older than that. Assuming that the Euphrates tunnel of Queen Semiramis was not merely a legend, the first subaqueous tunnel was more immersed than bored. Babylonian engineers dug a new channel for a mighty river during a dry season. After that they made a trench across the exposed riverbed. When the brickwork walls and arch roof was ready, the watercourse was re-diverted back to its original channel. Another story which more resembles myth rather than fact, was a proposal made by Henry Motray, British engineer who suggested linking England and France by means of submerged iron tube in 1803. It was only a year after the first design of a bored tunnel was laid before Napoleon Bonaparte by Albert Mathieu, a French mining engineer. But at the time every such scheme was seen by British as a possible route for continental invading forces.

Back in more recent times, but still before the aforementioned railway link was laid, numerous proposals of immersed tunnels had been put forward, many patents for improvements in this technology had been granted and several attempts to put the idea into practice had been undertaken. In fact, the Detroit River tunnel was the first immersed tunnel to be completed for passenger and freight traffic, however it was not the first immersed underwater passage to be built. Some fifteen years earlier a much smaller iron tube was built under Boston Harbor. It was a siphon under Shirley Gut dividing the Deer Island from the main land. It was intended to move sewerage to the outlet located several hundred meters from the shoreline. The work on the siphon began in June 1893, and was completed late the next year.

The Shirley Gut was at the time an inlet about 60 meters wide carrying tidewater from Atlantic Ocean twice a day, and distributing it over the flats. Although many skeptics said that it was almost, if not quite, impossible to put the tube across Shirley Gut, the project went ahead. Two rows of piles were driven into the bottom forming a dam, in which a trench was dredged and leveled . The work was directed by Howard A. Carson, chief engineer of the metropolitan sewerage commission. The tube sections, four in total, were swung into the trench and securely joined by divers, who handled cement, brick and all necessary material under water (fig. 1). Some will say that the siphon was not a tunnel; because its diameter was 2.7 meters, but there is no doubt that the principles developed for this relatively short piece of steel tube were the same principles that are used today in immersed tunneling.

