THESIS

FACTORS GOVERNING THE CONSTRUCTION OF TUNNELS

THESIS

SUBMITTED TO PROF. MILLER

OF

MICHIGAN STATE COLLEGE OF

AGRICULTURE AND APPLIED SCIENCE

IN PARTIAL FULFILLMENT

OF THE

REQUIREMENTS FOR A DEGREE

OF

BACHELOR OF SCIENCE

JOHN MASSEY

JUNE 1938

THESIS

12-4-51

9

264852

I wish to thank Prof. Lorin G. Miller, head of the Mechanical Engineering Department; Prof. Chester L Allen, head of the Civil Engineering Department; and Mr. John S. McDonald, of the Walsh Construction Company for their thoughtful cooperation and helpfulness.

- INTRODUCTION -

The following paper shall deal with the various means and factors governing the construction of modern tunnels. The sketches used in this paper have been obtained from the author's interpretation of this type of work while in the employment of the Peter F. Connolly Company who were under contract to the Ford Motor Company to construct a service tunnel beneath their turning basin in the Rouge River Plant. The author shall endeavor to relate to the reader the hazardous undertakings and the means used to burrow under these extraordinary conditions. It is his idea in writing this paper to make the essential operations cognizable to the common layman. Let us not think of the projects of tunnel construction as those connected with the mining industry; but rather those that are in step with our rapidly growing transportation problems. To facilitate and accelerate this rapidly growing traffic between various points which would have to be bridged, ferried, or routed around; tunnels have come into existence as a means to overcome these difficulties.

For clearness the author has divided the factors governing the construction of tunnels into three distinct phases; namely: construction, labor and power. These three phases shall compile the bulk of the material given here-in; but, feeling that they alone would not throw sufficient light on the subject, the author has installed a beginning and a conclusion that deals respectively with the types and uses of tunnels in general (not subaqueous alone).

The author is greatly indebted to the E.I. DuPont De Nemours & Company; the Ingersoll Rand Company; Messers Hewett and Johannesson, authors of, "Shield and Compressed Air Tunneling;" Mr. Archibald Black, author of, "The Story of Tunnels"; Mr. John S. McDonald, Chief Engineer of the Walsh Construction Company for part of the subsequent information.

A. TYPES OF TUNNELS

Meaning - Tunnels, in this paper, may be understodd to be built for the purpose of transportation. The objects to be transported may be persons, vehicles or any solid, liquid or gaseous matter.

Tunnels may be divided into three distinct classes; namely: rock tunnels, subaqueous tunnels and cut and cover tunnels.

Rock Tunnels: Those tunnels that must be built through ground that can only be penetrated by blasting are termed rock tunnels. The first principle that must be applied to rock tunnel driving operations is the methods of cutting out and moving the rock from the tunnel's heading. From start to finish, drilling, blasting, and loading the broken rock must be carried on with the utmost economy of time, not only as regards to each operation in itself, but also the co-ordination of one with another.

In order to aid tunnel drivers certain explosives manufacturers have made an extensive study in the past years of ways and means of reducing fumes after blasting. These researches have resulted in the manufacture and improvements of gel tin dynamites and in the use of a special paper for wrapping the gelatins. Together, these methods have automatically decreased the volume of objectionable fumes from the blasting so that less time is lost between blasting and mucking than in former years and the men can work more efficiently, particularly while the rock is being loaded out of the heading. With the straight gelatins there is some unavoidable increase in the volume of noxious fumes from the strengths above 60%, whereas with the ammonia gelatins the noxious fumes are kept to a minimum up to and including the 80% strength. Therefore, when 75% or 80% gelatin is necessary in close places, ammonia gelatin should be used rather than the straight gelatin.

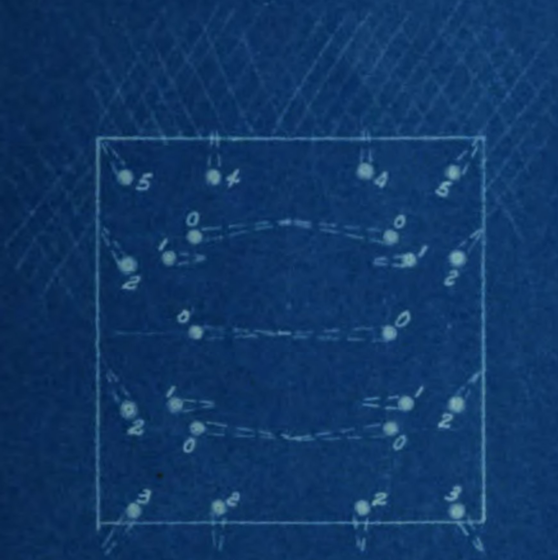


Fig. 1 - Typical
V Cut Fullface Round
for Tunnel

Fig. 2 - Typical
V cut Fullface Round
for Harder Ground

Fig. 3 - Pyramid
Cut Fullface Round
For Very Hard Ground

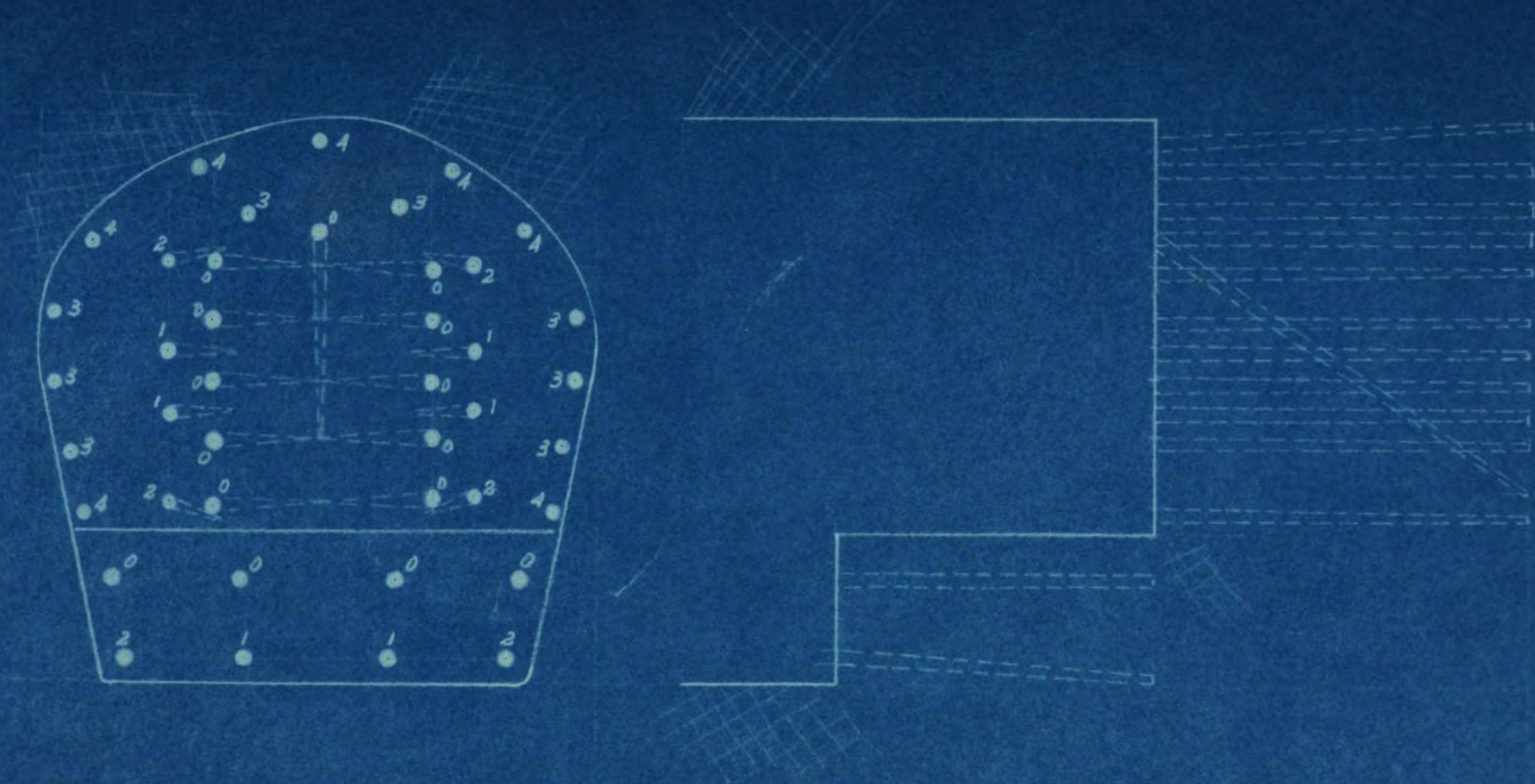


Fig. 4 - Bench Round Applied to Large Tunnel

The use of a suitable dynamite in tunnel blasting can quite appreciably effect the progress of the tunnel. It is apparent now that a dynamite of excellent fume must be used at all times; but also a dynamite of excellent water resistance and high velocity of burning seems to help fufill the tunnel driver's specifications for his dynamite.

The three most widely used methods of rock tunneling are the top heading and bench method, the pilot and pioneer tunnel method, and the Rove tunnel method.

In tunnels where the top heading and bench method is followed and mechanized loaders are used, the time required for cleaning up the rock thrown down the drift from the cut shots is of considerable importance. If the quantity of broken rock thrown to a distance can be reduced it means a worth while saving in mucking costs.

Figure 1, 2, and 3 show typical full-face tunnel rounds used in 8'x8' drifts and tunnels. The holes marked "o" are shot by means of instantaneous electric blasting caps. The other holes are shot with delay electric firing devices of the respective delays indicated by the numbers and explode in this rotation. The blast of three or more pairs of cut holes with instantaneous electric caps is very violent and the broken material is thrown a long distance down the drift. The cleaning up of this scattered rock very materially slows down the loading particularly when a mechanical loader is used.

To solve this loading problem the bench type of round shown in figure 4 was developed. This round is applicable only where electric blasting is used in rock tunnels that do not require timbering. The bench, which is shot with one or more lines of lifter holes, is kept one cut behind the face. By firing the lifter holes in the bench at the same time as the cut holes in the heading, the rock in the heading

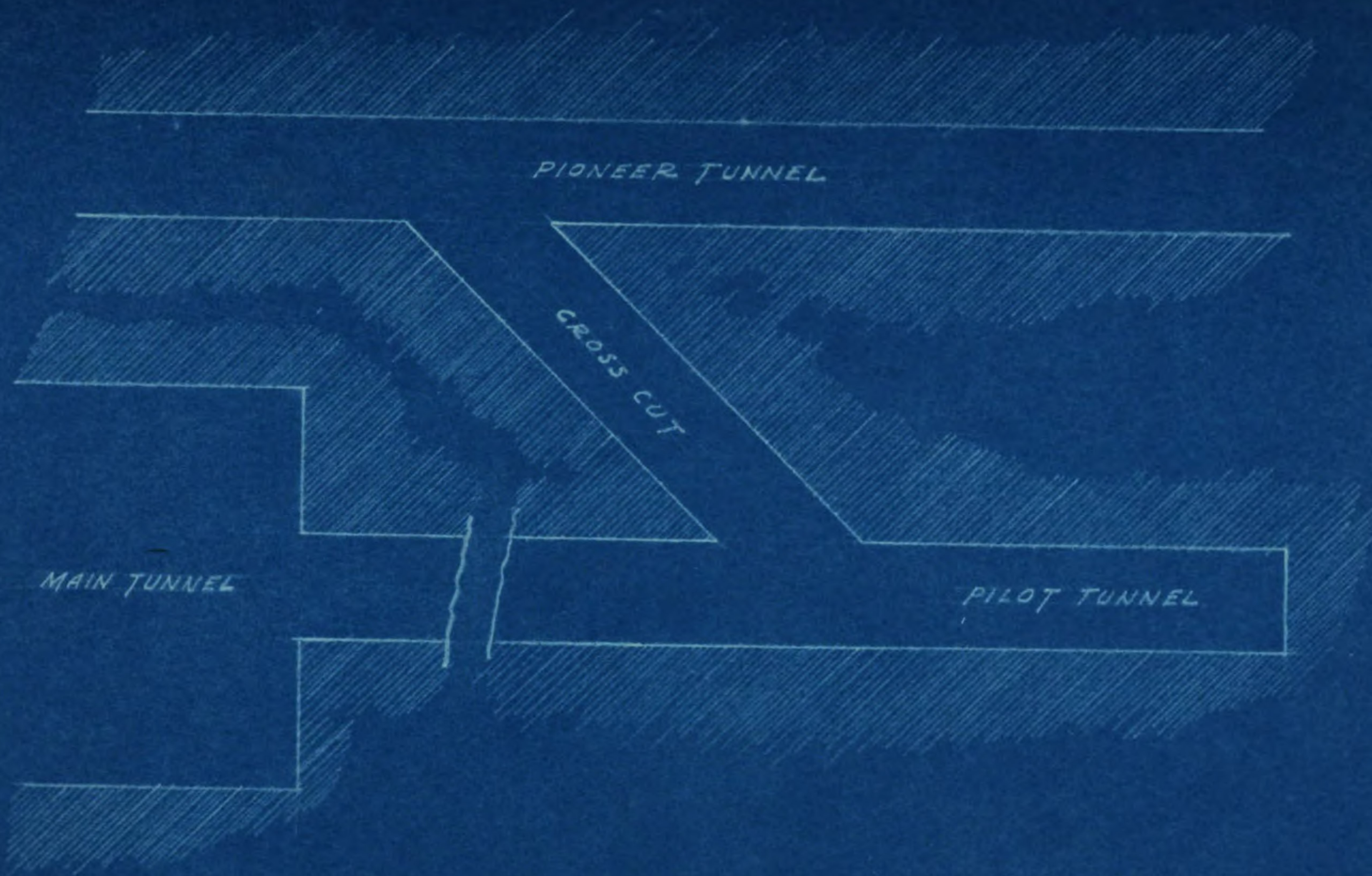


FIG. 5 – PLAN VIEW OF THE ROGERS PASS
SYSTEM OF ROCK TUNNEL DRIVING.

is met by the rock in the vench, that is moving upward; this prevents it from being hurled down the drift any great distance.

