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Construction Methods used on the East Boston Traffic Tunnel under Boston Harbor.

By

Jack R. Kalman Course 1

January 31, 1933

Professor A. L. Merrill
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Mass.

Dear Sir:

In partial fulfillment of the requirements for the degree of Bachelor of Science, this thesis on "Construction Methods Used on the East Boston Traffic Tunnel under Boston Harbor" is submitted.

Respectfully submitted,

Jack Kalman

Jack Kalman, I_3

I wish to take this opportunity to express my appreciation of the courtesy extended to me by Mr. Buck of the Silas Mason Co. in allowing me to use any information at his disposal. I also wish to thank the personnel of the City of Boston Transit Commission for some of the photographs used in this thesis.

Permit me to acknowledge my appreciation of the cooperation of Professor C. B. Breed under whose supervision this thesis was written.

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INTRODUCTION

One of the most serious traffic problems that the City of Boston has been called upon to face has been that of providing a short and adequate means of traffic communication between Boston and East Boston. Previous to the consideration of a tunnel, there had been but three connections. One was an antiquated ferry system carrying both passengers and vehicles. Another was a circuitous route through Charlestown and Chelsea and passing over several drawbridges--objectionable because of the frequent delays caused by the opening of these drawbridges to permit the passage of harbor traffic; and thirdly, a tunnel for electric trains.

The inadequacy of these facilities is readily recognized with a brief inspection of the growth of East Boston and its increasing relationship with the City Proper. The air traffic of Boston is closely linked with East Boston since the airport serving the city is located there. Further, there are many large piers and docks there, which are the destination and origin of much of the shipping traffic--both freight and passenger. These two reasons alone, demonstrate clearly the necessity for a more direct highway route between East Boston and the City Proper.

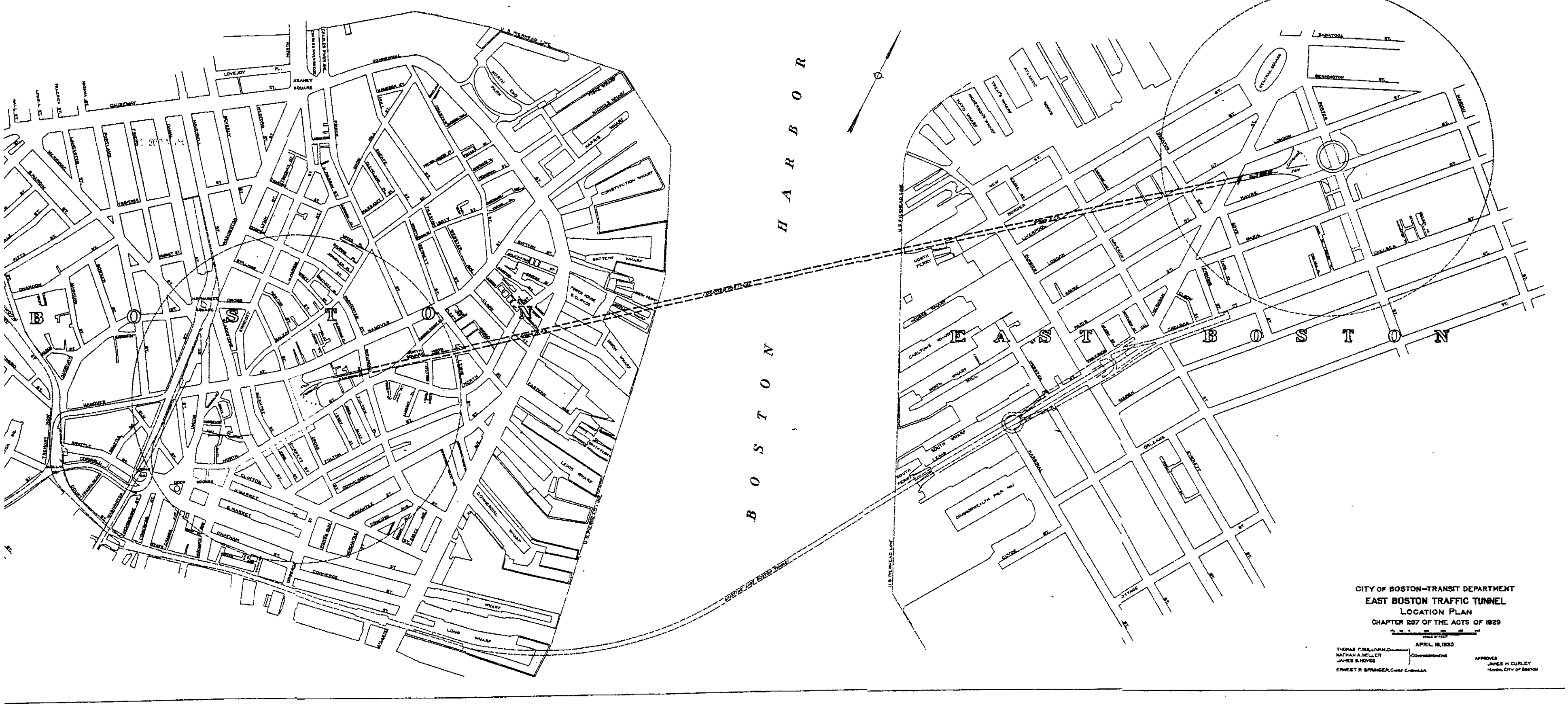
Two plans were offered for the solution of this problem. One was a suspension bridge from the main downtown district; the other a vehicular tunnel under the harbor. The first necessitated long approach sections to obtain the clearance for shipping as required by the War Department. This would have been impractical, since it would have required the condemnation of considerable taxable property at a great cost. A tunnel, on the other hand, would require much less land for the approaches; and, since it would pass at a considerable depth beneath structures, it would necessitate the condemnation of easements only, with the obvious resultant savings.

In 1929 the Massachusetts Legislature enacted a bill providing for the construction of a vehicular tunnel between East Boston and Boston Proper (Chapter 297, Acts of 1929.)

Thereupon, the City of Boston Transit Commission was assigned the projects--The plans and specifications for which were drawn up under the able direction of the Commission's chairman, Colonel Thomas F. Sullivan, and Chief Engineer, Ernest R. Springer. The contract for the shield driven portion of the work, the major part of which was under the harbor, was awarded to the Silas Masen Company of New York. Their use of devices and methods never before utilized in tunnel engineering, enabled them to complete their work in many months less than the allotted time.

In this thesis I shall endeavor to discuss the construction of this tunnel, pointing out the special methods employed by the contractors whereby they were able to make record time, also in some instances I shall criticise the design and methods employed and I shall draw a comparison between ~~them~~ and those used elsewhere, particularly the Detroit Windsor Tunnel where conditions were in many respects similar.

PLATE I


BOSTON HARBOR
EAST BOSTON
BOSTON
CITY OF BOSTON—TRANSIT DEPARTMENT
EAST BOSTON TRAFFIC TUNNEL
LOCATION PLAN
CHAPTER 297 OF THE ACTS OF 1929
APRIL 18, 1930
THOMAS F. SULLIVAN, Chairman
NATHAN A. HELLER
JAMES B. NOYES
Commissioners
ERNEST R. SPRINGER, Chief Engineer
APPROVED
JAMES M. CURLEY
Mayor, City of Boston

DESCRIPTION OF THE PROJECT

There are two open cut approach sections, one on the Boston side, and one on the East Boston side-- These are connected by a shield-driven tunnel 4850 ft. in length, of which about 1500 ft. is under the harbor. From portal to portal the tunnel measures 5650 ft. (See plan Fig. 1.)

From the construction shaft at Decatur St., East Boston (Fig. 2) to the harbor the grade is down 3.5%. From that point it changes on a vertical curve to a down grade of 0.5% (this being the minimum grade for proper drainage) to a point near the center where a pump well is located. The grade rises on a slope of 0.5% to the Boston pier-head line where it again changes on a vertical curve to a grade of 4.2%--This slope continues to the approach section where it changed to a 4.4% grade to the Boston opening.

The construction of the main section of the tunnel (shield-driven portion explained later) was awarded to the Silas Mason Company, of New York. This section is 4850 ft. in length, 1500 ft. of which is under the harbor, it included a construction shaft, and two ventilation shafts, one on the East Boston side and one on the Boston side.

The tunnel is composed of a steel lining, built up of steel rings, designed to support all loads that the tunnel is subjected too, and a concrete lining inside of the steel lining designed independently of the steel lining. The design was governed by the roadway requirements to obtain two-way traffic. A necessary roadway of 21 ft. 6 in. between curbs which resulted in a tunnel of the following dimensions:-

A height of 13 ft. 6 in. from the roadway to the ceiling and a total diameter of 31 ft. The space below the roadway and above the ceiling slabs formed ducts adapted for the purpose of ventilation--The space below to supply fresh air and that above to draw out exhaust air. At each ventilation shaft, a building with mechanical equipment was to be erected to draw out the foul air and force in the fresh air. The roadway is of granite block pavement, and the sidewalls finished in tile.

The tunnel is provided with an indirect illuminating system whereby the lights are set into pockets on each side of the tunnel in an angle formed at the ceiling, and side walls. These lights are spaced at 15 ft. intervals. There are traffic lights for the control of the movement of vehicles.

Tunnelling in water-bearing soil is usually done with the help of compressed air; the tunnel being walled off near its mouth and air being pumped under pressure into the enclosed portion to neutralize the inward pressure of the water and thereby preventing an inrush of water. Water exists in the pores of the earth under a pressure head. The water because of its cohesive properties forms a minute diaphram within the pores of the earth, and this diaphram will break easily under the pressure caused by the water head. The balancing power of the compressed air equalizes the water pressure, prying on the delicate membrane and holds it in equalibrium.

Often, the further protection of a shield * is used in conjunction with the compressed air, especially in the construction of tunnels under water. In the

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* Shield. Shield tunnelling is not a recent development. The inventor of the shield, Sir Marc Isamband Brunel, a Frenchman, obtained a patent in 1818, in which he describes his idea. It consisted essentially of an iron cylinder equipped at its front edge with an auger-like cutter, which, when revolved, was supposed to screw into the soil ahead and thus advance the cylinderical shield. The portion excavated by the shield was to be lined with sheet iron plating and strengthened by masonary.