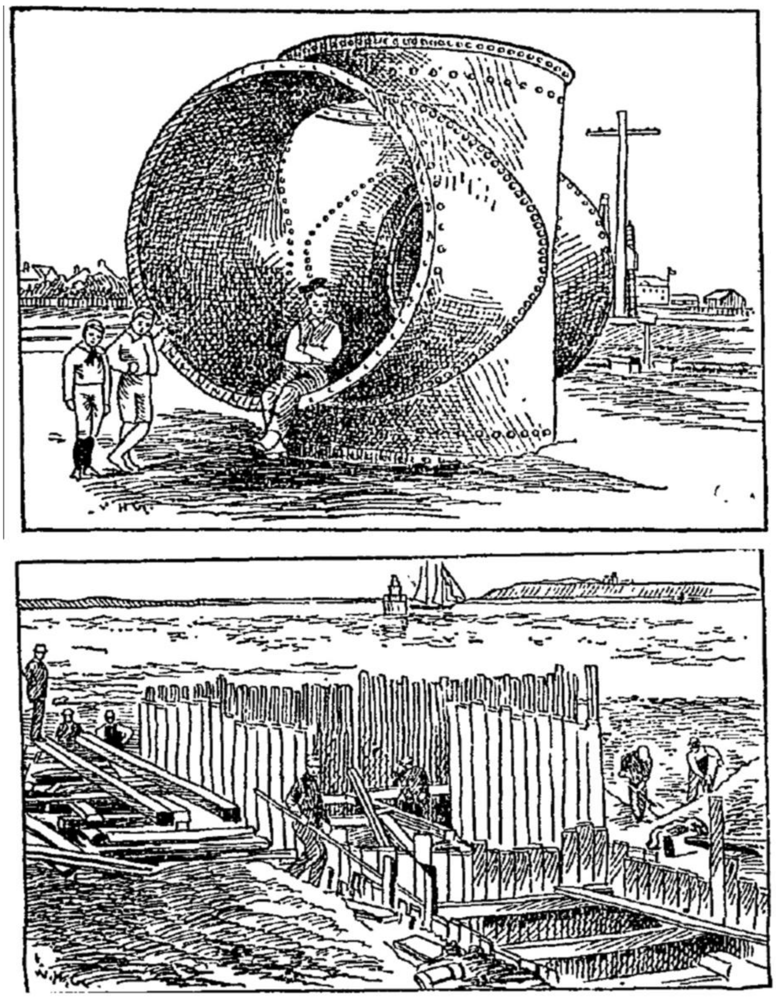

Fig. 1. The first immersed tube under Shirley Gut in Boston [Deer Island Dam 1893].

Later on, when the Deer Island Treatment Plant was erected on the island, the siphon conducted the sewage from the North Metropolitan Trunk Sewer. It was not until the late 1990s, that the siphon, the first immersed tunnel ever built, was replaced to meet the growing demands of a modern city.

3. THE THAMES RIVER

The first attempt to put that technology in use, not far from being successfully accomplished, was undertaken by two British engineers, Charles Wyatt and John Isaac Hawkins, in 1810. Two years earlier Richard Trevithick, already then a noted engineer, working for The Thames Archway Company, elaborated a plan of tunneling the river. Trevithick proposed to erect a cofferdam that would allow workers to build the tunnel partially as the cofferdam was moved across the river. Later he proposed the cast-iron segments be lowered into the cofferdam by steam crane, which he had invented few years before. If he had proposed that the segments could have been sunk into position in a trench, then it would be a true immersed tunnel . One way or another, the company rejected the plan, and it advertised a competition to find the best method of tunneling the river. By May 1810 the directors of the Thames Archway Company had received 54 proposals, which were scrutinized for technical practicability by Dr Hutton and William Jessop, the chief engineer for the Grand Junction Canal and the West India Docks. They decided that six plans were worthy of further consideration. As the final result they recommended a project of Charles Wyatt. He suggested excavating a trench across the river and sinking into it the brickwork cylinders forming the segments of a tunnel. The segments, each measuring 15 meters in length and 2.7 meters in diameter, were to be closed on both ends with temporary bulkheads. To prove that the proposed method is workable, Charles Wyatt assisted by John Isaac Hawkins carried out a test on The Thames in 1811. They sunk two segments 7.5 meters long and joined them underwater. Although the experiment was pronounced a success in technical terms, the method appeared to be too expensive for the company. In any case it was few years before Marc Brunel engaged himself in observing the life habits of shipworms.

In 1866, more than half a century after the Wyatt's trial, the construction of another immersed tunnel intended for regular use was started in London. It was designed for pneumatically operated trains working on a principle developed by Thomas Webster Rammell, who successfully demonstrated his pneumatic transit system on the Crystal Palace grounds in 1864. At first the company he had formed proposed a short link between Waterloo Railway Station and Whitehall near Great Scotland Yard. Later the line was to be extended south to Elephant and Castle, and north to the Tottenham Court Road and thus connecting the Metropolitan Underground Railway with Metropolitan Extension of Chatham and Dover Railway. The work begun in October 1866 under the supervision of the celebrated engineer Sir Charles Fox. Four enormous segments, 67.5 meters long each and weighing some 900 tons, were to be manufactured in Samuda's workshops in Poplar and then floated to the construction site (fig. 2). Each tube was almost four meters in diameter and made of sheets of boiler iron two centimeters thick and lined with brickwork. Only one section was nearly completed by the end of 1868; this can be seen on an engraving drawn from a contemporary photograph. The construction was eventually halted due to financial crisis rather than technical difficulties.