By the application of these methods the rate of progress of rock tunneling c n be greatly increased because of the shortening of the time of mucking.

Nearly all of the record-breaking achievements in tunnel driving have been made on what is known as the Rogers Pass system or the pioneer and pilot tunnel method. In this system two parallel headings, usually from 8'x8' to 9'x9' in cross-section, are driven from 50 to 100 feet apart and one of these is enlarged to form the main tunnel (See figure 5). The heading on the main tunnel line is known as the pilot tunnel and the other as the pioneer tunnel. Every 1000 feet a diagonal crosscut is driven slanting from the pilot tunnel toward the portal of the pioneer tunnel. All the broken rock from the pilot tunnel is taken out through the pioneer tunnel, this enables work to progress at all headings without unnecessary delay. Lost motion is cut out largely by having the drilling crew working in one heading while the other is being cleaned out. This allows the blasting to be done so that the broken rock is left piled up against the face in the most advantageous position for mechanical loading.

When a full size tunnel is being driven on the single heading plan, the time required to remove the amount of material broken by blasting such a large face limits the rate of advance. In the Rogers Pass system the pilot heading can be pushed forward independently at a maximum speed, and the ring holes for the enlargement of the heading to full size can be drilled and blasted as rapidly as desired. This ring blasting is generally kept well ahead of the revolving dipper shovel that does the mucking and this prevents the broken rock from

1, 2, 3. DRIVING THREE ADVANCE HEADINGS IN SUCCESSION.

4. WIDENING AND DEEPENING TOP HEADING.

5. CONSTRUCTING ARCH PIERS.

6. EXCAVATING CROWN BETWEEN THE THREE HEADINGS.

7. CONSTRUCTING ARCHES

8. REMOVING CENTER BENCH.

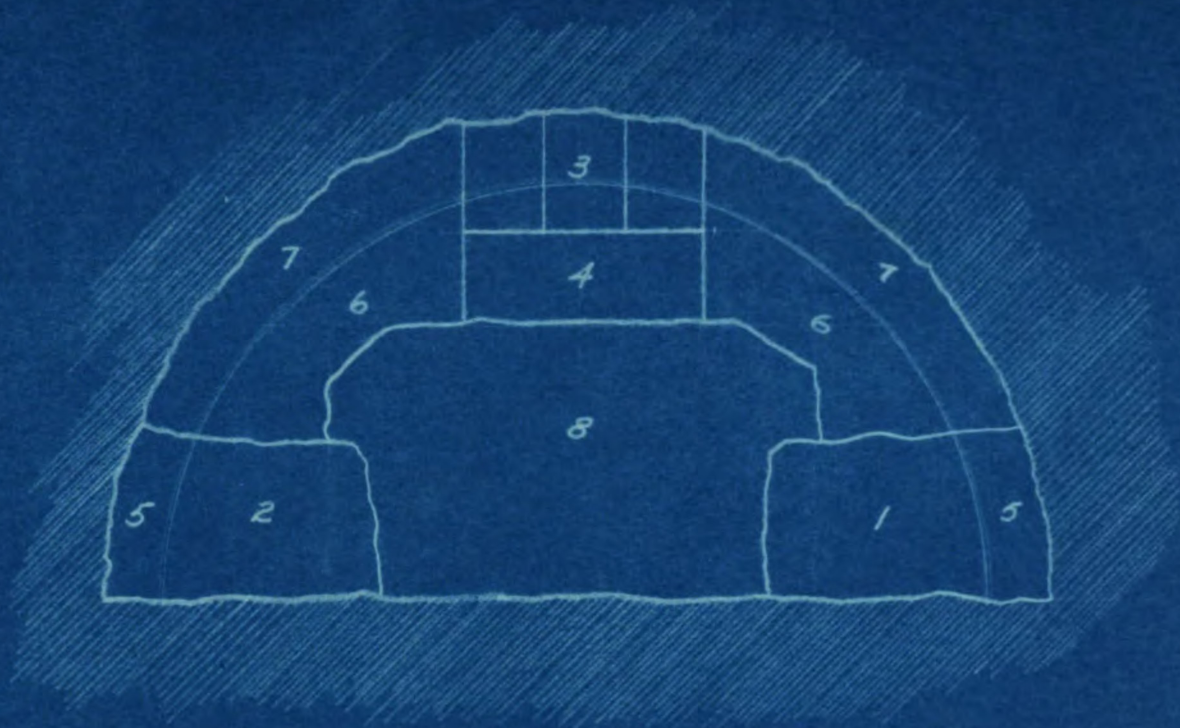


FIG. 6. – SECTION SHOWING SUCCESSIVE STEPS IN ADVANCING ROVE ROCK TUNNEL.

being thrown long distances and thus does away with cleaning up along the tunnel after the blasts. Furthermore, if the enlargement work is slowed down by the necessity of timbering and lining with concrete due to heavy ground, enlargement operations can be started at the end of each cross cut and carried ahead in both directions, thus speeding up the work.

In the driving of large tunnels in ground that will not stand by itself, it is sometimes necessary to work around the periphery of the tunnel and place the lining first. After this has been done the rock is removed from the core left inside, Figure 6. This method is called the Rove Tunnel method because it was used on the Rove Tunnel near Marseilles, France, which is the largest tunnel excavated up to the present time. Three headings are driven, one on each of the outside bottom lines and one on the center top line. Regular stopes are worked from the bottom entries to each side of the top and the lining is placed as the work progresses upward. Finally, when the lining of a section has been completed, the core of rock in the center is removed.

With these systems the first step in blasting is the driving of the heading in one position or another; consequently in all of them, the proper placing of the cut holes so that their bottoms will meet is of fundamental importance as largely determining the breakage of subsequent shots and the rate of advance of the tunnel.

It has long been established that in driving rock tunnels the advance per shift or per round of holes depend upon the depth to which the cut is blasted. The principle used in placing the cut holes, is the V method, whereby the plane of V cuts are parallel to the greatest

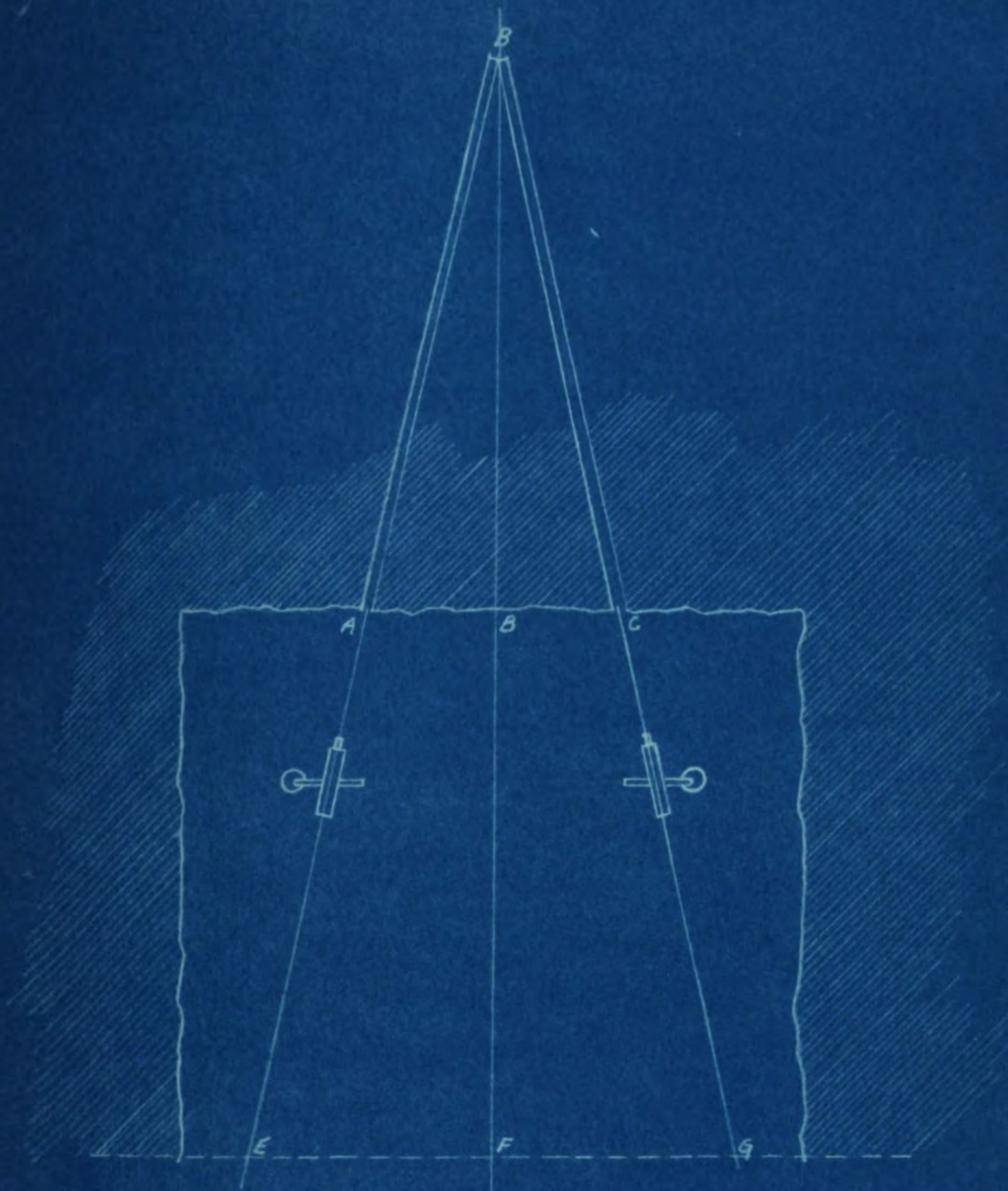


FIG. 7. – METHOD OF DIRECTING THE V CUT HOLES.

dimension of the tunnel, (see figure 7). In stratified rock the most favorable position for cut holes is across the stratum or grain of the rock, because holes so drilled will break easier and cleaner than holes drilled parallel to the lay of the formation.

Subaqueous Tunneling - Subaqueous tunneling as the name implies deals with the construction of tunnels under water or through ground that is water bearing. In this type of work the majority of the laboring must be carried on under a higher air pressure than that of the normal atmospheric pressure, because of this peculiarity subaqueous tunneling is sometimes termed high-air tunneling.

The consistancy of the ground, through which the tunnel is being driven changes the operation materially. In soft clay, where water seepage is quite apparent, care must be taken as to the regulation of the tunnel pressure and the excavation of the clay. If the clay at the tunnel heading is not mucked to a flat surface, that is, if the pockets are formed, a blow or sudden release of air from the tunnel will follow. When a blow occurs men and machinery may be sucked up into the pocket, or incertain instances, carried to the surface of a river. Life holds no greater horror for the old fashioned tunnel driver than liquid or semi-liquid mud. This material is very heavy, that is, it brings enormous pressures on the tunnel lining and shield set up to support it and to prevent it from caving in, and on the other hand it is so fluid that it is able to seep into the slightest crack or crevice. The old fashioned tunnel driver indeed had a difficult problem but by packing sawdust, straw, hay, manure, and like material into the mud he was able to get along with a minimum of difficulties.