Five years after the granting of the above patent, a company was formed to undertake the tunnelling of the Thames River, a task that had been attempted several times previously, without success. Brunel, as chief engineer, designed a rectangular shield as he believed that the stresses would be minimized if the strata penetrated were to be cut parallel to its horizontal bed. The shield collapsed due to its lightness, and a second shield much stronger than the first, was built, by means of which the work was completed with phenomenal success.

Since Brunel's accomplishment, shields have been used extensively in subaqueous tunnelling. The present-day shield is a highly developed mechanism. It is automatically propelled, erects the lining behind it, has hydraulic rams to support the heading during excavation, and in many cases has sliding steel bulkheads at the heading to support loose material.

building of the East Boston Tunnel a shield was used and compressed air used when necessary.

The shield used to bore under Boston Harbor, from East Boston to Boston, for the vehicular tunnel was a large monster. It was 31 ft. 7 in. in diameter and 18 ft. 9$\frac{3}{4}$ in. long, weighing over 400 tons. The tail, (that section that overlaps the steel lining put in place) was of steel plates totalling 2$\frac{5}{4}$ in. thick. The heading, or working section of the shield at the mouth of the tunnel, consisted of horizontal and vertical bracing of heavy built-up steel members. This bracing divided the working section of the shield into convenient working chambers. The floor of these chambers consisted of heavy steel plates that were rivetted onto table or face jacks. These jacks would be moved foward, bringing the floor or platform with it, and at the same time these jacks acted as rams supporting the face of the excavation. There were ten of these moving platforms and ram jacks (see Fig. 3) and when

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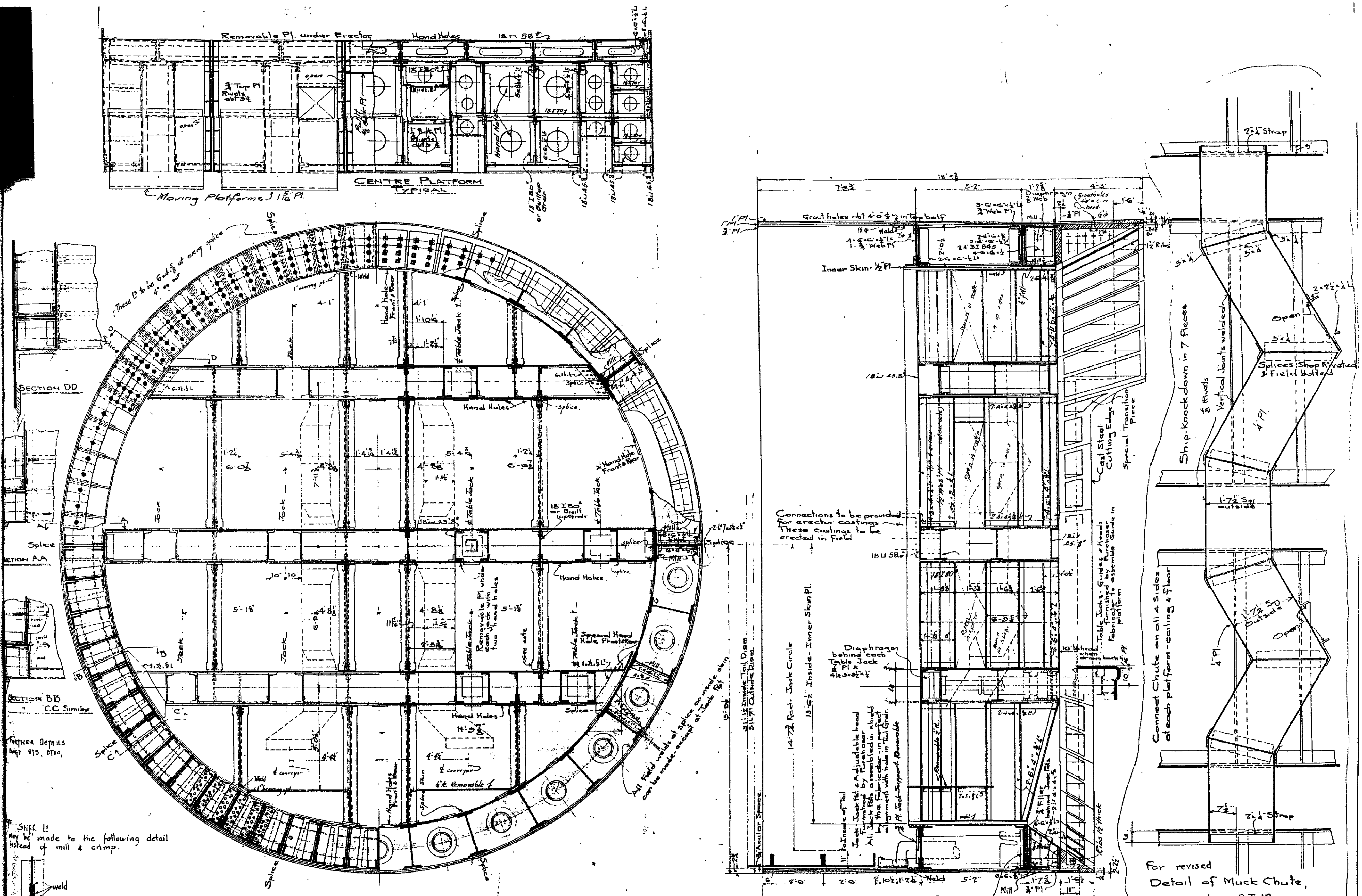
With slight exceptions, the designs of shields are based on experience and in accordance with the geology of the ground, the shell must be sufficiently thick to support the earth pressure without deforming at its tail, where there is no internal support. The cutting edge must be strong enough to withstand the pressure of the jacks and any head-on contact with some unexpected resistance.



Provide all necessary Hand Holes, both for erection and access to Hydraulic connections.
All hand holes covered with 3/8 Pl. & 4-3/8" ϕ Tap Screws. —— No Painting Reqd.
Csk and Chip all Rivets on outside of skin and inside of Tail. —— All Skin Rivets & Bolts 1 1/8" diam.
All bolts & Rivets for Cutting Edge 1 1/8" ϕ. Hex bolts. —— All Rivets in Top Platform Pls csk and chip.
Generally all other bolts & Rivets 7/8" ϕ. —— Where Possible field conns to be riveted.
All holes, shop & field to be sub punched and reamed —— Furnish field bolts & Rivets +10%
One Table Jack & One 10" Jack will be delivered to Fabricator for use as a pattern.
A Tolerance of 1/8" will be allowed for Tail diameter — and 1/2" for diameter at Cutting Edge
Entire shield to be erected in shop — After inspection knock down for shipment and matchmark.

New Jack Pots are furnished without holes in back for connection to ring girder. Old Pots have holes, but these must be plugged and new holes drilled & tapped for 1 1/4" Tap bolts 4 to each Jack Pot.

Silas Mason Company Inc
Boston Traffic Tunnel
Section A

Rev. June 8 - 31.
Rev. April 8 - 31.
Rev. Mar. 25 - 31.
Mar 12 - 1931

Drawing BT 1

they had been pushed forward to their maximum distance, slightly over $2\frac{1}{2}$ ft., the shield was ready to be advanced--Ordinarily wood planking is used in conjunction with the rams to support the face, but was unnecessary in this project because of the solidness of the clay. (See plan Fig. 4).

The motive force used to drive the shield ahead consisted of 30 circumferential Jacks driven by a hydraulic pressure of 6000 lbs. per sq. in. These jacks were connected to shoes (Fig.5) which were forced against the erected rings to counteract the thrust of the jacks, moving the shield forward. These rings, the lining of the tunnel of welded steel construction; were built up behind the shield (Fig. 6) and were designed to support all superimposed loads including the pressure exerted by the shield jacks. (Originally, temporary rings had been lowered into the construction shaft by a crane and built up, behind the shield, ready for the first forward thrust of the jacks). Each ring * weighed 12,750 lbs. and was composed of eleven segments, ten of which were approximately 6 ft. long. The eleventh consisted of a ring section

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* . There were two types of tools used to tighten the ring bolts, which were set into place by hand. One type was a pneumatic tool, which consisted essentially of a turbine-driven wrench that fitted the nut. The pressure of the air was 90 lbs. sq. in. (See appendix). This tool rapidly tightened the bolts until it was snug to the iron. This tool was supplemented by a hand ratched wrench that exerted a pressure greater than $\frac{1}{2}$ ton, due to its leverage. Both tools required a second man who held the head of the bolt to prevent slippage.

6 ft. and a key section 2 ft. (Fig. 5). The key was tapered just the reverse of a keystone of an arch, so that it could be wedged into place from the inside of the tunnel. These sections were of rolled steel and welded, the outer plate 3/8 in. thick, $2\frac{1}{2}$ ft. wide, inner angles 6 in. by 8 in. by $\frac{3}{4}$ in., 45 lbs. steel rails welded from angle to angle spaced every two feet, to transmit the stress from the shield jacks. There were 475 bolts required for each ring. There was a second type ring referred to as a taper. It was used at grade points and to align the shield. The key of this ring was 2 ft. 6 in. wide from which the segments tapered to the opposite segment which was 2 ft. 4 in. wide. This ring facilitated the bending of the section of the tunnel on the vertical curves and when it deviated from the line. It was also used when the skin of the shield tightened on the steel of the lining. When this condition occurred the narrow section of the taper ring was placed at the "tight" portion of the section, thereby loosening it. When the shield was pushed ahead to its new position, the eleven lower circumferential jacks were released, and the lower three segments of the ring were slid into place and bolted to the ring. Then, alternately, the other jacks were released and the remaining segments of the new ring were swung into place by a hydraulic erector arm

(Fig. 7) attached to the shield and the segments were bolted, hence adding to the lining a distance of $2\frac{1}{2}$ ft. As these steel rings were added, a temporary wooden floor was built up by putting 12 by 12 wooden beams across the steel rings and supporting the beams by wooden posts in the invert. A plank floor was laid across the beam sections on which the rails were set, (for material trains) and the belt conveyor system was set (for removing the muck, the soil excavated).