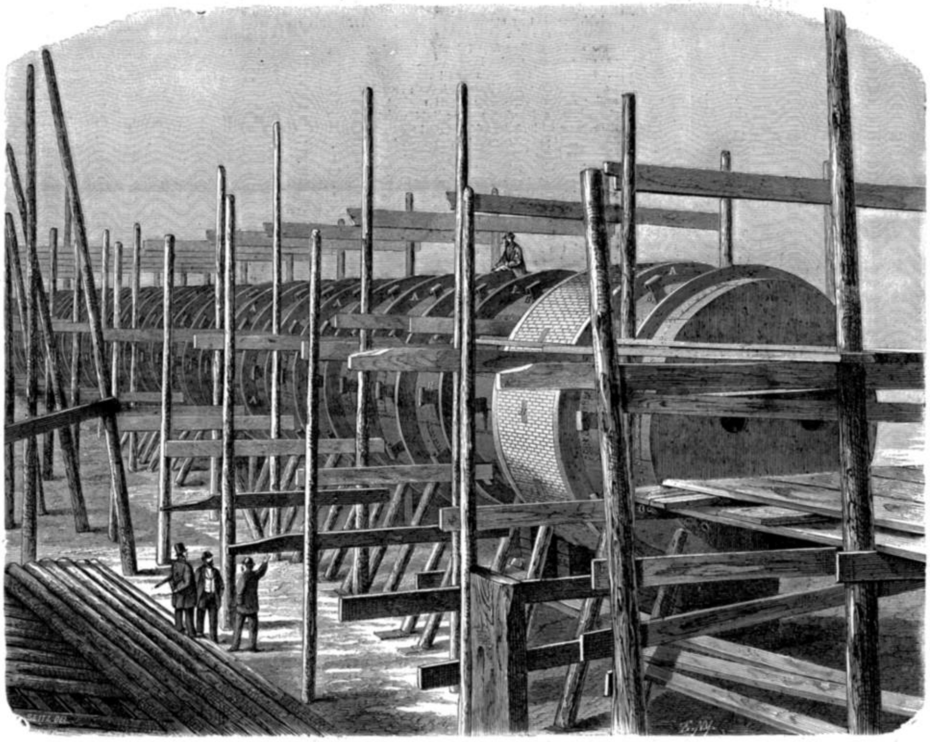

Fig. 2. The first section of the Whitehall and Waterloo Railway [The Pneumatic … 1867]

4. PRE-CHUNNEL

Some thirty years after Mottray the idea of connecting Great Britain and France was back again. Significantly, Thome de Gamond, a French engineer famous for his later engagement in promoting an idea of bored tunnel between two countries, was interested in immersed tunneling technology at first. In 1843 another project of that kind was submitted by Charles Franchot and Cyprien Tessie Du Motay . Shortly after that another engineer appeared with a similar design. It was John de la Haye, who proposed to run an atmospheric train through his proposed submerged tube. He estimated the cost of such tunnel at 2 million pounds. It was not the first or the last time that an immersed tunnel, being a scarcely sketched theory was proposed for air-propelled train; another imaginary idea. In some respects both seemed to fit each other perfectly. The piston-like carriages would have fitted into the circle or oval shaped tubes. According to the pneumatic principle they were pushed by air pressure and thus were able to ascend step gradients, virtually unattainable for steam locomotives. That was an important feature when going up through a tube, which usually renders the slopes of a river bank. Since the pneumatic trains were powered remotely from pumping stations, they produced no fumes or steam themselves; an essential advantage when traveling through long tunnels, like those under rivers or seas.

Such ambitious plans were submitted by numerous engineers, Jules Babut du Mares; an extraordinary Belgian inventor among others. He suggested laying the tube in a straight line across the channel in its narrowest point, between Dover and Cape Gris-Nez.