Today the highest rates of progress through soft clay and mud are made with the shield, but its peculiar characteristics must be understood in order to receive a definite idea of its operations. Figure 8 shows

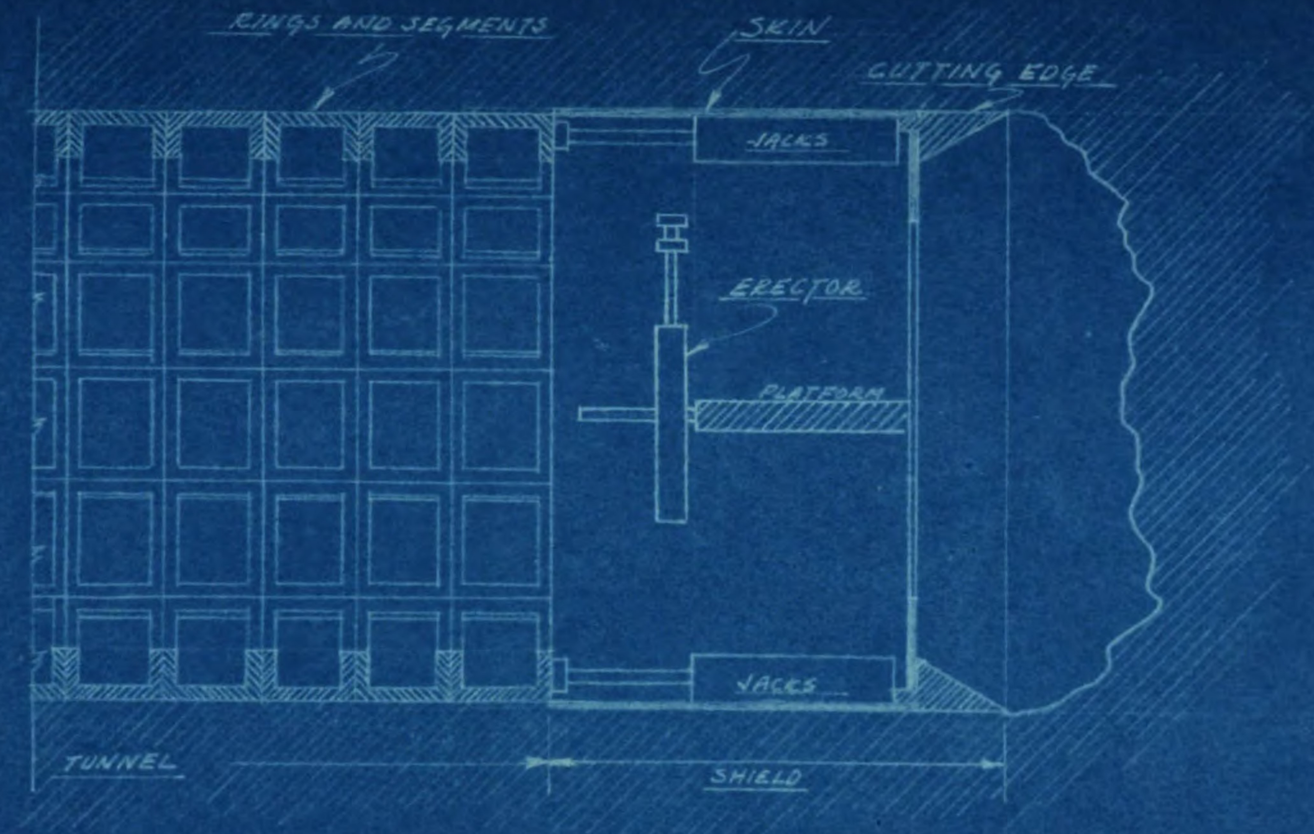


FIG. 8.— SHIELD IN SOFT CLAY

a sketch of a typical shield as it appears in operation in a tunnel through soft clay.

When the first modern tunnels were being projected, there was no thought of tunneling "shields" or similar devices in the minds of contractors or engineers. It was not until 1825 that tunneling with such tools came into the the minds of men prominent in the field. One of these men was Sir Marc Isambard Brunel, a civil engineer of the day who, in 1823, promoted a project to carry out tunneling with the aid of a protective device which became the predecessor of our modern tunneling shield. History cre its Brunel with having said that his conception of shield tunneling was suggest by observation of the marine tereds or shipworm, an insect that bores its way into wood piles or the hulls of wooden ships and lines its "excavation" with a tubular shell. His first conception of a tunneling shield was that of dividing the face of his excavation into smaller units so that the areas of exposed surfaces might be reduced and the danger of collapse thus lessened. In his patent, he showed a circular shield and stated his preference for cast iron to form the tunnel shell. At present as before, the shield is a cylindrical shaped mass of steel, weighing on the average "heavy" job approximately 500 tons. It is divided into halves by a horizontal platform and into smaller compartments by vertical members; here in these compartments the men work, extracting the muck from in front of the shield. The forward edges of the cylinder are tapered to form a cutting edge, this facilitates the rapidity of the progress of the tunnel.

As the shield progresses a lining is erected behind, by a mechanical contrivance called an erector. The erector consists essentially of an arm which swings on a horizontal shaft parallel to the longitudinal axis of the tunnel and which may be shortened or lengthened as desired.

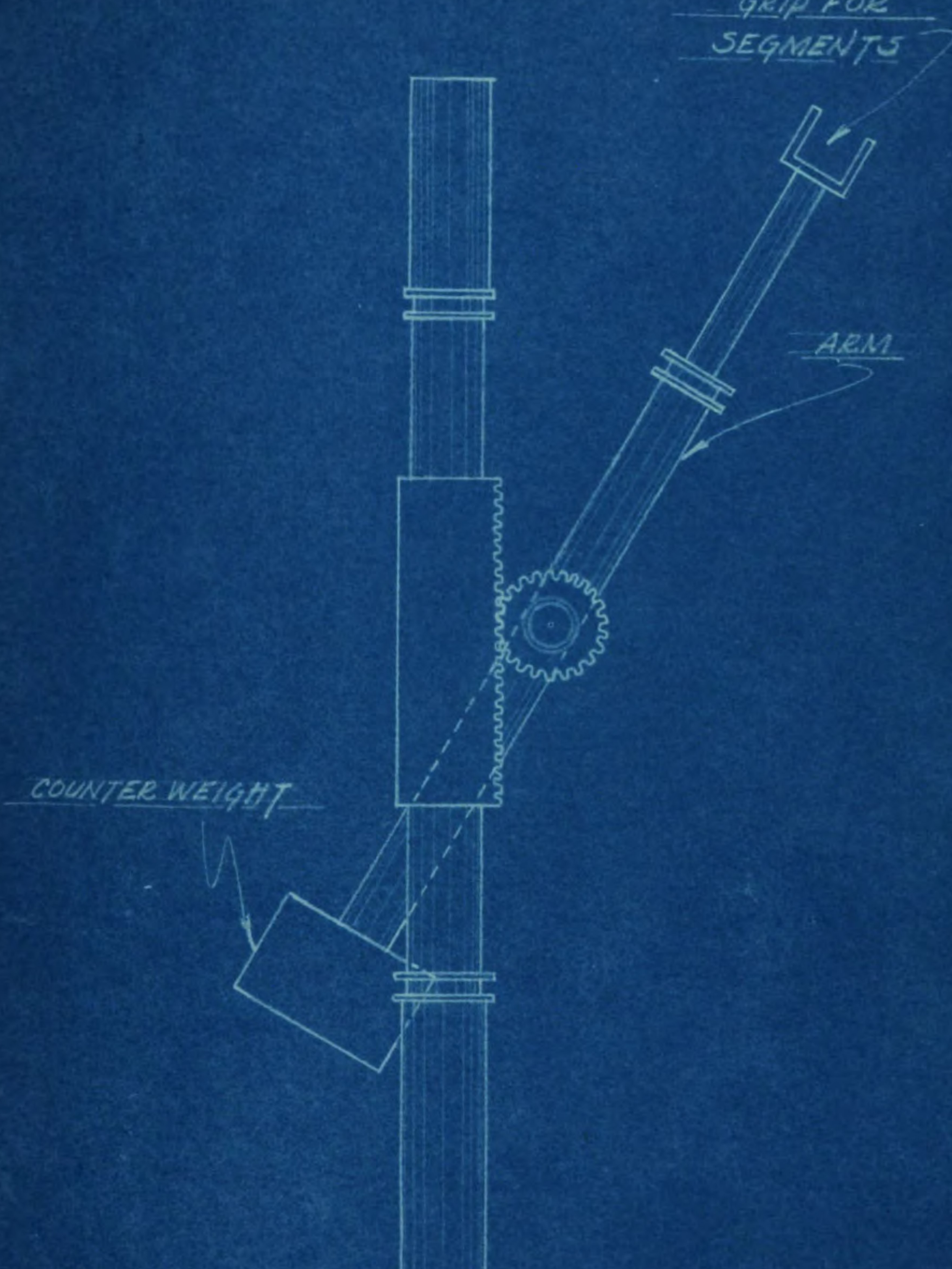
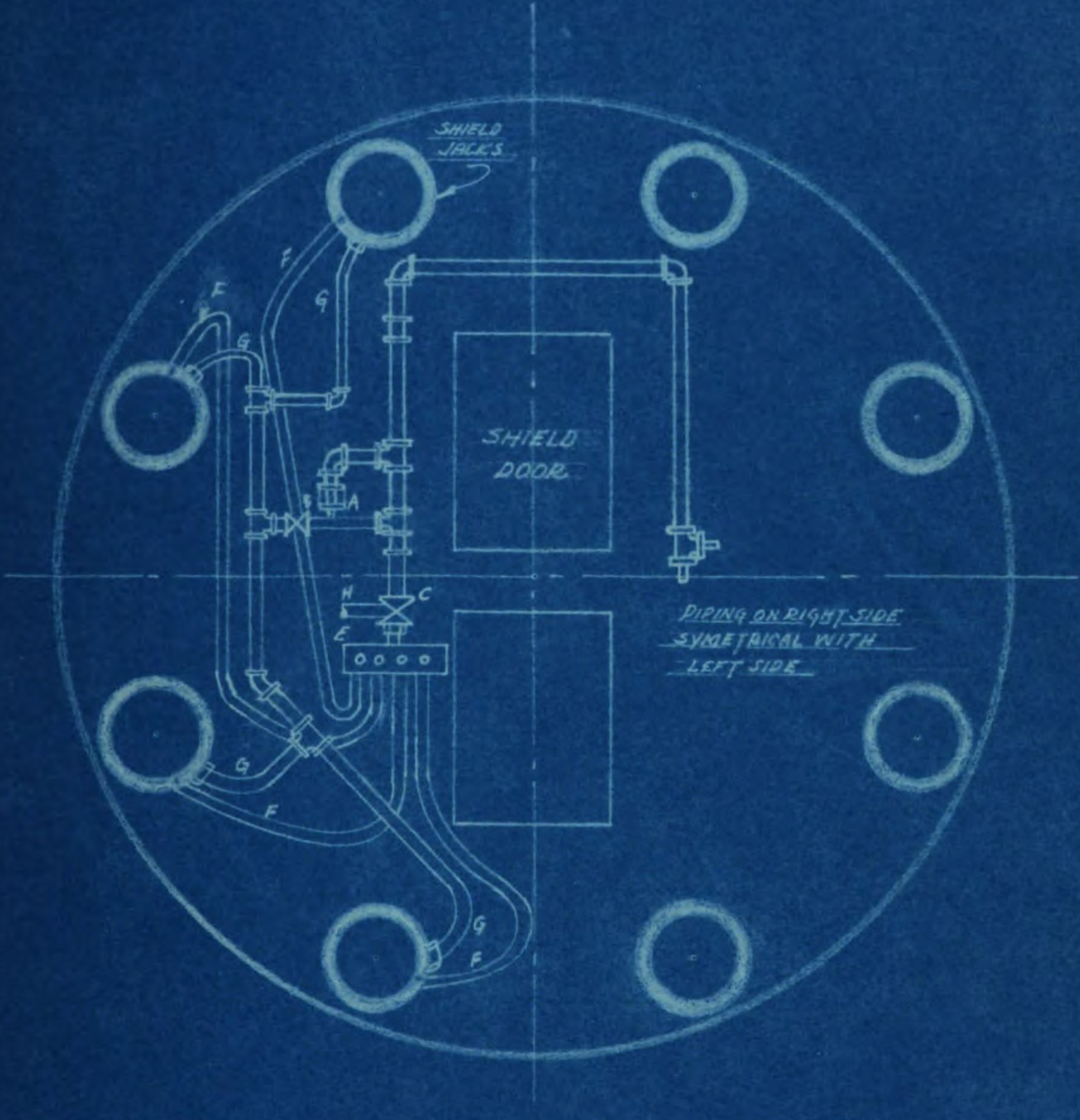


FIG. 9 - AN ERECTOR TURNED BY RACK AND PINION.

The erector may be carried on a separate stage behind the shield or may be mounted upon the shield. The principle advantage of the latter is that as the shield progresses the erector is moved with it into its proper position for erecting the lining, thus eliminating adjustments. The end of the erector (see figure 9) which carries the segments of the lining is furnished with a grip, bu means of which the segment is attached to the arm. The erector arm is that part of the erector which moves in a plane perpendicular to the axis of the shield and to which the segments of the lining is attached in erection. The arm should be placed so that the plane in which it turns is one-half of a ring width from the leading end of the last ring erected, when the shield has been moved forward a ring width. The erector arm consists of a double acting hydraulic jack and a stiff beam or frame. A counter weight is provided at the opposite end to the gripper, in order to decrease the turning moment.

The shield is motivated by a set of hydraulic jacks which are distributed uniformly around the circumference, their number corresponds with the diameter of the shield. Each jack is able to exert a pressure from 100 to 150 tons upon the completed sections of the tunnel. In order to move the shield forward resistances must be overcome to the friction of the ground on the exterior surface of the shield, the friction of the lining in the tail of the shield, and the friction of the ground in front of the shield which has not been removed by previous excavation. The hydraulic power furnished to the jacks is piped from the powerhouse to the shield through extra heavy lead pipe, designed to withstand a pressure of 8000 pounds per square inch to the shield valve control board. From the control board to the jacks, the power is carried in



A - MAIN INLET.
B - VALVE CONTROLLING PULL-BACKS.
C - VALVE CONTROLLING FORWARD PUSH OF JACKS.
D - VALVE CONTROLLING EXHAUST.
E - VALVE CONTROLLING INLET AND EXHAUST OF INDIVIDUAL JACKS.
F - PIPE CONNECTIONS TO JACKS.
G - PIPE CONNECTIONS TO PULL-BACKS.
H - EXHAUST PIPE WASTING INTO TUNNEL.

FIG. 10. - DIAGRAM OF HYDRAULIC PIPING & VALVES ON SHIELD.