The line and grade of the shield had to be set accurately, for the tunnel followed the path of the shield and could not have been corrected if the original path had deviated. Each $\frac{1}{4}$ in. error at the start would have resulted in a 4 ft. error at the other side. (When the shield tunnelled through at the other side the grade checked exactly, and the line checked to a $\frac{1}{4}$ in.). The line of the shield was set daily, and the grade was checked after every forward move of the shield. The shield jacks controlled the direction of the shield. A thrust on the right would direct it to the left, a thrust on the top would direct it down, and vice versa. (The engineer's reports and shoving instructions are shown in the appendix).

Compressed air was used during the tunnelling under the harbor. A concrete bulkhead (Fig. 8) was built 500 ft. ahead of the East Boston Ventilation Shaft to hold the pressure in the working chamber. One air lock was used to permit 50 "sandhogs" (Fig. 9) of the shaft to enter the high pressure chamber, another into which materials were brought, and a third used for the excavation. There was also an emergency lock to be used in the event of an inrush of water.

The power for operating the shield, tools, and to generate the compressed air, was supplied from a plant built for the purpose on the East Boston side. The plant was supplied electric power from two independent sources so that continuous operations was insured in case one source failed. The equipment included two high pressure air compressors, each having a capacity of 1,300 ft. of air per minute at 90 to 105 lbs. pressure. These supplied compressed air for the air-driven tools, grouting machines, and air drum hoists. Three low pressure compressors, capable of delivering 3,300 ft. of air per minute at 30 lbs. pressure, were used to supply compressed air to the air chamber. Two hydraulic pumps, together with one hydro-pheumatic accumulator, was used to deliver water at a pressure up to 6000 lbs. per sq. in., generating the power by which the shield was driven.

EXCAVATION

The material excavated was a sandy clay, blue clay, and gravel, also a short distance of ledge, (hard shale) in the lower portion of the tunnel. Soundings revealed 9 to 15 ft. of ground above the grade of the tunnel. The contractor deposited 7,645 cu. yds. of clay blanket by scows over the portion of the harbor bed where the depth of cover was uncertain.

Mucking at the heading was accomplished by means of three types of cutting tools. There were two types of steel knives. The first used was a flat long steel blade, pulled by cables at both ends. Two men were required to operate this knife, holding and directing it at each end. The cables were connected to air hoist drums and supplied the force necessary to pull it through the material to be excavated. This tool did not prove very successful since there was not sufficient room for two men to work effectively and safely in the forward end of the chamber. The slice excavated was too heavy and large for these men to handle easily.

The second style of cutting knife was therefore adopted. It had first been developed during the tunnel operations of the Detroit Windsor Tunnel. This knife has a grip section to hold and direct it and a sharp rounded section for cutting the clay. It was operated by a single drum air hoist, One man was able to handle this knife and cut out sections about 8 in. by 10 in. and from 2 to 3 ft. long, (Fig. 10) which could be dropped directly into the muck chutes. This knife proved very successful in clayey material. It was an important factor in making the high speed record established for lined tunnel driving. But the third tool, the pneumatic spade, was the most useful knife of the three. It was adapted to any type of material and was of special value in sandy clay. This tool would break the material from the heading, dropping it onto the platform where it was scraped into the chutes.

Ledge was encountered in the lower sections of the shield. During excavation it was necessary to blast this rock. Diverging holes were drilled at an angle of 50 degrees to the face of excavation into the rock,in this manner the rock was wedged in so that it would shatter when blasted and not fly into the shield. This method of drilling forms a frustrum of a cone with the large base within the rock and the smaller base at the face of the rock. When the explosion occurs, the tendency is for the rock to fly towards the larger base of the wedge. Since this base is within the rock section the force of the blast tends to shoot the section into the rock and not away from it.

The shield was protected from the blasts by means of sheathing at the face braced by the face jacks. Due to the method of drilling 50% more powder than is ordinarily required was used. The rock would lift into the clay and not fly to any great extent towards the shield.
One blast would clear the rock for a distance of 5 to 6 ft. permitting two forward shoves of the shield. The weight of the shield (400 tons) prevented the force of the blast from moving it backwards, lifting it above grade.
When compressed air was used, it did not offer a serious problem, inasmuch as the ground was fairly compact, There was little fear of a blowout (i.e. when the air pressure forces out the heading causing a gap that allows the compressed air to escape and since air cannot be supplied in sufficient quantities, water rushes in). and the pressure was regulated so as to keep the bottom of the heading dry. The air plant had a 100% reserve capacity plant which was not once called into use. At one or two gravel sections air leaked out and bubbles appeared on the water surface. One plant was capable of supplying sufficient air to balance the leakage in the chamber.

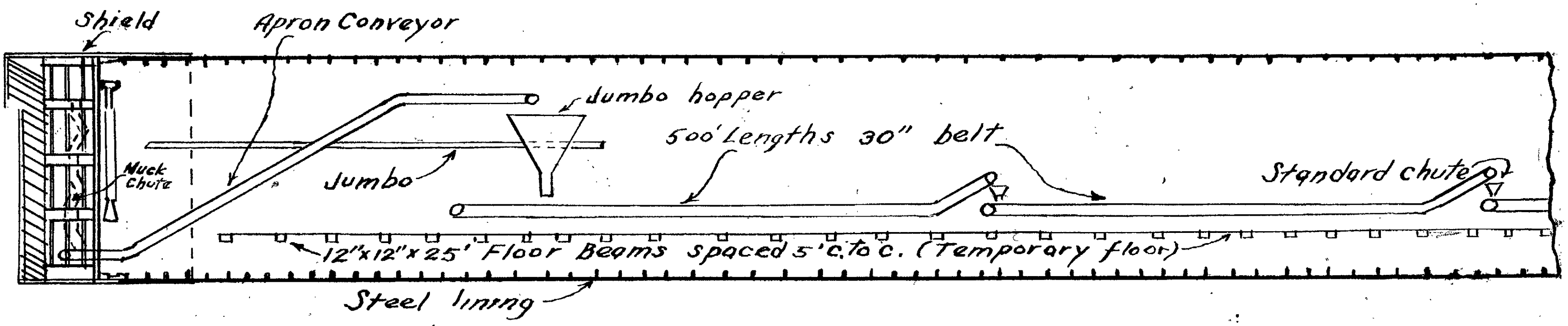
A compressed air-driven chain saw, with teeth on the chain, was designed to cut the piles encountered at the wharves and under buildings. The piles were cut above the hood of the shield. The chain saw was not a very efficient tool, and in many instances the use of axes had to be resorted to.

Due to the efficient mechanical devices used at the heading the speed of excavation was rapid. There is a large field for the development of other mechanical devices as well as for the improvement of those already in use.

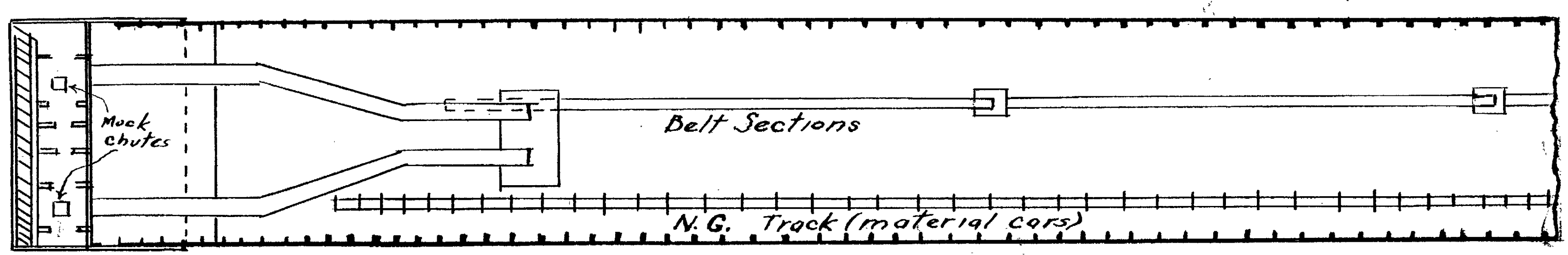
MECHANICAL CONVEYOR SYSTEM

The installation of the mechanical conveyor system, a novel method for handling muck in lined tunnelling, was undertaken after the shield had passed through the East Boston Ventilation Shaft. Previous to this installation, the progress of the shield averaged 5 rings, 12½ ft., in 24 hrs. With the conveyor system in use, the progress of the shield averaged 8 rings, 20 ft., in 24 hrs. As a result, a high excavation record for lined tunnelling of 32 ft. in 24 hrs. was established. The conveyor system made possible the excavation, with a single shield, of approximately 140,000 cu. yds. of muck in one year's time. This innovation proved successful since it removed the muck as fast as it was excavated and required little space and did not interfere with other operations.