As to the Channel Tunnel, it is worth mentioning the doubts existing in regard to the uniformity of the chalk deposit on its route as proposed by Thomas Gammond in 1870s. Those doubts led another engineer, P.J. Bishop to show up with a rival plan: a sunken tunnel laid on the row of piles driven into the seabed. His proposal was endorsed by P.F. Nursey, an eminent British engineer, who believed the tube would have been "perfectly practicable, much more so than the tunnel". Bishop's tube was elliptical in form, some 4.5 meters in the major and 3.6 meters in the minor axis inside – the space sufficient for a single rail line, therefore two parallel tubes were to be laid to assure communication in both directions. The segments 7.5 meters long and made of 16 millimeters boiler-iron and lined with 30 centimeters brickwork were to be floated to a pontoon anchored above the spot to which they were to be lowered. To facilitate that Bishop envisaged an immense pontoon 120 by 30 meters having an opening in the center 30 by 7.5 meters. The inventor proposed using the movable wrought-iron bulkheads on both ends of each section. The cost of double line tunnel was estimated at nearly 22 million pounds.

5. THE EAST RIVER CHALLENGE

The majority of American plans for immersed tunnels were for the East River. The need of establishing a permanent road connection between New York City and neighboring counties over the East River emerged as early as the beginning of the nineteenth century. Numerous plans of tunnels and bridges have been put forward since Thomas Pope suggested his "Flying Bridge" between New York and Brooklyn in 1811. Contemporary engineers had to overcome a great difficulty: to construct a bridge over the wide river while at the same time allowing the tallest ocean ships to pass under it. A bridge with a roadbed some 40 meters over the level of high water required a long approach on each side of the river. That would be a difficult and expensive task especially in densely built up Lower Manhattan. A tunnel, whether bored or immersed, would cause no obstruction for navigation and would require less demolition. Of course if it was accomplishable at all.

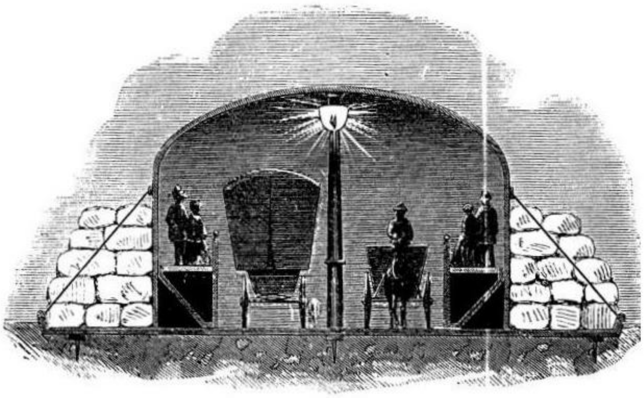

Fig. 3: Proposal of Polish engineer, Joseph de Sendzimir [Lotysz 2003].

Fig. 4: Holcomb's designs of 1857 [Holcomb's … 1857].

Although Brunel proved, that boring underwater is possible, the long and persistent struggle he had under The Thames gained for tunneling as many opponents as supporters. Still in 1870 an editor of Brooklyn Eagle wrote: "...the history of tunnels is not very encouraging to those who contemplate such enterprise. The Thames tunnel has been a success; but for one tunnel London has many bridges.

Human creatures are not inclined to borrow underground and travel in a chilly gas-lit tube, when they can as easily pass over a safe bridge, with a grand, beautiful landscape, or the animated scene of a city about them, the blue sky, fleecy clouds, genial sunshine overhead and the sparkling, dancing water beneath...". Such a walk under the fleecy clouds overhead was realized more than ten years later, when Brooklyn Bridge was completed.