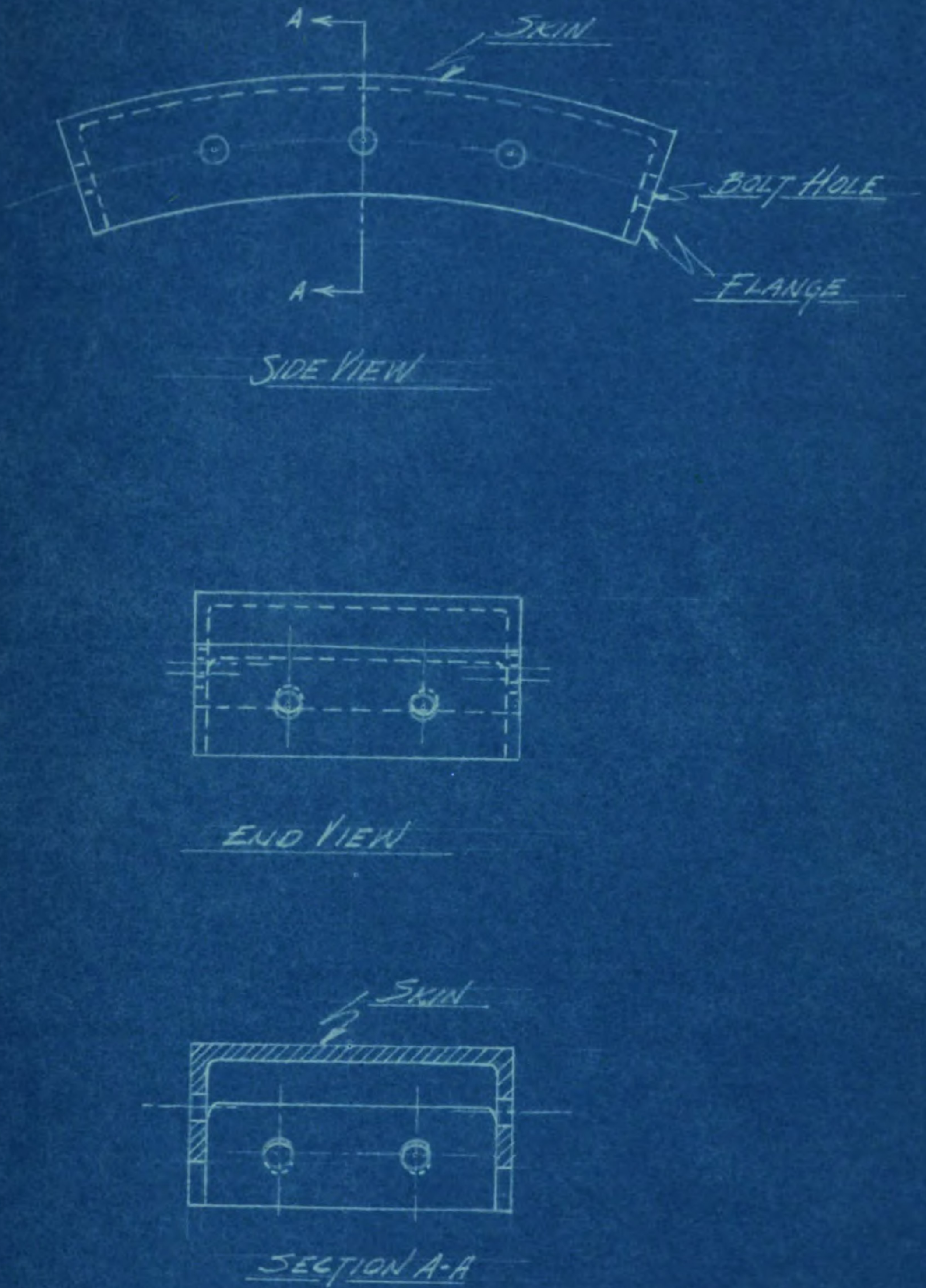


FIG. 11. - TYPICAL TUNNEL SEGMENT SKETCHS

heavy duty copper piping, figure 10. The controling valves are placed upon the shield so that they can be easily be maintained and manipulated by the shield driver who stands upon the shield platform.

The lining that is erected behind the driving shield is made up of a series of cast iron rings; each ring being divided into segments. The cast iron rings form what is known as the primary lining and is placed at the time of the initial erection. The secondary lining, constructed of reinforced steel concrete, is erected upon the completion of the primary line and when the tunnel is exposed to normal air pressures. A lining for a shield driven tunnel must be able to withstand certain forces which it might be subjected to, which are (a) the weight of the lining; (b) the earth pressure and (c) the thrust of the shield jacks; it must be permanent or in other words it must outlast the use of the structure. In the majority of tunnels the lining must be water tight. In those structures that are built under water that is subjected to tidal movement, the lining must be calculated for a pressure head of water at high tide; it also is subjected to seasonal changes that it, in a like manner, must be calculated for a pressure head to water at high level. Further, as the working in a tunnel is laborious, expensive, and dangerous, the primary lining must be brought into the tunnel in the finished condition to facilitate the speed of progress.

Figure 11 shows a typical cast iron segment. Each segment has a web or skin to conform to the curvature of the tunnel and is flanged on all four edges. When erected the skin forms an enveloping cylinder which is stiffened by the flanges. Through the flanges are drilled holes, the segments and rings are connected together by means of bolts. The number of segments per ring varies with the diameter of the tunnel, for an example a tunnel of 20 feet in diameter would be made up of

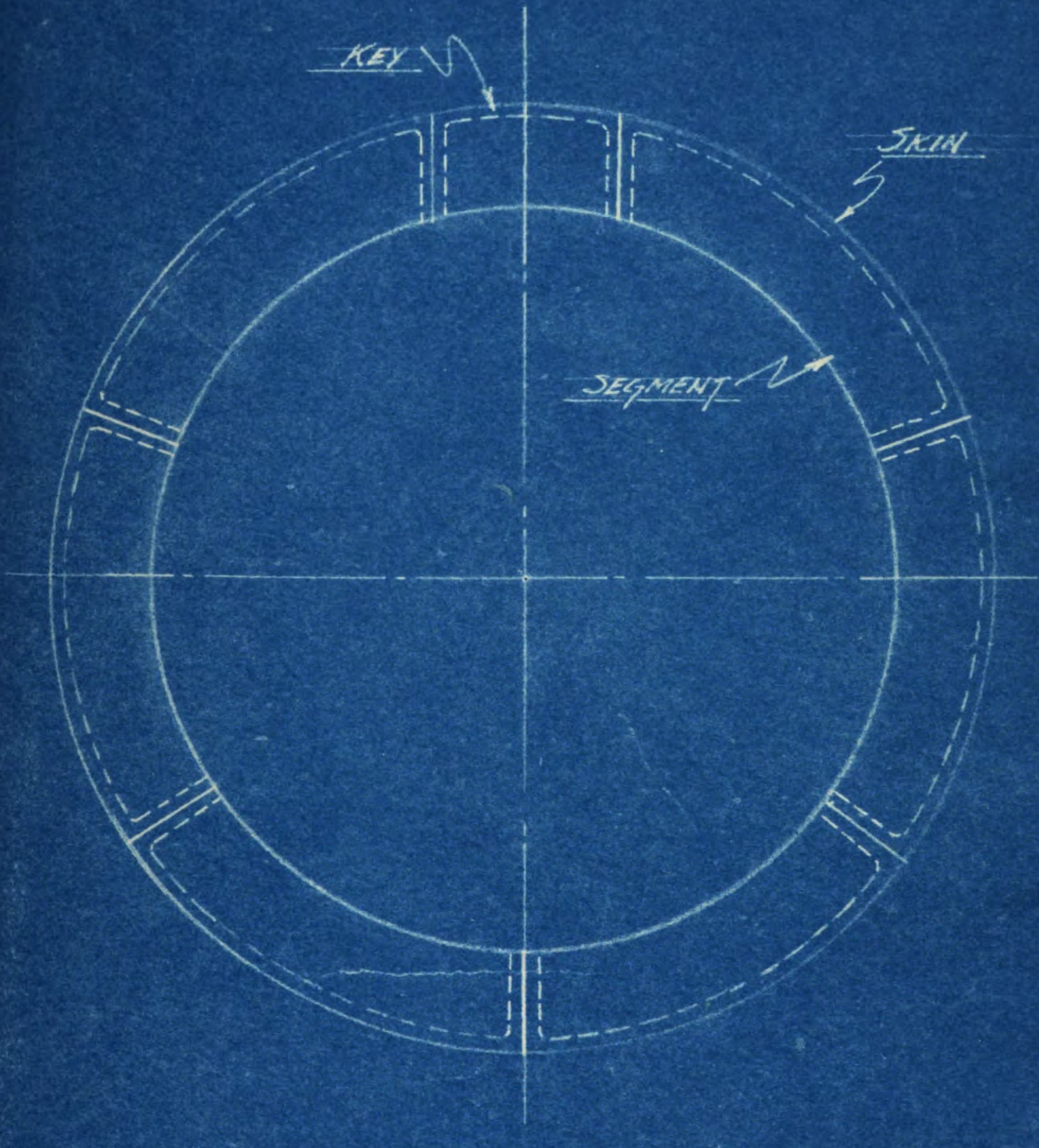


FIG. 12 – TYPICAL 6 SEGMENT AND KEY TUNNEL LINING RING

nine segments and a key (see figure 12), each ring would form a cylinder 20 feet in diameter and 2 feet long. The cross joints are radial except, because of erection conditions, at the key or last segment to be placed. When a ring of cast iron lining is being erected within the shield of a tunnel there is no space available in front of the ring. The erection space, therefore, is limited to the length of the ring proper and the segments must be moved radially into place. This condition necessitates that the space left for the insertion of the key must be at least as wide as at the outside of the lining. Where curvature in the tunnel lining is necessary tapered rings are furnished. The curvature may be necessitated by either, specification of tunnel, change in plans or faulty surveying technique. For long radius curves the difference between the longest and shortest width of the ring must not exceed one inch. Three types of tapers are needed, one for horizontal deviation, one for vertical elevation and one for vertical depression. In each taper ring every segment is special and must be marked. The joints between segment must be chalked with some water proofing material to secure water tightness.

Tapped holes are provided in each segment of the tunnel lining. After each shove of the shield gravel and grout are forced through these holes into the back side of the ring, this fills in any cracks or cavities that might exist behind the rings and keeps the tunnel from settling. Upon the competion of the grouting a water tight plug is screwed into each hole.

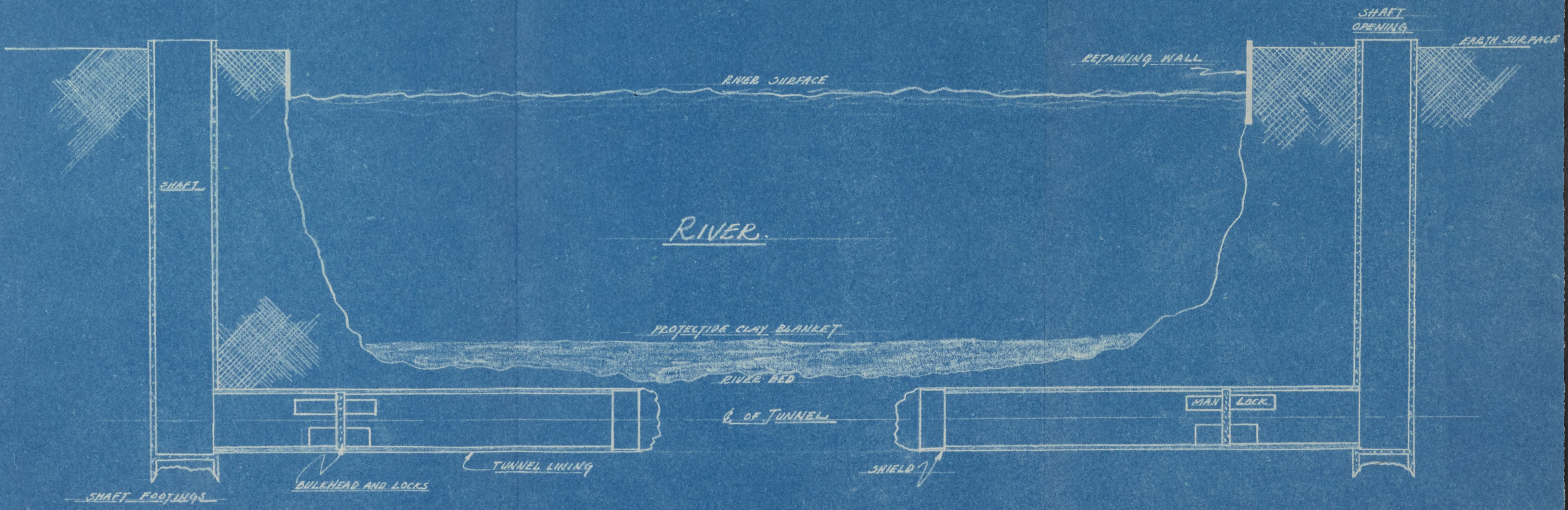
The excavation of the muck from the tunnel in soft clay of course is no difficult problem. Modern mechanical methods have greatly reduced the time of loading and unloading the cars that carry the muck away from the tunnel heading. Where the muck is of such a consistency that it cannot be handled with a shovel, it may be pumped directly from the heading to the surface. In a great number of cases it has been found that the tunnel shield could be moved ahead with all the doors closed or by having the compartments boarded up in such a manner that no muck whatsoever entered the tunnel. This is known as shoving blind.