At the head end of the tunnel excavation was accomplished by means of steel-cutting knives and by pneumatic knives. Two muck chutes (Fig. 4) built into this shield

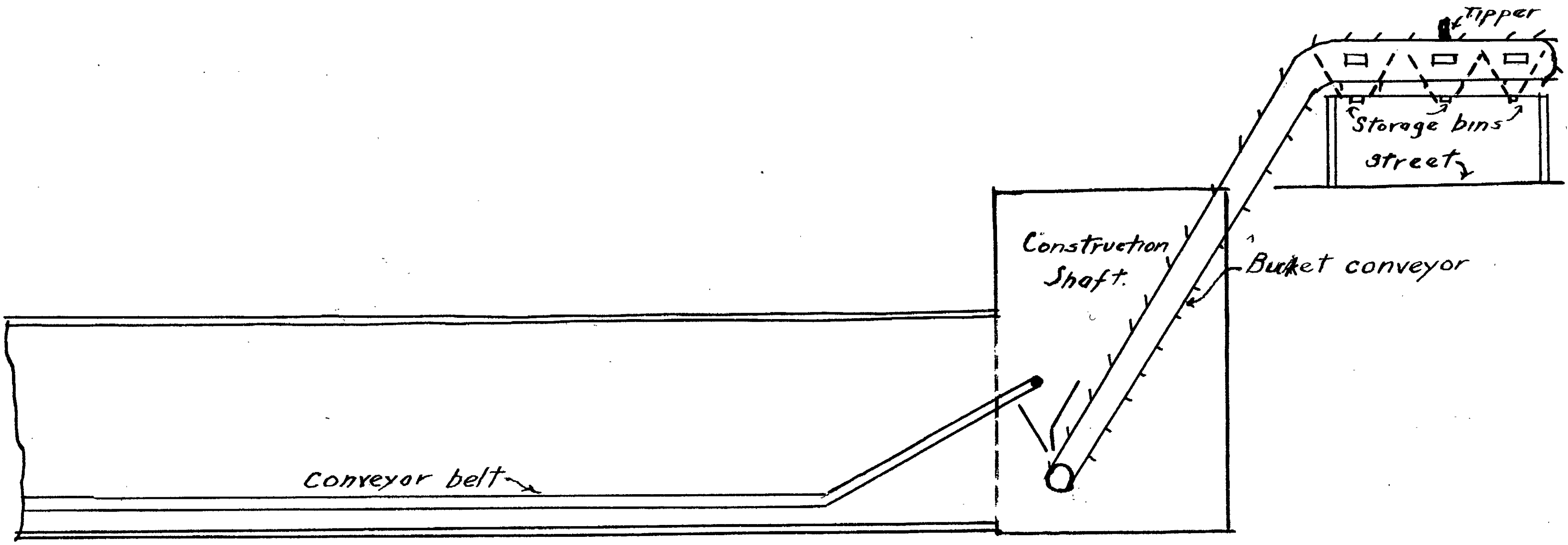


Elevation on ℄

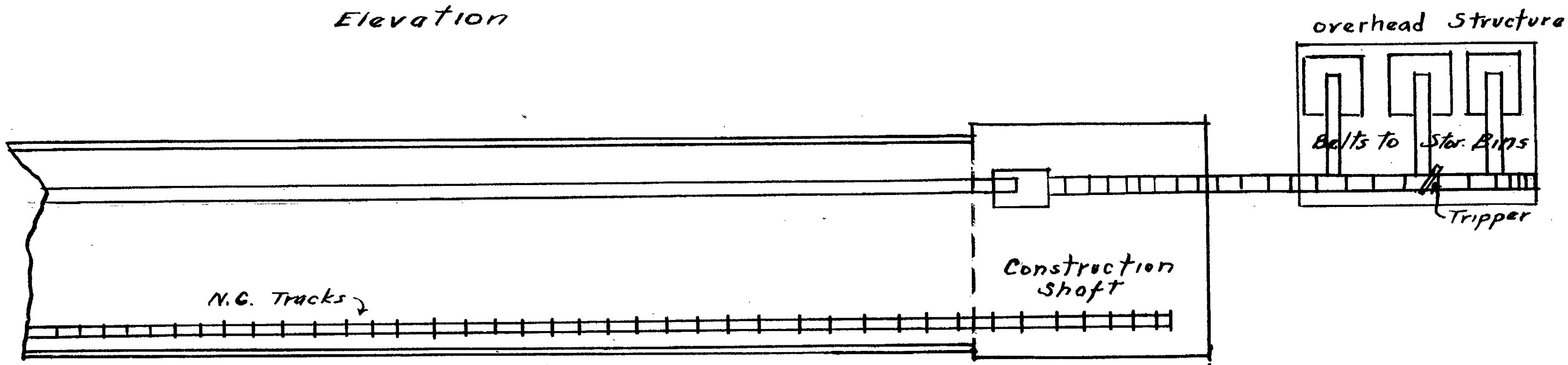


Plan on ℄

Diagram of Conveyor System
Section at Shield



Elevation



Plan

Belt Conveyor System.

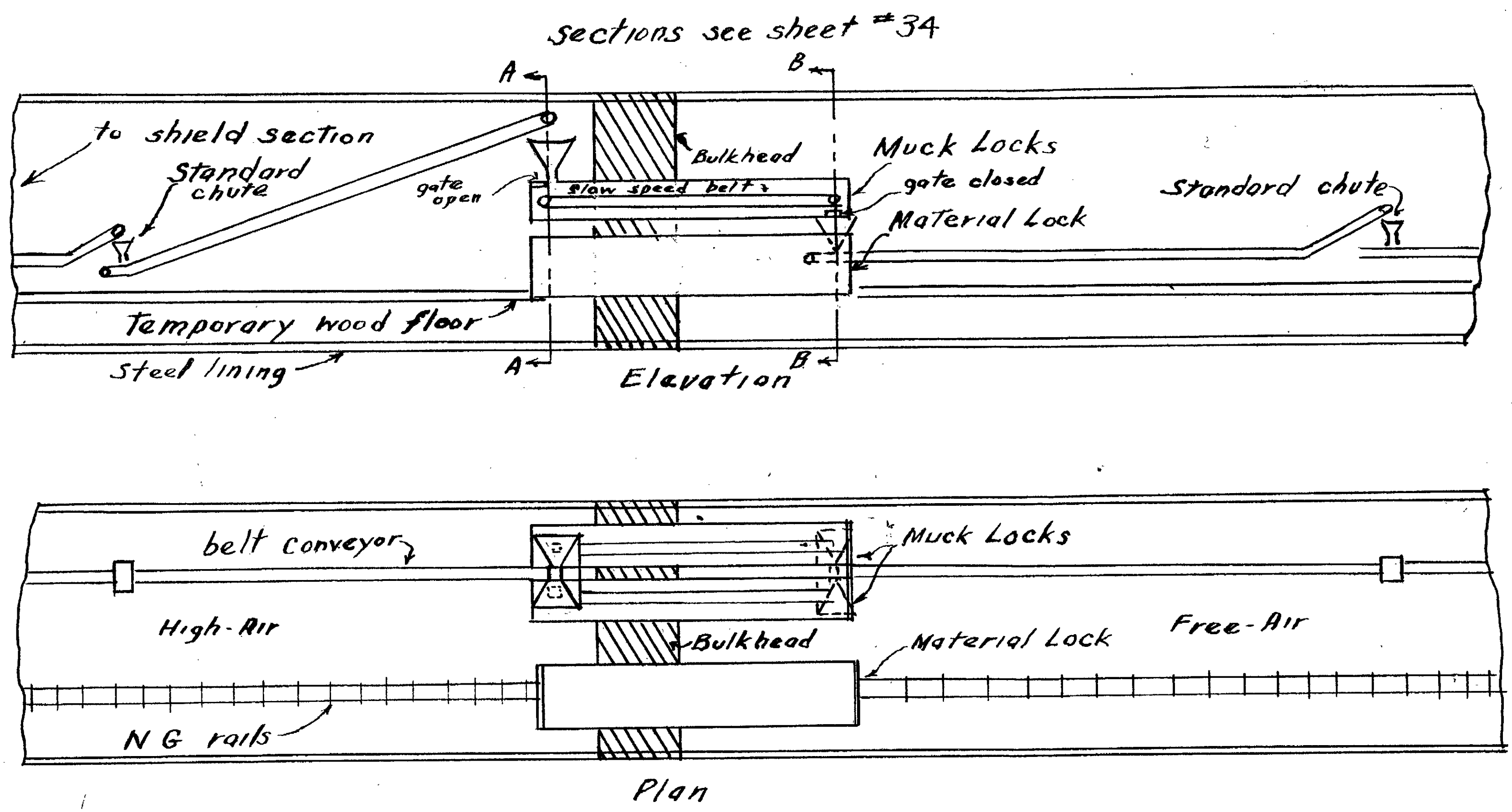
Dumping Plant

received the muck and deposited it onto apron conveyors (See page 26, also Figs. 7 and 11), which were hung by angle irons to the lower pockets of the shield. The apron conveyors extended parallel with the axis of the tunnel into the shield. Six feet behind the shield it was inclined upward thirty degrees to the axis of the tunnel so as to raise the muck to a higher level. Thence the apron conveyors were built into the jumbo (Fig. 12), a working platform, where the upper segments of the rings were tightened, and grouting operations were performed. These conveyors were operated by two 7½ HP motors, the belt travelling at a speed of 75 ft. per minute. The muck was dropped into a hopper that deposited it onto a 30 in. horizontal conveyor belt system (Fig. 13), which extended from the jumbo hopper to the construction shaft. The belt was composed of sections 500 ft. each; each section driven at a speed of 150 ft. per minute by a 20 HP motor. The linkage of one section with the next was accomplished by standard chutes. The length of the belt was increased by increments of 20 ft. lengths as the shield progressed. It required eight minutes for a crew of six men to make this installation.

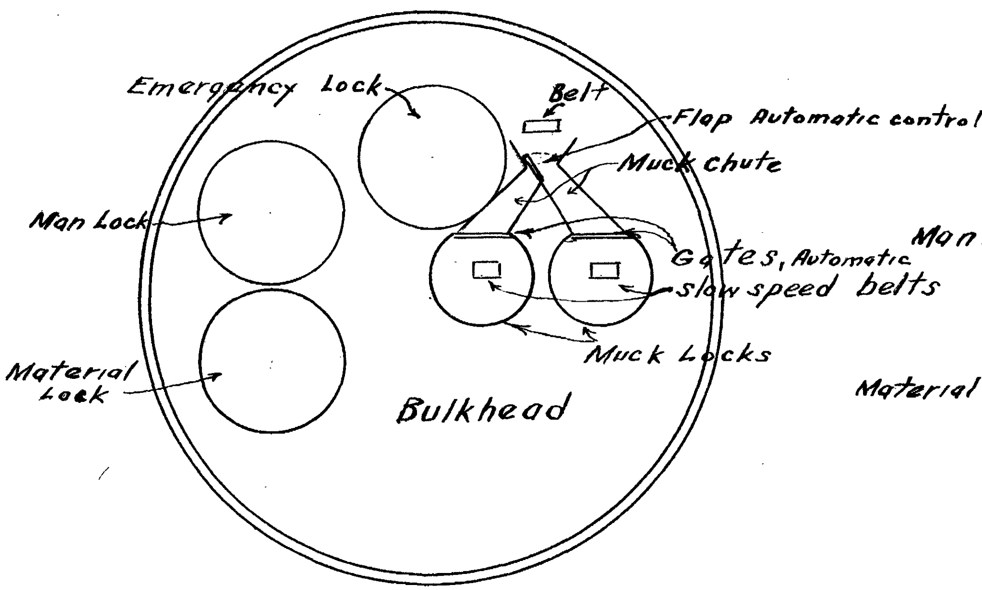
At the construction shaft, Decatur St., East Boston, (See page 27) this conveyor belt system empties into a hopper that deposited into a tractor type conveyor, (Fig. 14) 36 in. wide.