Since those skeptical voices referred to the bored tunnels, the immersed ones would possibly be met with a better reception. Of course if they appeared to be as cheap and easy to build as advertised. One of those "wonderful solutions" was proposed by Joseph de Sendzimir, an inventor of Polish origin living in Amityville, Long Island. In April of 1857 Scientific American published a detailed description of Sendzimir's project (fig. 3). The inventor proposed to lay his immersed tunnel in the deepest part of the East River, connecting Fulton Street in Lower Manhattan with the street of the same name in Brooklyn. The segments were to be manufactured from sheets of boiler iron on barges anchored close to the construction site. Each segment consisted of a flat bottom and arched roofing firmly bolted together. Two platforms outside were intended for ballast in addition to the tunnel being fastened to the river's bed using iron bolting. Each segment had to be made watertight at both ends and then floated to its destination, and then by adding the ballast on the platforms outside, each segment had to be sunk and firmly connected to the part of the tunnel already made. The bulkheads from each segment had to be removed to make a free passage, but not before completing the entire tunnel, therefore no pumping out of water was necessary. Sendzimir's proposal included a road for horse carriages and two sidewalks for pedestrians in the tunnel, everything being lit by artificial light. The tunnel laid on the river's bed would have the same acclivity as the bottom and the slopes close to the river banks. On the northern side it was not a problem, but the slope on the southern side was too sharp. Joseph de Sendzimir proposed to curve the tunnel to make the way easier. In order to prevent any obstruction at all to navigation on the river, Sendzimir's tunnel could also be laid in a trench. Sendzimir estimated the cost of the tunnel at 200 dollars per running foot, which added up to approximately $320,000 for the entire tunnel. It was stated that the cost was one- twelfth of a bridge in the same location. As we know the total cost of the Brooklyn Bridge was about 15 million dollars upon its completion in 1883.

Shortly after Sendzimir's proposal, another inventive genius showed up with similar project. H.P. Holcomb was an engineer from Winchester, Georgia (fig. 4). His tunnel, unlike Sendzimir's was designed as cylindrical tube of 6 meters diameter. About one-third of this was to be occupied with stone serving as ballast and at the same time forming two lane roadway and two paths for pedestrians.

The pneumatic railways were proposed in connection with submerged tunnels also in the United States. In New York City, the Union Pneumatic Railway

Company was formed in 1866 apparently on the assumption that Rammell's enterprise in London would be a success. The company planned a network of pneumatic railways in New York, but also connecting Manhattan with neighboring Brooklyn and Jersey City. Those underwater links were to be built as the submerged iron tubes. Also the company envisaged laying the pneumatic tubes along the shores of the island instead of boring under the streets and avenues, closely packed with pipes and sewers beneath, and always overcrowded above.

Shortly after that a kind of underwater pneumatically operated shuttle was contemplated for conveying three hundred passengers per trip across East River from Manhattan to Brooklyn in three just minutes. A.S. Beers, a Brooklyn based engineer, designed a tube 3.6 meters in diameter and made of sheets of iron 2.5 centimeters thick. The next year another similar connection between two cities was proposed, but this time it was designed to carry one thousand passengers per trip every five minutes. That would have exceeded, it was estimated, the contemporary needs more than twice. In 1870 another underwater pneumatic ferry was to be built under Ohio River between Louisville and New Albany. Finally, a submerged tube was suggested for linking San Francisco and Oakland in late 1880s. None of those ambitious plans were ever realized. Most of them were never started. In late 1880s Americans still had no underwater tunnels, except a railway passage under the Chicago River! At the time two other great enterprises, a bored tunnel under St. Clair in Detroit and under Hudson River in New York, were abandoned mainly because of technical difficulties. In 1887 an editor of Manufacturer and Builder referring to the failures in New York and Detroit, complained: "...For some reasons not apparent, they appear to be more successful in the construction of submarine tunnels abroad than in America... their history is not of such character as to make us proud of them as evidence of native engineering skill".