Tunnel driving thru hard clay with a shield does not differ materially from driving in soft clay. The density compactness, and uniformity of hard clay aids the progress of the tunnel greatly. Hard clay is impervious to water and many tunnels are driven through it without the use of compressed air; this method may prove dangerous in cases where the exact composition of the ground that is ahead is not known. Certain hard clay formations support sockets of quicksand and underground rivers, so, it is best to use light air pressures rather than to run the risk of flooding the tunnel. The muck is usually excavated by allowing it to ooze through the open compartments of the shield and the men cutting off slabs with draw knives. The necessity of the shield in hard clay is sometimes questioned, but is found advantageous to use one due to the fact that the clay swells up on its exposure to air. This makes possible a procedure with large and length exposure of the ground.

In many cases it is necessary to take the shield through solid rock before excavation in clay can be made possible. In rock the shield makes a poor showing, and the shield is exposed to damage upon the collision with it. Further more the rock must be excavated by blasting and flying fragments also damage the shield structure. As much as possible the rock should be completely removed before the shield comes to it. A cradle or skids should be made to allow the shield to slide upon it, in a manner, that the tunnel will keep the required alignment.

The drilling and shooting should be done with as small charges as possible to reduce the violence of flying particals. Other than having the shield present, work is carried on in the same manner as in open air rock tunneling.

Floating tunnels or trench tunnels are the most modern methods of tunnel driving. In this type of work large sections of the tunnel are preconstructed on shore or in dry docks and floated out into the river and sunk to their prearranged positions. It is a similar operation to the laying of iron pipe in river beds. Dure to the fact that the information concerning this type of construction is limited the author will not be able to enlighten the subject in any further detail.



LAYOUT OF TUNNEL ADVANCING FROM BOTH SIDE UNDER RIVER

B. FACTORS GOVERNING TUNNEL CONSTRUCTION

The process of driving a tunnel must be done with the least possible danger to the tunnel itself and to nearby structures and in such a way that the greatest possible speed of advance is attained. The first objects to consider are a suitable design, an efficient working force and an adequate, suitable power plant and accessories. To obtain the second important factor under consideration the face of the excavation must be under complete control at all times. Difficulties will be met in the course of driving. It is essential that the engineer should be able to forestall these difficulties, recognize them when he sees them and know how to overcome them. The engineer's first job upon biding for a contract for tunneling should be to check all previous drawings of the locality to be tunneled through, for piles, pipes or any other such objects that might hinder progress or call for extra work upon the part of the contractor. Secondly borings should be made of the ground that is to be tunneled, keeping a careful watch for underground rivers, quicksand and change of texture of the soil. Of course the contractors first obligation upon starting operations is to install suitable offices, a work house or hog-house, shops, and a power plant to comply with his needs. These projects shall be taken up in the latter part of the paper.

<u>Design</u>: The type of tunnel to be used in any particular case is governed by the varying characteristics of the ground through which it must be driven. It is therefore necessary that the characteristics of the ground be known before design operations are begun. The factors may be obtained from various geological maps, ground inspections, borings and drawings of piles and footings of structures in the immediate vicinity of the tunnel operation.

Usually on city projects the city engineer is able to furnish harbor pile drawings, dredging specifications, and foundation and footing drawings of public buildings. This information plus geological surveys and borings are usually sufficient information for the contractor to conceive a relatively reliable bid. Borings should be made, not only close to the proposed centerline, but also several hundred feet on either side of this line. When the local conditions permit such borings may bring forth a better location for driving the tunnel. In waterbearing ground the borings should not be made too close to the immediate proposed location of the tunnel, for such holes may facilitate blows from the tunnel upon its construction through such ground.

If possible, a tunnel shoud be void of curves or rather unnecessary curves since they lead to undue increase in the cost of construction. If curves are unavoidable they shoud be driven at the largest possible radius as the existing ground formation and substructure will permit. The maximum gradient of the tunnel is fixed by the use of the tunnel upon completion. In railroad tunnels, where electric locomotives are used, a 2 percent gradient is permissable. While on those tunnels where railroad and motor driven vehicles form a multiple system the maximum gradient permitted is 4.5 per cent. In highway tunnels the maximum gradient is the same as that fixed for bridges and public highways. The minimum gradient, as indicated by experience, is fixed between 0.25 per cent and 0.5 per cent to allow for proper drainage. In no part of the tunnel should there exist a level gradient. At the intersection of gradients, when considering drainage at both ends of the tunnel, vertical curves should be introduced. These gradients must not be overlooked when considering the preliminary layout of the tunnel as they greatly effect the length of the tunnel, and thus introduce added expenses to the contractor.

All tunnels must be driven from some predetermined point. In the cases of tunnels to be driven through mountains or hills the problem of selecting these points is quite obvious and simple. The problem becomes more involved in the case of tunnels under water-ways. Shafts must be sunk for a point for the shield to start from. The shafts should be situated such that their openings on the surface are located in a convenient manner to

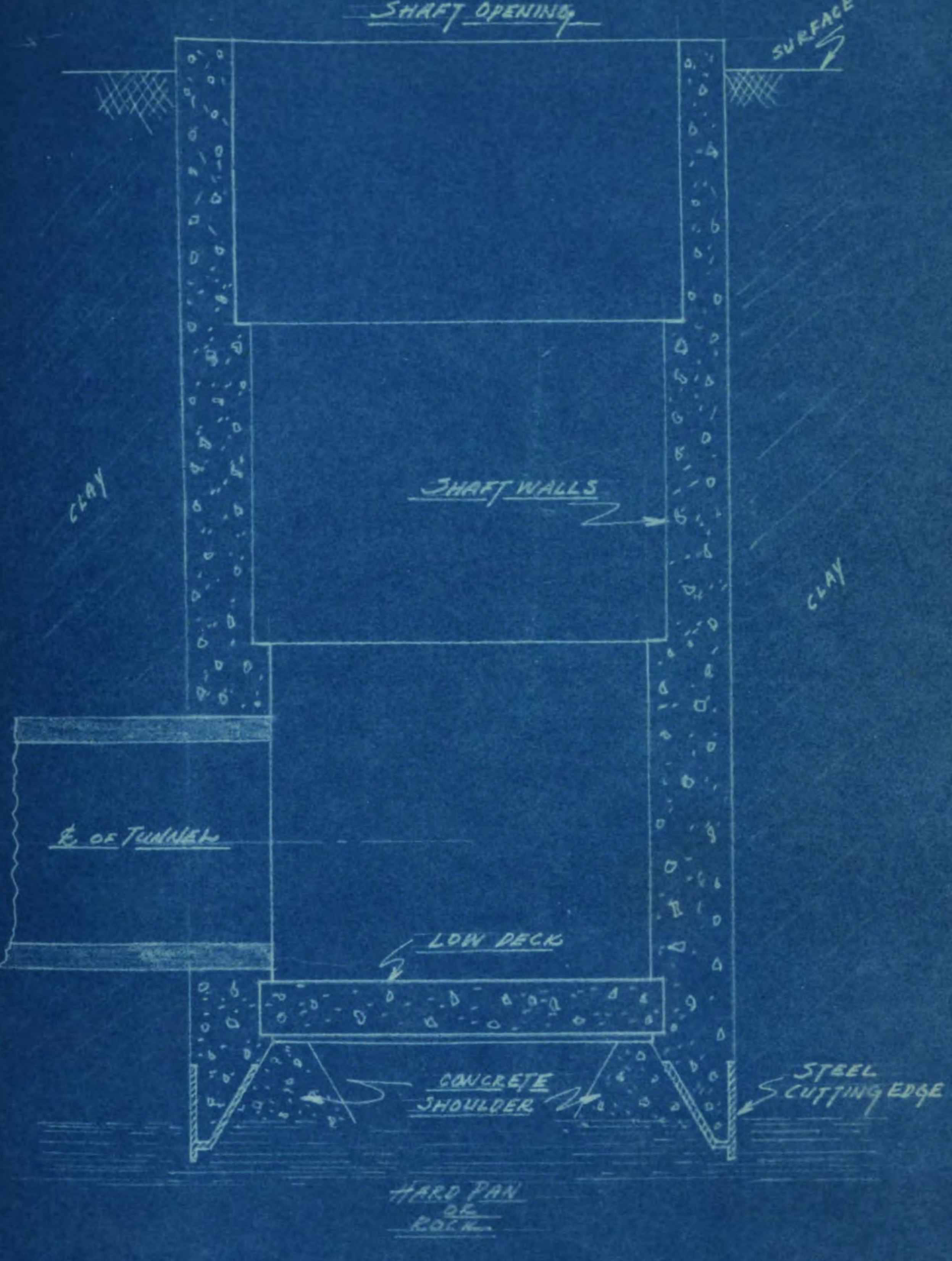


FIG. 13 – CAISSON IN CLAY

facilitate unloading and receiving of materials. Close proximity to water-ways or railroads or both is desirable. In soft clay or waterbearing ground the shaft will be a caisson sunk under pressure and kept under pressure until the shield has advanced sufficient to permit the erection of a bulk head in the tunnel. Figure 13, shows a typical caisson for soft clay. In rock or stiff clay a unsupported shaft may be used and lined in a similar manner as the tunnel. The shafts are often filled in, but in the majority of constructions they form the ventilation shafts or entrances.

To return to the major problem at hand, design, let us first consider the lining. As stated beforehand the choice of the lining depends upon (a) the purpose of the tunnel; (b) the size of the tunnel; (c) the character of the ground; (d) the economy of construction. Owing to the magnitude of uncertainty of the pressure that the external earth shall force upon the tunnel, tunnel linings are rarely determined by rational methods; experience and judgement form the bulk of material to determine the design, rather than, figures and computations. Many tunnels linings are proportioned in accordance with those already built, consideration being given to changes in size of the tunnel and in the character of the ground through which the tunnel is to be driven. This method of determining the dimensions of the lining is safe, but not necessarily economical, as long as the lining to be designed is of a size within the limits of those already built and when the ground in which it is to be used is similar to that in which such tennels have been driven previously. If, however, the tunnel is larger or the ground different, the proper dimensioning becomes most uncertain. On the following pages shall be given a prescribed method of determining the stresses in a tunnel lining. The method is rather lengthy and involved, so the author has left certain assumptions to be visualized by the reader. It involves the determination first, of the external forces; and second, of the stresses produced in the tunnel lining by these forces. Where the uncertainties of the earth pressures have not permitted a definite value to be assigned, limiting values of the pressures will be used. The tunnel lining will be treated as a statically indeterminate structure and the stresses will be determined accordingly. With the stresses determined, the proportioning of the tunnel dimensions follows.

In a tunnel the lining supports the external forces, while the weight of the lining itself is the dead load. The live load is partly inside and partly outside of the lining. The inside live load is the traffic to be handeled by the tunnel; it generally has little effect upon the design of the lining. The outside live load is the pressure that is exerted by the ground surrounding the tunnel, acting on every part of the external surface of the tunnel lining. If the earths pressure were known the stresses on the lining might readily be computed. There are certain uncertainties and differences of opinion that make impossible to assign definite values to these stresses.

The external forces in action upon the lining are: (See Fig. 14.)

(1.) The weight of the lining of the upper half of the tunnel, marked (1).

(2.) The weight of the earth within the area marked (2).

(3.) An upward force, marked (3), balancing (1) and (2) and distributed uniformly over the horizontal diameter.

(4). The weight of the loading above the top of the tunnel, marked (4).

(5.) An upward reaction, marked (5), balancing (4) and distributed uniformily over the horizontal diameter.

(6.) The horizontal pressure due to the water above the top of the tunnel, marked (6). This pressure is uniform from top to bottom and its intensity is equal to the weight of the water above the top of the tunnel.

(7.) The horizontal pressure due to the weight of water from top to bottom of the tunnel, marked (7). The intensity of this pressure at any point is equal to the weight of the water above this point measured vertically to the top of the tunnel.