This was sloped at an angle of 60 degrees to the horizontal. The conveyor raised the muck 80 ft. above the floor level of the shaft, then it was built level. There was a tripper which directed the conveyor to empty into any one of three apron conveyors which in turn emptied into hoppers or storage bins, built on an elevated steel structure above Decatur St. The structure was designed so that it would not hinder vehicular traffic, by a clearance of 15 ft. 9 in. above the roadway. The hoppers were emptied by means of sliding doors operated by compressed air, directly into trucks under the structure. At the structure, a man was stationed to operate the sliding doors, to control the tripper and to remove the muck from the bins so that the operation of the hopper would not be hampered by setting muck.

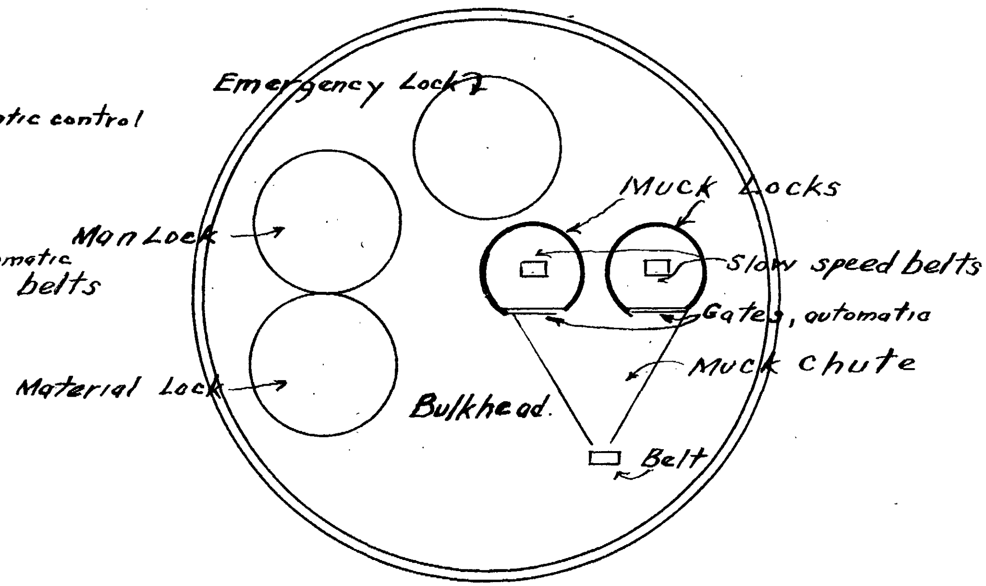
With the introduction of compressed air in the tunnel the success of the belt conveyor system depended upon developing a method of continuing the movement of the material mechanically through the bulkhead from the compressed air to the atmospheric pressure. Two locks had been designed for this purpose, (Fig. 15), each 5 ft. diameter, 34½ ft. long with sliding gates to be operated b compressed air. At the high air side the gate was on the top, at the free air, normal pressure, the gate was on the bottom.



Belt conveyor System
Section thru Bulkhead



Section AA



Section B.B.

Belt Conveyor System

Cross Sections of Bulkhead

At the ends of the locks there were doors bolted on that could be removed for repair work inside the locks. During the building of the first bulkhead section these two muck locks were set at the upper level. The end doors were not bolted in place and the present belt was elevated and went through one of these locks.

The final design was as follows:- (Diagrams, pages 33 and 34.) The belt was raised above the two muck locks overlapping a metal chute. This chute flanged out into two individual chutes. There was fitted a flap gate (See section AA) controlled by a compressed air piston at the mouth of the flanged chute by means of which the muck is automatically directed alternately into the two muck locks. The lock receiving the muck had the upper gate open, the muck falling onto a 36 in. belt within this lock, travelling at a rate of 15 ft. per minute. It was so timed that when the muck travelled to the lower gate at the free air side, this gate would automatically slide open and the upper gate would close. The belt would speed up to $22\frac{1}{2}$ ft. per minute, depositing the muck into a metal chute (See section BB), which dropped it onto the belt conveyor below, thence to the horizontal belt system. These automatic operations were synchronized by a time clock that controlled electric motors, operating change gears that opened and closed the gates and controlled the speed of the inner belt. The time of a complete operation was 141 seconds. While one lock was loading, the other was discharging. One laborer was required to maintain watch over the flap operation. When the muck piled up and blocked the flap, he turned off the control switch which stopped the conveyor belts from the shield to the bulkhead. (The muck locks were still operating). He then forced the muck below the flap into the locks, as soon as the locks were operating satisfactorily, he would start up the conveyors and the operation of the system was resumed.

The procedure of maintaining the use of the conveyor during the construction of the second bulkhead is of interest. Two locks of similar design as those referred to above were erected. One lock was built around the present conveyor. The en doors were not installed. The belt and lock was lifted into the bulkhead section and the masonary was then placed. A control system, a duplicate of the other described above was built. One lock was equipped with belts and motor, the second lock was used as a continuous passage for the belt. Work at the heading had been stopped over Sunday, as had been the practice, and the transfer was then made. There was no delay and Monday the new lock was in operation, the muck passing through the old lock on a continuous belt. There were only two difficulties encountered with the belt conveyor:-

1. At times, the belt crawled up on one side of the rollers, causing the muck to drop off the belt and to fall onto the under side of the returning belt which clogged some of the rollers. There was a tendency for the belt to tear under those conditions. This condition could have been remedied by alignment of the steel frame.

2. When moist material was encountered the friction side of the belt and the drive wheel would become wet causing the belt to lose traction and slip. When this occurred the contractor placed dry cement on the friction side of the belt and within a short time the belt would continue with regular speed. This condition occurred only when the maximum length of the belt was employed. On the other hand its advantages were numerous:- It was possible to concrete the portion of the tunnel already excavated, since the belt conveyor utilized very little of the available space in the tunnel, a practice that had never been attempted previously in tunnel construction. When the shield tunnelled through at the Boston Approach Section, the concrete was completed to the half way point in the tunnel and the invert was poured 25 ft. behind the shield.

The conveyor system eliminated handling of the muck by hand. The only hand labor was the digging at the heading. Material once cleared from the heading was mechanically conveyed through the tunnel to the street, where it was deposited into trucks.

In cleaning the invert, preparing for concrete, the wasts earth was hoisted by buckets to the floor level and dumped into the passing belt, in this manner back waste could be disposed of without necessitating the use of a muck car.

The use of the conveyor system is confined to certain types of material. It is excellent in clay, gravel and sand. It is less valuable in rock and not required in silt or quicksand. The difficulty in the first instance (rock) is that the rock would break the hoppers and tear the belts, also large rocks would clog the chutes and block the operation of the conveyor. In the second case of silt or quicksand let us refer to the mucking of the Holland Tunnel connecting New York and New Jersey, under the Hudson River. This tunnel passed through silt, a loose material and the shield was equipped with a bulkhead section to push the silt aside. No excavation was necessary. The pressure of the shield jacks caused the cast iron rings already erected by the shield to rise above grade, and the weight of the silt on the front of the shield about 50 tons caused the shield to settle (on nose) below grade. To remedy this tendency the shield diaphram was moved forward and the lower doors were opened to admit about 30% of the silt previously displaced. This silt was deposited on the invert of the (back iron) those rings already erected to weight it down and prevent "floating." It is evident since silt was admitted only as a ballast that a conveyor system was not necessary for excavation.

GROUT

Grout, composed of pea gravel and neat cement , is ejected outside the steel lining to fill the voids in the ground forming a close packing around the periphery of the steel rings of the tunnel. This causes a uniform distribution of the earth pressure. The grout also tends to create a water-proof envelope around the shell; furthermore the grout hinders the electrolytic action of the salt water on the steel lining, therefore lengthening the life of the steel. This process prevents excessive settling of superimposed structures, tunnelled under by the shield.

The greater percentage of the voids in the ground, around the periphery of the tunnel are caused by the difference of diameter of the shield and of the steel lining. For example, in the East Boston Vehicular Tunnel, the outside diameter of the skin plate of the shield was 31 ft. 7 in. that of the steel lining was 31 ft. leaving a void of 3½ in. around the lining.

If each section were not grouted immediately after placing the steel rings, settlement would have occurred, which would result in a deflection of the tunnel lining causing many stresses due to bending, unequal loadings and irregular footings.

The O'Rourke patented method of grouting was used, which consists of a pressure tank that forces a stream of grout through a hose, which is tapped to the ring sections, there being a tap in each segment of a ring. Grout was forced through the taps under pressure of 90 lbs. per sq. in. Pea gravel was first forced into the void left by the motion of the shield and at twelve rings back neat cement was injected into the gravel surrounding the line. At times 115 cu. ft. or more pea gravel was used at one tap. But on the average three cu. yds. of grout sealed the void created by one shove of the shield. ($2\frac{1}{2}$ ft.) The volume of the void in cubic yards = (mean dia.) x (π) x (width) x (length of shove) x 1/27.

void cu. yds. = 31.29 x 3.14 x 0.29 x 2.5 x 1/27.

= 2.6 cu. yds.

When the shield was passing under buildings great care was taken to do a complete grout job to minimize the settling. It was found that settlement took place directly above the shield with no noticeable settlement to either side of the path of the shield. The settlement depended largely upon the type of ground tunnelled through. At the East Boston shore of the harbor, where the ground was a consolidated fill, a maximum settlement of 5 in. took place. The grout operations, no matter how skillfully done, could not prevent this settlement. Grout forced its way through cracks in the ground and flowed out on the surface of the street, whereas on Moon St., Boston, where a hard clayey sand was tunnelled through, no settlement was evident.