6. NEW MATERIALS - NEW CHANCES

From the early 19th century, when the idea of submerged tunneling technology was conceived for the first time, the engineers have been envisaging the use of iron for the construction of tunnel segments. Usually they were to be surrounded with brickwork or ballasted by stone, earth or moored to the bottom. Some inventors, like Joseph Miller of Jersey City, planned to cast the segments entirely from iron. From around 1870 concrete was proposed, initially as a material for lining only and ballasting the tubes. Later it developed into steel shell concrete tunnels, the type of immersed tunnel most commonly used to this day. In the late 19th century however a concrete tunnel was still just an imaginary concept which was constantly improved by following inventors. Charles Spear of New York was one of the earliest to somewhat naively believe in the water tight prosperities of concrete. He designed a tunnel with a wooden frame-work covered in concrete. It seems like a step back when comparing to the project of Thomas F. Rowland, of neighboring Brooklyn. His iron tube was to be encompassed with prefabricated concrete blocks. The latter inventor patented the method of fastening the blocks to the iron cylinder. Another patent for a double tunnel made of concrete was granted to Charles H. Buckelew of Plainfield, New Jersey in 1899. The main feature of his improvement was a combination of a series of adjustable piers with a bearing plate outside each section. Such a device was very helpful to properly adjust the segments.

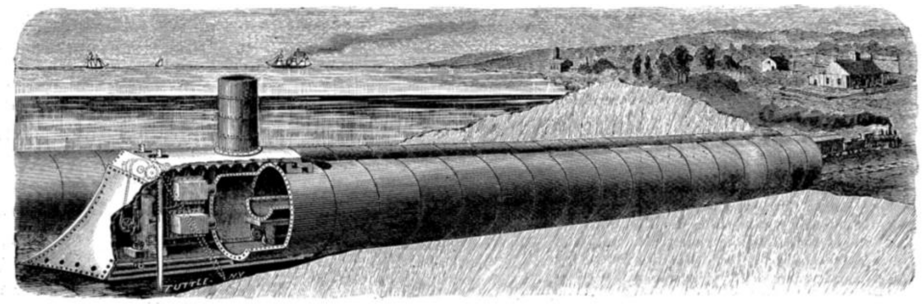

Fig. 5: Hall's machine for crossing the waterways [The Hall … 1886].

Although during the 19th century no single immersed tunnel was built, the inventors and engineers were tirelessly looking to perfect the way the segments could be laid and joined underwater. For instance John Trautwine of Philadelphia, proposed sinking a segment along with a floating raft or barge, on which the segment was assembled. But one of the most significant improvements in the field was made by Hayden H. Hall of New Hamburg in the state of New York (fig. 5). Apparently he followed a rule saying that the "Americanization" often means "mechanization". His new method of laying submarine tunnels and tubes consisted of movable caisson with a bow and attachment for a chain at one end. The caisson was to be hauled by a stationary engine situated on one shore, and supplied with materials for constructing the tunnel from the second one. The ready-made segments were transported through a previously finished part of a tunnel to the caisson, in which they were mounted into place. Although the proposed mode of construction differed from that employed in ordinary immersed tunnels, it would have produced a similar tube laying on the bottom. The inventor founded the Hall Submarine Tunnel and Tube Co., which was contracted to build a railway tunnel from Prince Edward's Island to the main land. The enterprise finally failed, but attracted great attention from the world of engineering at the time.

Another improvement in immersing tunneling technology that was invented too early to be practically implemented was one, which produced so called submerged floating tunnel. For immersed tunnel technology in general the depth of a waterway is not too important. However if it is too deep, the segments can be anchored and kept at some distance from the bottom; a kind of floating tunnel. A similar connection across the Bosporus in Istanbul was designed by Haddam, an engineer working for Turkish government in 1875. The proposal was to submerge the tunnel some 10 meters under the surface of the water, and moor it to the bottom by holding-chains . A very similar buoyant submarine tunnel was patented by Henry Anderson of San Francisco in 1872, and then by Henry Moeser almost twenty years later.