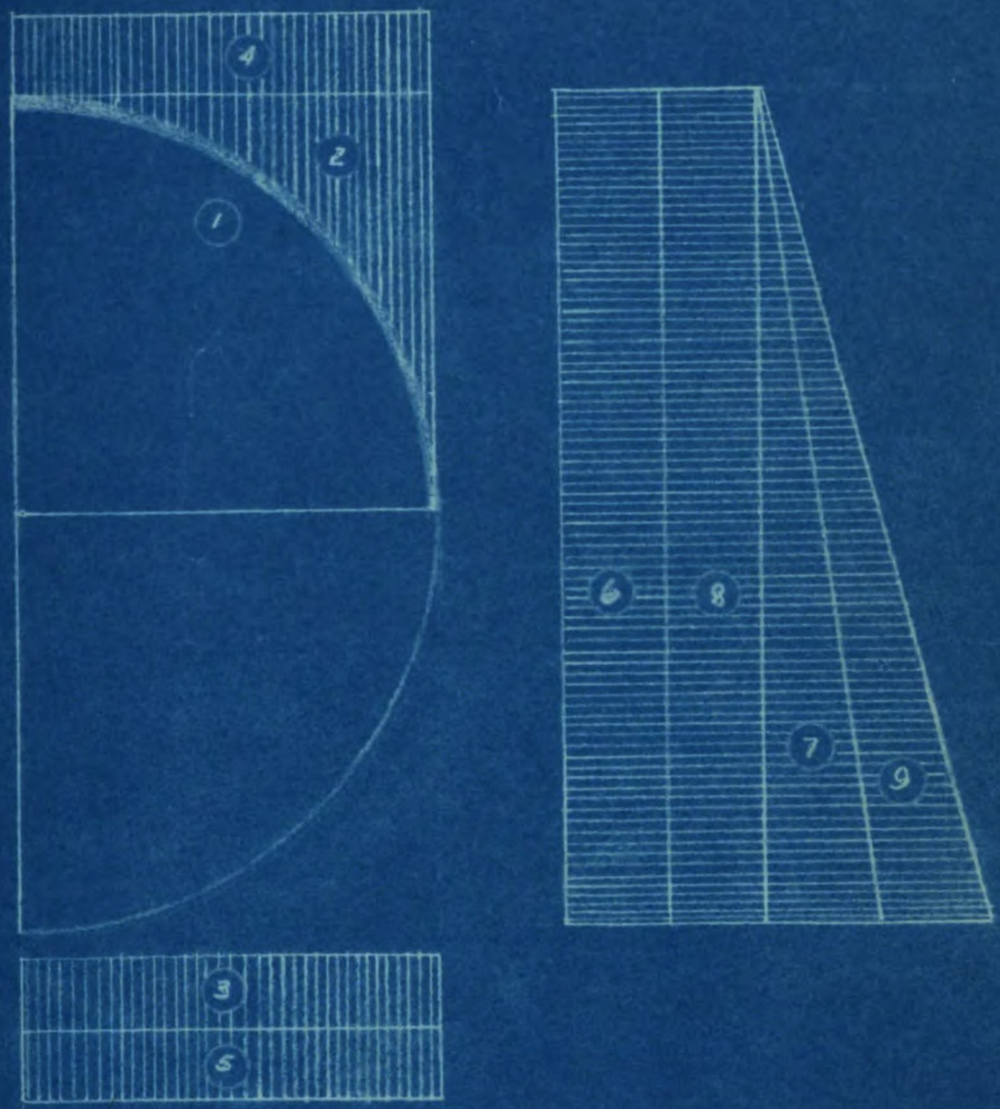


FIG. 14.

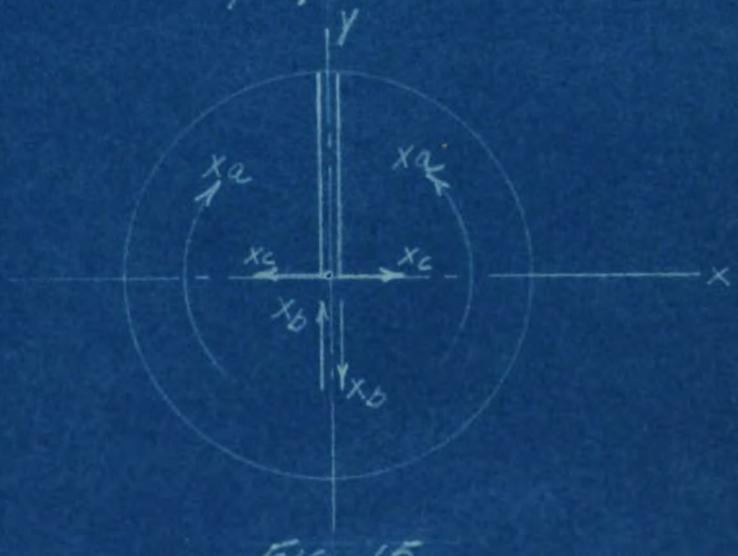


FIG. 15.

(8.) The horizontal pressure due to the earth above the top of the tunnel, marked (8). This pressure is uniform from top to bottom and its intensity is equal to the weight of the earth (if in water as weighed in water) above the top of the tunnel, multipled by a factor t which is greater than c and less than 1/c. "c" is a constant that varies with the consistancy of the ground.

(9.) The horizontal pressure due to the earth between the top and the bottom of the tunnel, marked (9). The intensity of this pressure at any point is equal to the weight of the earth (if in water as weighed in water) above this point measured vertically to the top of the tunnel, multiplied by the same factor "k".

To derive the necessary equations of moments and thrusts, introduce an elliptical ring with uniform cross-section, Figure 15, and select the system of coordinates as shown. Cut the ring at the top and introduce the unknown moments and forces x_a, x_b and x_c as shown, required to establish the conditions existing prior to the cut. In the cut ring let M_o represent the moment for the external loading and M_a, M_b, and M_c the moments for the loadings $x_a = -1$, $x_b = -1$ and $x_c = -1$, respectively, then the three unknowns may be determined by

$$0 = \int M_oM_a ds - x_a\int M_a^2 ds - x_b\int M_aM_b ds - x_c\int M_aM_c ds.$$

$$0 = \int M_oM_b ds - x_a\int M_aM_b ds - x_b\int M_b^2 ds - x_c\int M_bM_c ds.$$

$$0 = \int M_o M_c ds - x_a \int M_a M_c ds - x_b \int M_b M_c ds - x_c \int M_c{}^2 ds.$$

On account of the symmetry

$$\int M_a M_b ds = 0$$

$$\int M_a M_c ds = 0$$

$$\int M_b M_c ds = 0$$

$$\int M_o M_b ds = 0$$

so that the equation first given may be written

$$0 = \int M_o M_a ds - x \int M_a{}^2 ds$$

$$0 = -x \int M_b{}^2 ds$$

$$0 = \int M_o M_c ds - x_c \int M_c{}^2 ds$$

or

$$x_a = \frac{\int M_o M_a ds}{\int M_a{}^2 ds}$$

$$x_b = 0 \qquad (1)$$

$$x_c = \frac{\int M_o M_c ds}{\int M_c{}^2 ds}$$

The moments at any given point in the uncut ring may be expressed by

(2) $M = M_o - x_a - x_b x - x_c y$, and the thrust by

(3) $N = N_o + x_b \sin\vartheta - x_c \sin\vartheta$

where N_o represents the thrust in the cut ring.

Applying equations (1), the equations (2) and (3) will read

(4) $M = M_o - \frac{\int M_o M_a ds}{\int M_a{}^2 ds} - y \frac{\int M_o M_c ds}{\int M_c{}^2 ds}$.

(5) $N = N_o - \frac{\int M_o M_c ds}{\int M_c{}^2 ds} \cos\vartheta$.

For any given point $M_a = 1$ and $M_c = y$;

Therefore by inserting these values in (4) and (5), these equation will read:

$$(6)\quad M = M_0 - \frac{\int M_0\,ds}{\int ds} - y\,\frac{\int M_0 y\,ds}{\int y^2\,ds}.$$

$$(7)\quad N = N_0 - \frac{\int M_0 y\,ds}{\int M{2_c}^2\,ds}\cos\vartheta$$

in which $\int ds = s$ represents the length of the circumference of the ellipse. These formulas require an expert knowledge of intergration and the theory of moments and thrusts, but can be worked out if sufficient information pertaining to the various load factor and constants are available. Such factors and constants are readily found in handbooks and texts pertaining to the subject. To thoroughly enlighten one upon the intergration and direct derivation of these formulae, the author would have to spend hundreds of pages, and upon completion it is with little doubt that he feels the reader would not be justifiably rewarded for his troulbes. The formulae were merely introduced to give the reader an idea of the difficult problems that confront the designer.

Upon completion of the calculation of the moments and thrusts in the lining the stresses may be determined by

$$(8)\quad s = N/A \pm M/S$$

where

s = unit stress in pounds per sq. in.

N = thrust in pounds per linear foot of tunnel.

A = cross-section area of the wall of the lining, in square inches per linear foot of tunnel.

M = moment in inch-pounds per linear foot of tunnel.

S = section modulus of the wall of the lining in inches cubed per linear foot of tunnel.

The moment is taken as positive when producing tension at the inside of the lining; direct tension stress is positive and compression negative.

The formulae given thus far have dealt with the stresses in the lining. As stated in previous chapters the cast iron segments and rings make up the primary lining which must support the loads and pressures exerted upon the tunnel. The thickness of the skin of the segments is determined by the stresses parallel to the longitudinal axis of the tunnel, produced by the pressures of the earth and by the thrust of the shield jack. The earth's pressures produce a bending stress and the shield jacks a compressive stress. The thickness of the skin, therefore, must be so that the tensile stresses from the bending alone and the compressive stresses from the combined forces are both within safe limits. The thrust from the shield jacks may be assumed to be distributed uniformily over the circumference of the skin. The minimum shin thickness may be determined by

(9) $R/t + pl^2/2t^2 - 14{,}000$ #/□"

(10) $pl^2/2t^2 = 5{,}000$#/□".

where

R = thrust in pounds per linear inch of circumference.

t = thickness of skin in inches.

l = unsupported length of skin between the circumferential flanges in inches.

p = earth pressure in pounds per sq. in.

The safe compressive stress = 14000#/□".

The safe tensile stress = 5000 "/□".

As the reader has observed the engineer's most important problem is the calculation of the size of the tunnel and its members. He meets numerous pitfalls and undeterminable factors in the course of his computations. The engineer must be experienced and intelligent enough to blend his conclusions with those of past eonstructions to form a satisfactory collection of data, before starting his own operations.

While in general the design of the shield for subaqueous tunneling is somewhat the same for whatever size of the tunnel or nature of the ground, these factors effect the internal design of the structure. In all cases this includes an annular structure stiffening the skin and extending from the cutting edge to the tail. If the shield is small and the ground good, this may form the whole internal structure, or it may have a diaphragm immediately behing the cutting edge with an opening affording access to the face. If the diameter is greater than 13 feet there is room to introduce horizontal and vertical bracings, or both, and still retain openings large enough for convenient access to the face. Such bracings add greatly to the strength of the shield, divides it into convenient working chambers and affords means for attaching the various appliances with which such shields are furnished.

The diameter of the skin of the shield is determined by the diameter of the tunnel lining, which is erected within the cover of the tail. A certain clearance is necessary between outside of the tunnel and the inside of the tail of the shield, partly to facilitate erection and partly to allow for movement of the axis of the shield from that of the tunnel lining. Usually the skin is made of one or more thicknesses of steel plate of a single width from front to rear and in as many pieces circumferentially as the size of the shield requires. The skin should be thick enough to support the earth pressures without sensible deformation at the tail where it has no internal support. The plates may be welded or riveted together at their joints. It is expected that in the future welded shields shall replace the riveted shield because it gives greater strength, less work of erection and lessened cost.

By cutting edge we mean the annular structure of the shield at its extreme front. As its name implies it is the tool that is subjected to severe head-on contacts with the clay and obstacles as may be in the way of the shield, it must be so constructed as to receive these shocks with a minimum of damage. The cutting edge merely consists of the skin plate reinforced about 12 inches from the front edge by inclined plates.

Excavation: In clay tunneling the principle tool of excavation is the shield. As related in the previous chapters, it receives its motivating power from the shield jacks. As excavation is the first essential operation of construction, the shield must be so designed that the work can be carried on at the highest possible rate of advance. As the shield advances the muck oozes forth through the shield doors as tooth-paste does from its container. Large slabs of the clay are cut off by knifes and spades and loaded into a conveyor or directly into small cars. Throughout the tunnel there must be furnished a system of track on which the cars can be pushed by hand or drawn by small locomotives. Where the clay is extremely tough and hard pneumatic spades are used to excavate the heading.

In rock tunneling the problem of excavation is entirely different. The rock must be first blasted free of the facing before the true excavation can be started. The drilling of the block holes for the blasting requires the use of such tools as drills, drifter drill hammers, and drill mountings. In large tunnels, to facilitate block-holing, a movable heading with drills mounted upon it is used. In many tunnels the movable platform is fitted with chutes so that the top cuts can be loaded by gravity into cars. The platform is mounted on wheels moved along a track by a locomotive or by hand. It is equipped with a large number of heavy springs that act as shock absorbers.

The upkeep of the cost of drill may be greatly reduced by the introduction of a drill carriage. Water for drills is accumulated in a pit and tranferred to a tank from which it is forced to the points used by air pump.

The loading of the excavated rock from the bottom of the heading is done by scrapers. The scrapers are dragged by means of tug hoists. Where the tunnel is large enough to occupy a power shovel, such machines are used in excavation.

<u>Blanketing:</u> A blow occurs, or is apt to occur, when the air pressure in the tunnel is greater than the pressure of whatever cover, earth or earth and water, there may be lying over the roof of the tunnel, the denser the ground the less danger of a blow. In order to have this denser ground over the top of the tunnel a blanket of clay may be placed in the route of the tunnel. The clay is deposited from barges before the shield moves along. The clay must be suitable for the purpose. It must be able to pack densely and must not be washed away by the current of the water, and it must stand up well against the air when it is trying to escape. The The thickness of the blanket should be as great as possible. When the work is being done in navigable waterways the permissable depth of the blanket may be regulated by public authorities. In open ground the engineer should strive for at least a ten foot blanket and more if he can get it. Even if the blanket must be dredged up after its use this is cheaper than fighting blows. In certain cases a permanent blanket may be laid.

Survey: The work of the surveyor in tunnel construction has peculiar importance as compared with that in many other lines of construction. The reason for this is that it is not possible to judge the correctness of the work simply by eye as is possible with work on the surface. The surveyor's work may be prescribed under the following headings:

(1.) The preliminary survey.

(2.) The subsurface exploration.

(3.) The precise surface survey.

(4.) The transfer of the working line and level from the surface to the tunnel.

(5.) The carrying forward of the line and level in the tunnel.

(6.) The checking of the true position of the shield and the tunnel with respect to line and level.