Many of the superimposed structures were underpinned. Temporary footings were established by means of timber sills on the ground; I-beams were supported on these footings; screw jacks were set on these I-beams and rails and I-beams were supported on the screw jacks and were placed under columns of the buildings. These columns were then made independent of the original footings and were supported by the temporary footings. During each move of the shield settlement levels were taken and if settlement was then noted;by the use of the screw jacks the structure was lifted back to its original position. After the shield had passed under the structure the columns were set back on the original footings and steel plates were used, if necessary, to maintain the original levels. In this manner the foundations would settle but the buildings were held at grade during construction and sufficient time was allowed (usually 48 hrs.) after the passage of the shield, to insure against further settlement.

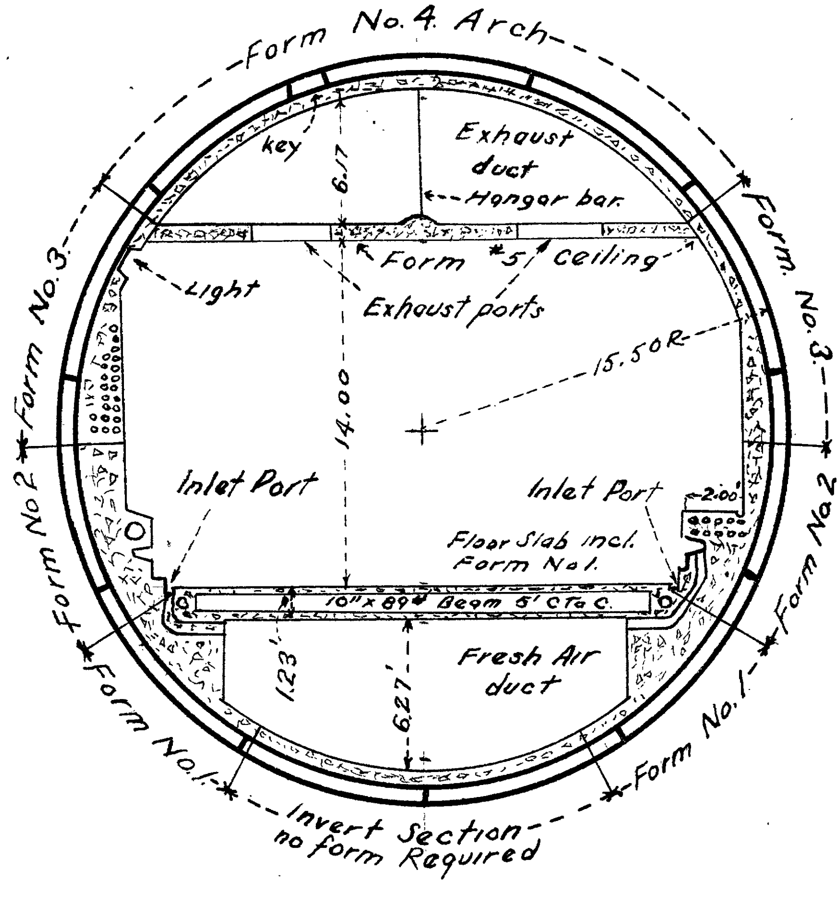


Diagram of Concrete Steps
Invert poured first. Forms poured
in numerical order.

CONCRETE LINING

A concrete chute was-built at the East Boston Ventilation Shaft where transit mixed concrete was received. The concrete was delivered through the chute into the tunnel to trains of six hopper dump cars, hauled by storage battery locomotives. These trains ran on the narrow gauge tracks built within the tunnel, delivered the concrete to the section being poured. (Fig. 16). The concrete was poured in six progressive steps. The first pour being that of the invert. The remaining five pours requiring the use of steel forms, built up the side walls, arch, and ceiling slab, working up from the lower section to the roof in successive pours. The belt conveyor that removed the excavation from the heading operated through the structure of the forms without interference. All the steel forms were equipped with screw jacks and turnbuckles so that they could be set to line and to grade. Pneumatic hammers were used to vibrate the steel forms, so that the concrete would compact and run into all spaces. Pour No. 1. The invert. (no steel form used). (See page 46). The timber platform or temporary roadway was hung by cables from the steel lining of the tunnel and the supporting timber posts removed. The steel lining was thoroughly cleaned, the waste earth hauled up to the

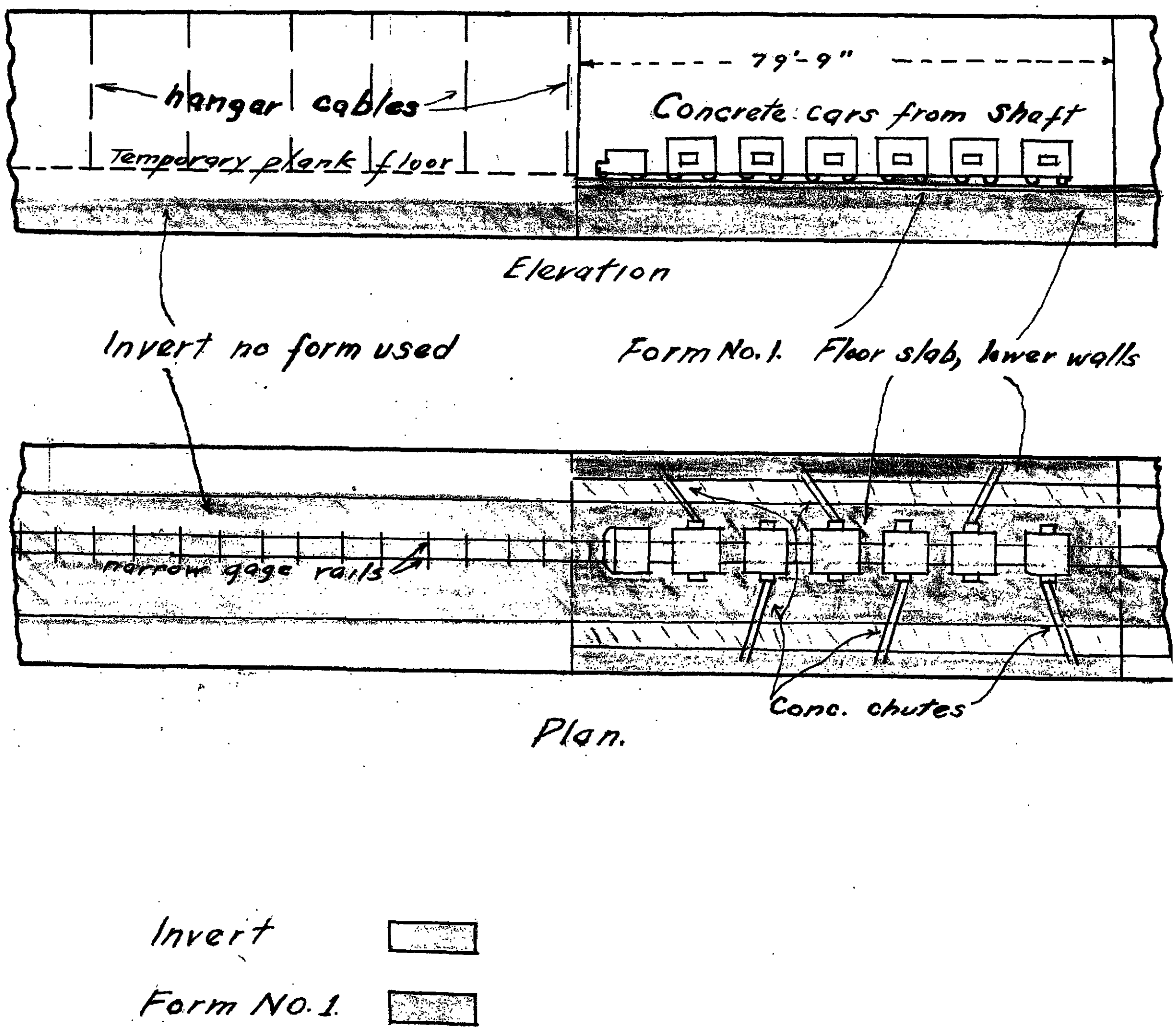
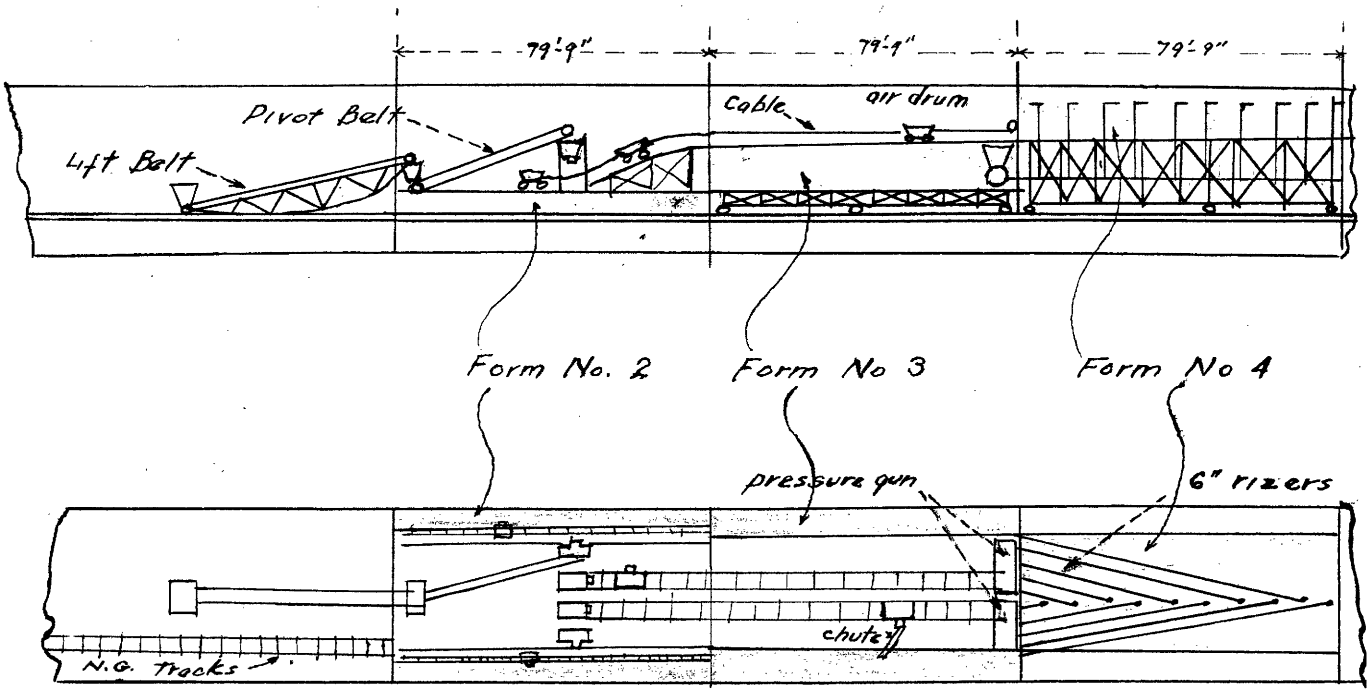
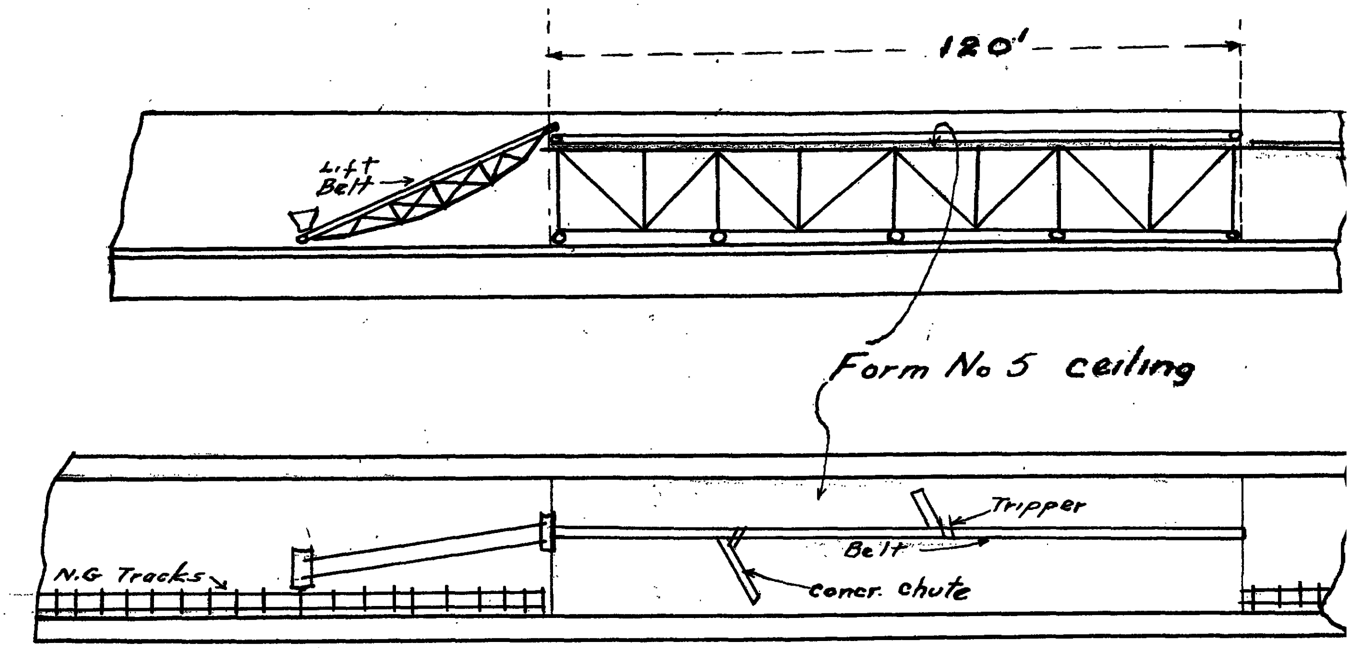