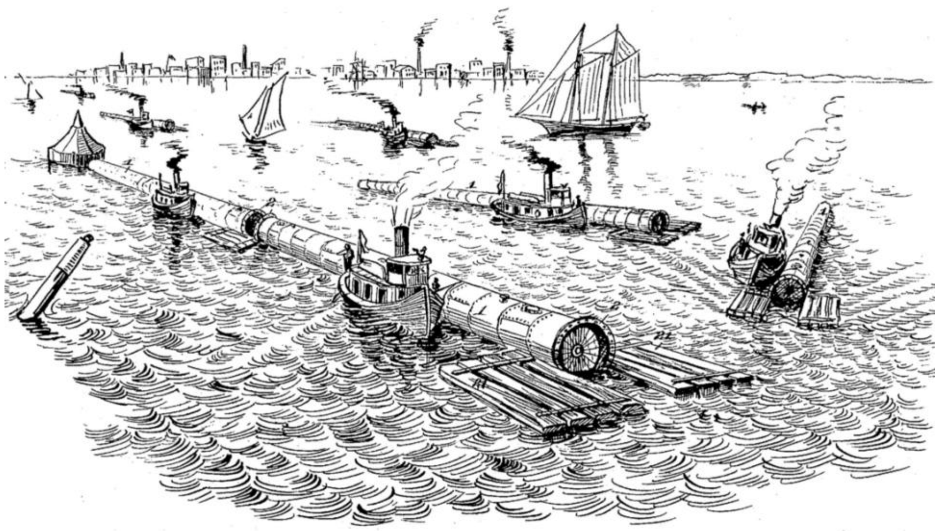

Fig. 6: Powell's view of floating tubes [Powell 1992].

7. CONCLUSIONS

In 1892 Robert Powell, a Cleveland based engineer, sketched a scene of a river or sea with plenty of steam tugs and floating tunnel sections (fig. 6). Since 1910 when the Detroit River tunnel was completed and the immersed tunneling became a part of engineer's routine, such a scene should not be surprising. But sometimes it is. In early 1960s a young engineer, Walter Grantz, took position in a major tunneling company. When he learned about company's plan of a new tunnel he laughed: "They plan to hook up sections of tunnel underwater? They must be crazy! This I have to see". He did so on see it, in fact. During his career he immersed more than ten tunnels. After another forty years he acclaimed "...underwater tunneling is less like digging a mine and more like docking the space shuttle".

From today's point of view some technologies appear to be invented too early to be successfully implemented. But what does this mean? There were no proper materials or financial resources available to put them into effect? Or simply no one needed the technology at the time? It is often the case that a new invention is promoted as something that is going to replace the prevailing system. But that is not the case. Immersed tunnels are a cheaper and better solution, but only in certain circumstances. Usually they are used in connection with bridges (like in Oresund link between Denmark and Sweden built several years ago) or with bored tunnels (like in the projected railway tunnel under Bosporus).

Today some of the designers and contractors promote the immersed tunneling as a new idea. We all like to have something new. But perhaps when it comes to the field of engineering we would prefer to stick to the solutions with better established practice. Although today the technology is very sophisticated, the principle of immersing tunnels has not changed much since it was proposed for the first time two centuries ago.

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TUNELE ZATAPIANE: KRÓTKA HISTORIA ROZWOJU TECHNOLOGII

S t r e s z c z e n i e

Pierwszy tunel wykonany w technologii zatapianych segmentów został wykonany w 1896 roku. Był to krótki odcinek kanału ściekowego w Bostonie. 10 lat później zbudowano tą metodą pierwszy tunel kolejowy, również w Stanach Zjednoczonych. Od tamtej pory na całym świecie powstało przeszło 100 konstrukcji tego typu. Początki technologii budowy tuneli poprzez zatapiania na dnie zbiornika wodnego gotowych segmentów sięgają początków XIX wieku. Teoretyczne rozważania, dziesiątki projektów i kilka nieudanych prób sprawiły, że zanim technologia ta została wdrożona, była szczegółowo opracowana a jej podstawowe założenia opatentowane. Dzieje rozwoju technologii tunelu zatapialnego to doskonały przykład koncepcji wyprzedzającej swoje czasy.