In the preliminary survey for well settled districts or large towns accurate official maps are at hand. Check measurements may be made on the ground to make sure that no serious mistakes exist. This proved, the line of the proposed tunnel is laid down on the map and a profile drawn from the elevations on the map. This will give a fairly correct ground work for a preliminary estimate of of the quantities for work involved and the consequent probable cost. This outline sketch will enable the engineer to decide where to place the borings he must make for the exploration of the sub-surface conditions. Where no survey maps exist, a preliminary survey of the terrain must be made. Ordinary survey methods will be used and that most suitable for the country and the men available will be chosen. What will be sought at this stage is not high accuracy but rather a rapid taking of the topography on which to base the outline of the project and means of placing the borings, test pits and other exploration work.

The need of thorough exploration of the ground through which the tunnel is being bored cannot be overstressed. The tunnel must be built far out of sight, buried deep down in the earth. In order to escape avoidable difficulties and dangers and to afford a basis for rational design of the structure a complete sub-surface exploration must be made. This brings us to the second phase of the prescribed work of the surveyor and engineer.

The sub-surface exploration will be made largely by borings. This subject has been touched upon throughout the preceding part of the thesis but further consideration is necessary at this point. The first problem will consist of deciding how many borings to put down, where to put them and what type they are to be. These questions depend upon the general geological features of the territory and on the knowledge and features which are available. The retention of the geologist best qualified by his local knowledge to act as adviser to the engineer is often an investment that will pay heavy dividends in the avoidance of tro ble.

Using the preliminary survey as a basis, the engineer will draw up a general scheme for the borings. These will lie along the route or that route tentively choosen for the tunnel. The depth of the borings should extend to the lower most point of the tunnel. If the earth's formations are to be considered uniform throughout the tunnels length, two to three borings may be sufficient per mile. If the formations are complex; that is if varying formations are present, changes of elevation, or faulted formations, then enough borings should be made to give the engineer a picture of the ground to be driven in. Under such conditions the geologist's opinion should be asked.

The borings may be made by the engineer himself or the work may be let to a reliable drilling contractor. Where the drillings are contracted, a skilled inspector should be present at all times to verify the depths made, to collect and store the samples and to keep a log on the positions of the holes as to elevation and plan. When rock is met in the process of drilling the diamond or shot drill shoud be used. For tunnels crossing waterways some of the borings can be made from floated scows. In waterways crowded with ships and with a strong current this process is hazardous and tedious. Underwater borings are made by driving or washing down a casing pipe of a diameter of 6 to 10 inches. When a hard substance is reached the foot of the casing is landed as firmly as possible and the core boring is carried on within its protection.

When all the borings are made a geological profile is drawn whowing the different materials penetrated by the drill. On this profile the tentative profile of the tunnel is laid out. The tunnel position is selected through ground that is most apt to give a minimum of trouble.

For tunnels across a body of water a series of soundings at 25-foot intervals should be taken covering a strip from 500 to 1000 feet wide on either side of the proposed tunnel. This will determine the depth of cover over thestructure and enable future soundings to detect any lowering of the river bed due to blows or dredging, any raising due to shoving the shield blind or any other deformation formed during construction. Ordinary sounding methods will be used. No description of these will be attempted here.

The object of the precise survey is to provide the basis for the final design of the tunnel in respect to its line and gradients and to afford a means of driving it in the prescribed manner with shield driven tunnels. These will be two main kinds of survey presented: (a) where the streets of a town have to be followed and (b) where a body of water has to be crossed.

In tunnels following the streets of a town the system introduced is to use a published map of the streets on as large a scale as available and on this map to lay out a series of traverse lines following the general course of the tunnel. The intersections of the traverse lines are scaled from the map, taking distances from street corners or other objects which can be located on the ground. A party then goes out with these notes and establishes the intersection points on the ground. A monument is established at each intersection and a traverse run from point to point, measuring the length of each line and the angle at the intersection. The topography is taken at the same time by offsets or triangles from the traverse lines to the building lines, curb lines and other fixed objects on the street.

The traverse lines may or may not follow the center line of the tunnel. If they do not the intersecting points of the tunnel center line are computed from the traverse lines. When this has been done the intersection points of the tunnel center line should be laid out on the ground and the distance between them taped and the angles of intersection read as a check of the computations. With tunnels following streets the shafts will not be much farther apart than one half a mile. All lines should be taped both forward and backward and repeated if a discrepancy of over 0.01 feet is found. Corrections for temperature and slope and for error of tape should be applied. Angles should be read by a series of successive additions followed by reversals, with at least two independent observers.

The leveling work is simple and consists in running from the nearest established bench mark to the line of the work and taking an elevation at each tape end position. The established bench mark should be checked also from other established bench marks, as in some cases a displacement might have occurred. In crowded streets, it will be found convienient to do most of the work at night or early in the morning before traffic gets heavy.

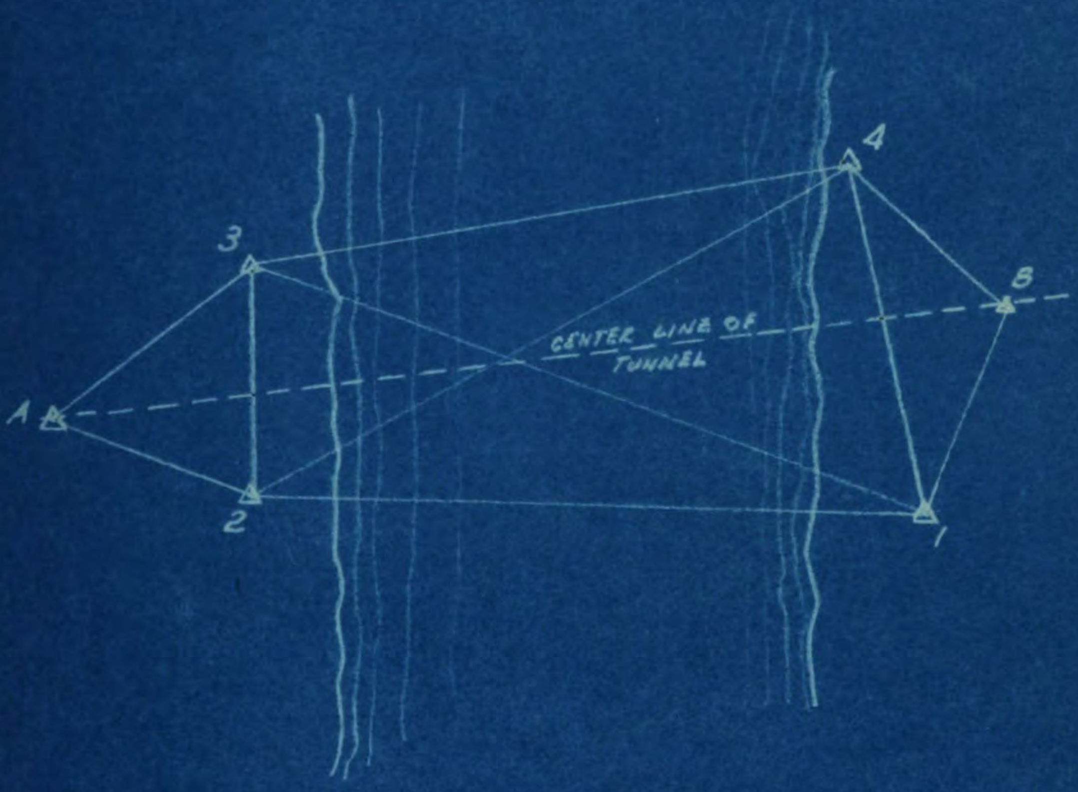


FIG. 16 - DIAGRAM OF TRIANGULATION TO ESTABLISH THE CENTER LINE OF A TUNNEL CROSSING A WATERWAY.

when the tunnel line crosses a waterway, the neccessity arises for a triangulation. In Figure 16, the line A-B represents the center line of a tunnel which has to be driven across a waterway. It is not possible, of course, to measure directly across a waterway of any great width and, therefore, a measured base line has to be laid out on each shore as at 1-4 and 2-3. The terminal points of these base lines being visible. The contained angles of the quadrilateral 1-2-3-4 can be read and consequently the lengths 1-2 and 3-4 can be computed. This network forms the basis of a complete topographical survey across the waterway. The center line of the tunnel, being marked on the ground on both sides, can be tied into the base lines, and a supplementary triangulation will give the length between A & B and the direction of the line A-B with reference to the lines 1-4 and 2-3. The case presented is the simplest possible and supposes that all the points marked are mutually visible and can be reached by direct lines on the ground. Such conditions seldom will be found.

Much ingenuity often has to be exercised in the choice of the base line terminals so that the other observation points are visible from them. Sometimes the terminal points are placed on observation towers so that they can be seen from the other base points. The tower is constructed so that the observer and instrument are on seperately supported towers. The structure that supports the instrument must be rigid so that it will be free to vibratory motion.

Several general principles in measuring the angles must be observed. These may be summarized as:

A. Use several independent observers.

B. Use a system of successive additions and subtractions of angular measurements and thus minimize inaccuracy of graduation in the instrument plate and variations due to faulty adjustments.

C. Set the verniers at random.

The fourth phase of the surveyer's work is the transfer of the working lines and levels to the tunnel. Most tunnel work is conducted with shafts. The shafts may be on the line of the tunnel or offset from the tunnel and connected by a cross heading. The center line and level bench mark having been established on the surface must then be transferred to the tunnel upon the completion of the shaft. The line and level must be transfeerred so that the least amount of error will exist at the bottom of the shaft.

It is the usual method to transfet the center line to the bottom by means of a strong steel wire supporting heavy weights. The general method that is followed when the shaft is sunk in direct line with the tunnel is relatively simple. It consists of the establishment of two known points on the center line at the bottom of the shaft. This is accomplished by lowering two heavily weighted wires, whose suspension points are on the sufface center line, to respective points at the bottom of the shaft. If an instrument is then set up at some point and brought in line with these two points the resulting line will be symetrical to the surface line. Where the shafts is not in direct line with the tunnel but offset to one side or the other, a similiar operation is carried on as in the afor mentioned case. A line is transferred to the bottom of the shaft that is parallel to the center line of the tunnel. From the shaft is next driven a cross heading, perpendicular to the tunnel's center line, to a point on the center line of the tunnel. At this point on the center line a perpendicular to the cross heading's center line will establish the center line of the tunnel.

To transfer the level to the bottom of the shaft or to the tunnel a bench mark is established near the top of the shaft. A standardized tape is supported several feet above the surface and hung down the shaft. Standard tension is obtained by hanging a weight on the lowered end. At the surface the level reading is taken at the bottom from a level to the tape. The difference between the two readins, corrected to the temperature at which the tape is standard, is the difference in elevation between the two instruments. Since the elevation of the line of collimation of the upper instrument is known, that of the lower is known also. At the bottom of the shaft a tunnel bench mark is established and the level is transferred to it from the instrunment. The operation is repeated by different observers until a consistent value is obtained for the lower bench mark.

The carrying forward of the line and level in the tunnel is the fifth phase of the surveyor's work. This process is either simple or complicated depending upon the conditions under which the tunnel is driven. If the tunnel is driven through hard clay or rock and is under normal atmospheric air pressure then it is a comparatively simple operation to carry forward the lines and levels. If the tunnel is to be constructed under compressed air then the resulting surveying operation becomes complicated as the lines and levels must be carried through bulkheads and air locks. If ground through which the tunnel is being driven is soft mud or silt, the surveying work become still more complicated as the

the structure is in the state of movement both vertical and horizontal. Constant renewals of lines and level at points of unstability must be made from points in more stable ground.

In conditions of normal air pressure the heading or the shield will be continually moving forward. It is consequently, important to check the shield or heading after each "shove" forward. A precise alignment with the previously constructed part of the tunnel is desired at all times. In the case of the shield a large painted target may be placed on some stationary part of the shield. In rock tunnels, monuments may be established every 200 or 300 feet and thus a careful check may be kept as to its line and level. Caution must be taken that the surveying operations do not interfere with the construction work in progress.

In tunnels driven under compressed air the only complication added to the case on hand of tunneling in normal air is the air lock. When the tunnel is large enough there will be two or three air locks through each bulkhead wall. Whatever lock is used, its position in the bulkhead wall should be laid out with reference to the carrying forward of the working lines through it without having to make a special offset in the line to get through the lock. The transit should be set up inside the lock. Special arrangement should be made before the installation of the lock to allow for a stable method to set up the instruments.