Diagram of Concrete pours
Invert, Lower side wall, Floor Slab.



Concrete Steps

Pour 3, 4 & 5.



Concrete Steps
Pour No. 6.

floor level and dumped into the passing conveyor. Simple wooden end forms were used. A few floor boards were removed from the wooden floor and the concrete dumped directly from the concrete cars into the invert, and then shoveled into place. A travelling guide formed to the contour of the invert (called a screed) was used in order to obtain the correct curvature. The invert was poured for 120 ft. at a time using the following materials:-

111 cu. yds. of concrete.
4320 lin. ft. of 1 in. sq. stress rods.
1170 lin. ft. of 5/8 rd. temp. rods.

Pour No. 2 (Form No. 1) Lower side walls and floor slab. (See page 46).

The temporary timber floor had been built above the grade of the permanent floor slab so that the permanent concrete slab could be poured without interference. The wooden floor was used until the permanent slab had set (48 hrs. allowed). Tracks were set on the invert after pour No. 1 had set and a steel form 75 ft. long on wheels was used. This form included a flat slab, the floor form, and steel side plates, the lower side walls forms. The steel form was set to line and grade and the concrete was poured directly from the concrete trains, traps were made in the wooden floors by removing some of the floor boards and the concrete dropped to the slab; the side walls were poured directly from the cars by means of chutes to the side forms.

Beams were set into the floor slab 5 ft. centered to center 2 in. above the steel form of the floor, mortar was used to fill in the 2 in. space below the beam, wire cloth was used around the beam bottom to hold in the mortar. The following material was used:-

150 cu. yds. of concrete.
4 cu. yds. of mortar.
2912 lin. ft. of 1 in. sq. stress rods.
2901 lin. ft. of 5/8 rd. temp. rods.
15 floor beams, 89 lbs. 10 in. wide.
494 sq. ft. wire cloth.
150 lin. ft. of 6 in. C. I. pipe.
10 sheet metal fresh air flues.
45 tie rods (around C. I. pipe).

After the concrete had set the temporary plank floor was removed and the tracks and the belt conveyor were set on the concrete floor.

Pour No. 3 (Form No. 2) Side walls (See page 47). Rails were laid on both sides of the concrete floor slabs, making a track 25 ft. wide, to carry the three steel forms numbers 2, 3, 4, which were on wheels and had an axle span of 25 ft. These forms were in tandem, and each one was 79 ft. 9 in. long. Form No. 2 includes the sidewalk on the North wall and a water pipe niche on the South wall. The hopper dump cars emptied into a belt that in turn emptied into a pivoted belt that was swung to empty into hoppers along this side; cars, driven by cables, were filled from these hoppers and they in turn emptied into the form.

Pour No. 3 Required the following material:-

90 cu. yds. of concrete.
4 cu. yds. of mortar.
2494 lin. ft. of 5/8 in. rd.
temp. rods.
398 lin. ft. of 3 in. fiber ducts.
398 lin. ft. of $3\frac{1}{2}$ in. fiber ducts.
80 lin. ft. of 6 in. C. I. pipe.
Anchor plates, 80 ft. long on
either side.(used to bolt on
the baffle plates for ventilation)

Pour No. 4 (Form No. 3) Side walls (See page 47). This pour brought the side walls up to the level of the arch. The concrete belt on form No. 2 was now pivoted to the center hoppers on form No. 2. The concrete was run from the hoppers to cable cars up the ram to form No. 3. These cars were pulled by an air hoist and were emptied into concrete chutes directly into form No. 3. The following materials were required:-

90 cu. yds. of concrete.
2961 lin. ft. 5/8 in. rd.
temp. rods.
420 lin. ft. of 3 in. fiber
ducts.
1050 lin. ft. of 3½ in. fiber
ducts.

Pour No. 5. (Form No. 4) The Arch (See page 47) The same cars used to fill form No. 3 was used to feed two concrete guns (pressure tanks to shoot concrete into pipes) each pressure gun had a capacity of ½ cu. yd. of concrete and fed into five 6 in. header lines, leading into ten riser pipes that were equipped with elbows within the forms. The risers were worked in pairs, one gun feeding one and the second gun the other. The pipes could be swung around by hand to control the direction of the nozzle. A slight difficulty was encountered in filling the very top of the arch, for the concrete would not rise above the elbow, where the riser emitted the concrete. This was overcome by using alternate risers forcing the concrete at the other riser. Then the elbows were removed and the concrete forced directly into the section. The following materials were required:-

100 cu. yds. of concrete.
2640 lin. ft. of 1 in. sq. stress rods.
1029 lin. ft. 5/8 in. rd. temp. rods.

Pour No. 6 (Form No. 5) Roof Slab (See page 48)
A steel form 120 ft. long built on wheels, with an axle form 25 ft., was used. This form followed the preceding series on the track previously laid. The concrete dump cars were emptied from the floor level into a riser belt that dropped the concrete to a second horizontal belt. Side chutes were adjusted to the horizontal belt and poured the concrete onto a steel plate (part of the form) forming the ceiling. The concrete was graded by a screed and by hand. The following materials were required:-

55 cu. yds. of concrete.
1083 lin. ft. of 5/8 in. rd. temp. rods.
240 lin. ft. of 6x4x3/8 angles.
12 ceiling hangers (spaced every 10 ft.)

220 sq. ft. wire cloth.

500 lin. ft. of 3/4 in. steel conduit.

120 lin. ft. of $1\frac{1}{4}$ in. steel conduit.

The use of steel forms for the concreting of a tunnel lining is not a new procedure. The design of the forms used in the East Boston Vehicular Tunnel possessed many features that resulted in greater efficiency than ever attained before.

In contrast to the Holland tube where steel forms were used, gravity was relied on to eliminate hand labor. This necessitated the construction of overhead rails, suspended from the lining of the tunnel. The construction of switch tracks and spur tracks were required. Whereas, in the East Boston Tunnel a belt system that was self-contained was used; hence eliminating the erection of overhead rails the length of the tunnel. The arch was poured in the Holland Tunnel by shovelling concrete from these cars to the overhead steel form. This type of labor is slow since it is necessary for men to lift the shovels of concrete above their head, twisting the shovel and then force concrete into the small overhead gaps. Other men would ram the concrete into the forms. This procedure not only was slow but wasteful, since the concrete would constantly be dropping to the ceiling level. On the other hand the Silas Mason Company designed the arch form so that once concrete left the cars at the floor level it was put in place mechanically. (Fig. 17) The concrete was emptied from the cars into a high speed belt from which it was transferred to a pressure system that forced the concrete in place.

In the Holland tube the forms were only 15 ft. in length, in order to facilitate concreting the curve. The East Boston Tube is a straight tube, hence the forms were built as long as desired, the only limiting condition being that of slight vertical curves. This factor also resulted in greater speed for the East Boston project in contrast to the Holland Tube, inasmuch as forms had to remain in place from 24 to 48 hrs.

The concrete that has set in steel forms obtains a smooth and finished appearance. (Fig. 18).

LEAKAGE

There are three sources of leakage through a steel lined tunnel.

1. Grout holes.
2. Bolt holes.
3. Joints between the segments.

The leakage due to grout holes may be considered of minor importance. Beyond making sure that all grout holes have their plug well fitted in position. Nothing need be done about grout holes and they seldom offer any problem.

The only precaution taken in the care of bolt holes was to use steel washers under the head and nut of each bolt.

The method used in prevention of leaky joints between the segments, was the application of master puddings, a roofing cement, "buttered" onto the joints of the rings.

A tunnel has the tendency to perform the function of a drain for the surrounding soil. When the water in the ground is present under a head the lining must be water tight to prevent leakage into the tunnel. After completion of the East Boston Vehicular tunnel some leaks were evident. In my opinion there are numerous factors that may have caused this condition.

The master's pudding was not satisfactory as far as making a water tight joint between segments, for it flowed too freely under ~~the~~ pressure. This was demonstrated when the neat cement was ejected under pressure outside of the steel lining, it oozed into the tunnel through the joints of the rings displacing the master's pudding. The pudding was caused to further flow by the heat generated by the setting of the cement.

The steel rings deflected during erection, and the pressure of the shield jacks loosened the back iron, necessitating retightening. This deflection no doubt, caused the grout shell to crack and separate from the steel lining and also caused the segmental joints to open. When concrete was poured the sectional weights would cause the individual segments to separate opening up the joints.

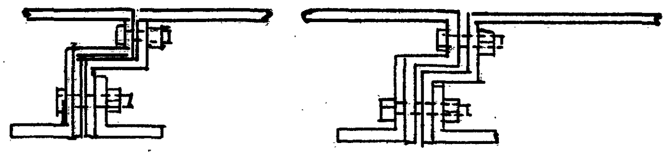
In my opinion the following precautions should be taken to insure as near as possible a water tight tunnel.

The rings should be designed so as to impede the flow of water. If the path that water had to travel was a winding one, its progress would be hindered.

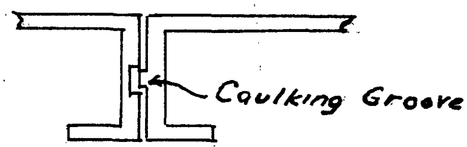
If the flanges were designed as shown in page 60, the flow of water would be impeded.

The ideal calking material would be one that would be pliable, yet solid, would not flow under pressure, would adhere to the lining, will not deteriorate with age, and not cause corrosion of the lining. Lead very closely approaches this ideal.

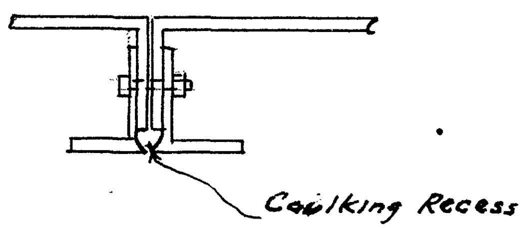
In the Holland tunnel a groove was provided in the lining for calking purposes. This groove was cast into the lining segments and machined, as shown page 60.



Flange design to impede water path.



Design of caulking groove used in the Holland Tunnel.



Design proposed for caulking steel lining.

A wire lead was drawn into the groove establishing a fairly tight joint. The East Boston Tunnel did not have any provisions for calking the joints.

I believe that if the outstanding legs of the flange angles of adjacent rings were designed to facilitate calking, it would be of assistance in sealing leaking joints. If a design such as shown on page 60 were used, this calking could be accomplished by filling the recess formed. Connections of the member segments must not be neglected and a similar design at these joints employed.

The formation of a concrete shell around the periphery of the lining by means of grouting operations offers resistance to the head of water and in many cases has almost completely stopped perculation. If the perculation is reduced sufficiently by grouting, the design and calking should make a substantially water tight structure.

In the Detroit Windsor Tunnel a design similar to that used for the East Boston Vehicular Tunnel was used. The grouting operations sealed all water bearing gravel sections and the clay was of a drier character than that under the Boston Harbor, resulting in a fairly dry tunnel. This condition was also true on the East Boston side of the tunnel. On the Boston side and under the harbor where the clay was wet, the tunnel showed occasional leaks, even though grouted. It was therefore necessary to resort to back grouting which was done by the opening of the grout plugs and forcing dry cement into and through the plug to fill the openings that permitted the seepage. If after the back grouting had been resorted to and there still was seepage it would be necessary to resort to calking of the joints or if that would not stop the leaks, then electric line welding could be employed which would result in a most perfect water seal.

It is important that all necessary precautions be carried out to insure as a dry a tunnel as is possible before the concreting of the inner section is undertaken, since the concreting conceals the steel lining of the tunnel it would be difficult to remedy any leaks that might occur after the tunnel is completed.

In the East Boston Tunnel the further precaution was taken before poring concrete to extend the grout plugs through the thickness of the concrete by pipes so that after the concrete was pored any leaks could be sealed by grout ejected through those emergency plugs.

COMPARISON CAST IRON RING TO STEEL RINGS

In older practice many of the important structures were made of cast iron, including bridges and columns. Now structual steel is used in its place. Structual steel has many qualities in its favor, principally greater tensile strength and therefore greater reliability.

The outer line of the tunnel should be so constructed that it will withstand the weight of the earth above and any other superimposed load together with the forces to which it is subject by the use of the shield jacks and must be a permanent part of the tunnel and as water tight as possible.

In the East Boston Tunnel steel lining was used. in preference to cast iron which has been used in former tunnel construction.

In cast iron lined tunnels, there is no danger from deformity of the rings since the cast iron does not bend and it is easier to bolt the joints because of the rigidity of the cast iron, since all holes are machine drilled and fit when one ring is placed against the other. There is however the danger of breakage. In a steel lined tunnel the steel lining is subject to deformity and because of such deformity it will transmit to some degree the stresses to the concrete lining forming the tunnel, therefore the concrete must be reinforced to take whatever loads are transmitted to it. The practice in steel lined tunnelling is to design a concrete tunnel independently of the steel, hence requiring heavy reinforced concrete and a double design.

The economy of steel lining is an important factor in its favor. The weight of a cast iron ring is about three times that of a steel ring. The cost per pound is practically the same as steel. The saving in a 30 ft. diameter tunnel using steel lining in place of cast iron is approximately $1,500,000 per mile of tunnel. Since steel is fairly flexible and weighs 1/3 as much as the same size cast lining it is possible to handle larger segments. But there are more bolts required for a steel tunnel since deflection causes stresses that must be transmitted to the back iron. In a cast iron tunnel the pressure of the flanges and the shear, due to weight of iron, does not require as many bolts.

In a cast iron tunnel breakage is slight. In the Holland tube approximately one segment broke to 40 rings or about 0.2%. This expense is equalized in steel tunnelling by delays caused by "tight iron" which is a result of deflection.

If the shield deforms to such an extent that cast iron rings could not be placed, it is probable that steel rings could be erected after burning out new bolt holes since those in the iron would not fit. Hence under such emergencies steel would be beneficial when it was of economy to continue construction rather than stop to repair the shield.

There are many details of the East Boston Vehicular Tunnel construction that I did not attempt to describe, suffice to say under the able management of the contractor the work proceeded in a smooth manner with a minimum of accidents to the men employed and not a single fatality, although the working crew was inexperienced in tunnel construction and the use of compressed air is always a source of danger to the men.

The Silas Mason Company did everything in their power to protect the health of the men employed, and I have attempted in this thesis to point out some of the new methods employed by the contractor in constructing the tunnel.

Appendix

CITY OF BOSTON — TRANSIT DEPARTMENT

TRAFFIC TUNNEL

SECTION A

Date Feb. 15 1932 Shift 12--8 Am

Shield Check after Shove to Erect Ring No. 3585 Iron Check on Ring No. 3584

DIST. FROM INDEX PTS.	LEFT SIDE	RIGHT SIDE	STATION INDEX POINTS	STATION
Iron at S. L.	2015	20.03	45-20	45-40.09
			Top Flange	
			Bottom Flange	
Diaph. Shield	455	4.55		45-44.64

Station of Cutting Edge (+8.37)

Station of Rear Face of Erector (—4.00)

Side Lead: Iron .12 left Shield .05 left

Ring No. 3585 Horiz. Diam. 2970 Vert. Diam. 29.64

Theoretical Diameter of Flange, 29.67. Overhang of Iron 1.08

Plumb Line on Shield 1.60 Overhang on Shield 1.13

Dist. Base Line to Plumb Line Dist. Plumb Line to Axis-Erector

Dist. Base Line to Axis-Erector Theo. Deviation

Dist. Base Line to Left Flange of Iron Theo. Deviation

Dist. Base Line to Right Flange of Iron Theo. Deviation

Alignment-Shield Erector .05left C. E. Tail

Elevation Shield Erector 0.12 H C. E. Tail

LEVELS

B. S.	H. I.	F. S.	ELEV.	OBJECTIVE	THEO.	DEVIATION
2.20	28.50		26.30	B. M.		
7.73			36.23	Axis Er't'r	36.11	
				Bot. Flange		
				Top Flange		

Computed by

Signed

Checked by

Engineer's report of shove.

CITY OF BOSTON—TRANSIT DEPARTMENT
TRAFFIC TUNNEL
SECTION A
SHIELD REPORT

BEFORE SHOVE TO ERECT RING NO. 3585

DATE Feb. 15, 19 32

TIME 12 PM

POSITION:

0.05 LEFT ______ RIGHT

0.12 HIGH ______ LOW

INSTRUCTIONS FOR SHOVING:

KEEP 1" LEAD ON Left SIDE

PLUMB 1.58

SIGNED ______

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