The sixth and last phase of the surveyor's work is the checking of the position of tunnel and shield. In any shield driven tunnel the work of the alignment party will be divided into two main parts, namely:

A. Running the precise lines and levels through the tunnel so that a means is afforded of knowing whether the shield is traveling

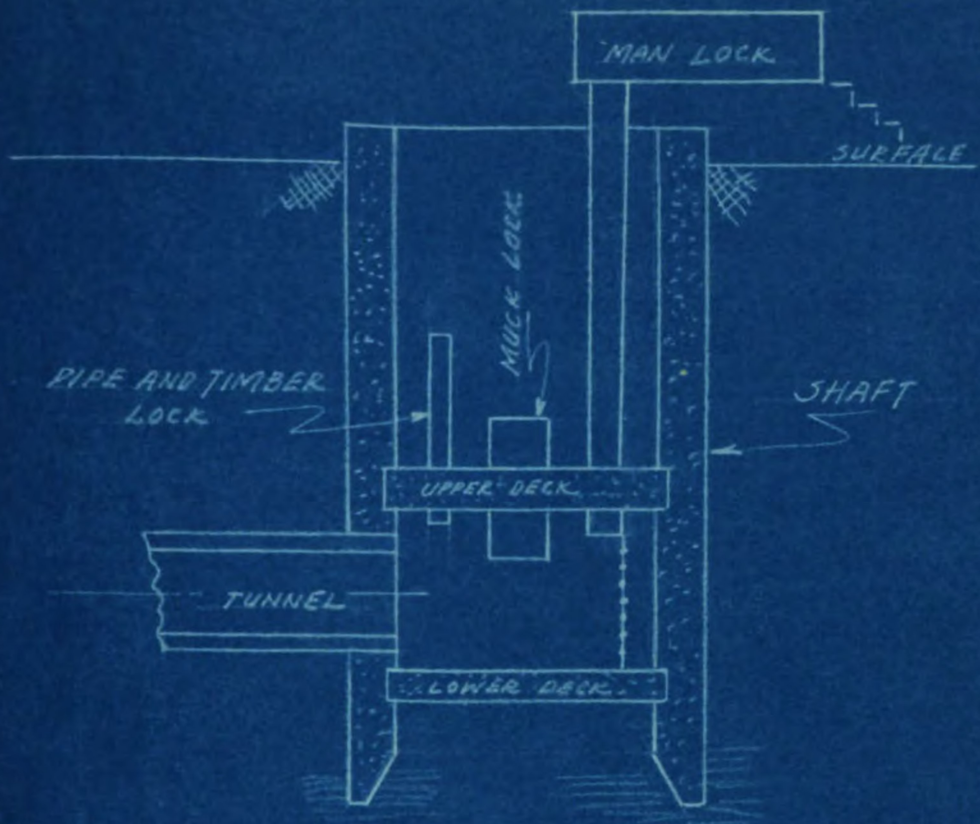


FIG. 17 - LOCK SYSTEM IN SHAFT

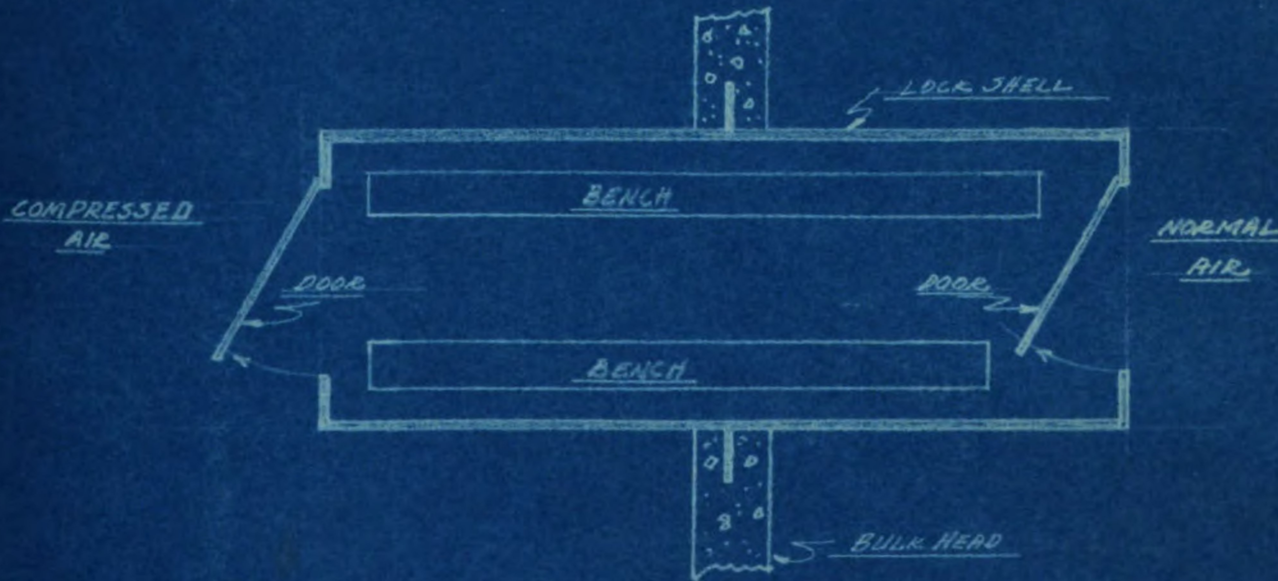


FIG. 18 - TOP VIEW OF TYPICAL MAN LOCK.

on the predetermined lines and gradient.

B. "Checking" on or testing the position of the shield in order to see whether it is traveling in the direction desired and at the same time observing the general shape and condition of the lining erected.

The conditions in rock tunneling do not vary widely from those given above, except in the case of the shield. The methods in general have been discussed and accounted for in previous chapters, so deeming it no longer necessary to relate them we shall close the topic of the survey.

Air lock systems—In tunnels that are being built under compressed air, air locks are necessary to transfer men and material to and from normal atmospheric pressure. A simple door can not be used in entering the air chamber for the force to open it would be enormous and once opened the air from the tunnel would rush out, thus, making it impossible to close the door. The locks may be situated either in a bulkhead in the tunnel or in a deck in the tunnel shaft. Where the tunnel is of great length and the volume of air required to fill it is large, bulkhead locks are used. The shaft locks are used in short tunnels, Fig. 17.

The operation of the lock is divided into the compression period and the decompression period. The decompression period occurs when men or materials are moved from the tunnel the pressure going to normal pressure. Compression is the opposite, the movement from lower pressure to high pressure. The lock consists of a long cylinder with two air-tight doors at each end, Fig. 18. During decompression, the doors are closed and the air in the lock is under the tunnel pressure and is exhaused to the atmosphere. In compression the air is pumped into the lock. The doors of the

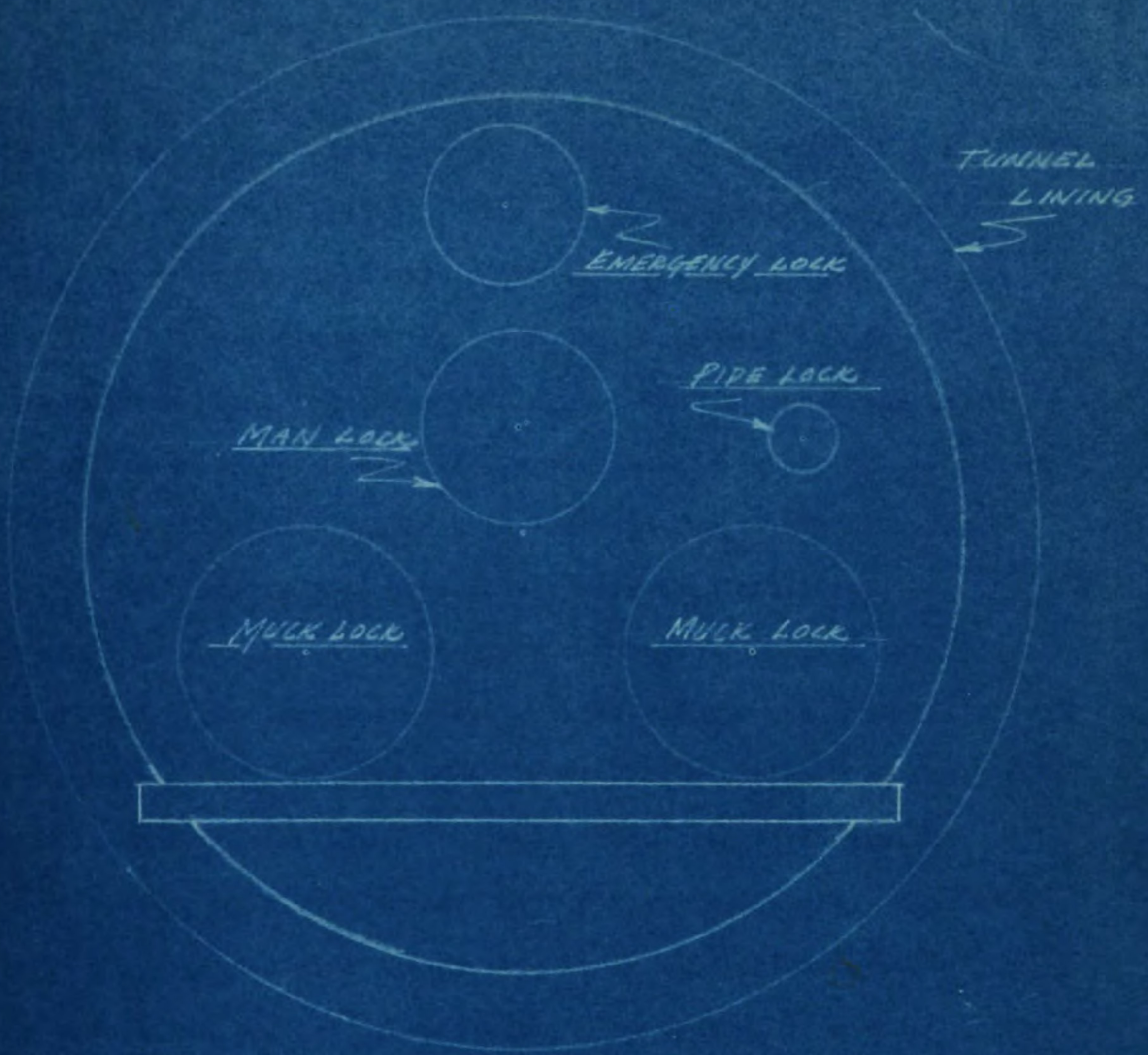


FIG. 19. - AIR LOCKS IN BULKHEAD.

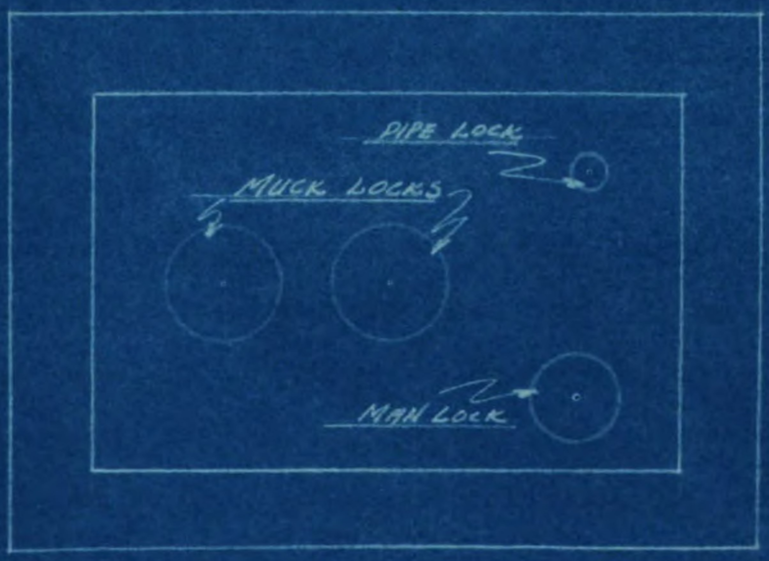


FIG. 20 - AIR LOCKS IN SHAFT DECK.

lock are rubber gasketed in order to make them as air-tight as possible. The door leading to the tunnel swings out away from the lock, while the door exiting to the atmosphere swings into the lock. It can be seen that when the pressure is up in the lock only the door leading to the tunnel can be opened and in decompression only the door leading to the atmosphere can be opened. For each passage only one lock full of compressed air is lost.

If the tunnels that necessitate more than one lock, that is the tunnel is large and numerous passages of men and material occur. locks must be seperately provided for men and material and an emergency lock must be at hand. The material lock are used in taking materials in and out. They are provided with large valves, usually 4 inches, giving a quick transit. The men locks are provided with valves to give the correct compression and decompresssion periods, they transmit the passage of men to and from the tunnel. The emergency lock is used for escape by the men when the tunnel becomes flooded. Where long timbers, rails, beams, or pipes must be brought into the tunnel an additional lock is usually furnished long enough to enclose the needed materials.

A suggested arrangement for the locks in a bulkhead and in a shaft are shown in figure 19 and 20 respectively.

The material lock or the muck lock, as it is sometimes called, should be built on a level with the tunnel track so that cars can be moved in and out of it. This lock should be as long as the outside diameter of the tunnel plus 2 or 3 feet to allow the longest members that might be required at the heading to be passed through the lock. It must also be remembered that room must be allowed so that one door can swing inward.

Ventilation-A problem that does not necessarily confront the tunnel builder during construction is the ventilation of the tunnel upon its completion but the author feels that in touching upon this subject it will further enlighten the reader on the difficulties encountered in this type of work.

The system most generally used in ventilation is the Transverse Flow type. The fresh air from the blower fans flows through a duct under the lower slab of the flooring. Air is introduced into the main tunnel through a continuous expansion chamber and a narrow adjustable slot located at the lower part of the tunnel and connected to a duct below by flues spaced apart throughout the tunnels length. A uniform distribution of the fresh air is obtained by adjusting the asbestos slide in each flue inlet according to the static pressure in the duct.

The exhaust duct is formed by the ceiling slab and the upper part of the tunnel shell, the vitiated air being withdrawn through adjustable cast iron ports, placed in pairs, one on each side of the centerline, and spaced at intervals longitudinally. These exhaust port casting vary in size, and in addition have adjustable stainless steel slides so that the area of each port opening can be set as required by the static pressure in the exhaust duct at the point where the port is located.

The tunnel might be divided into four ventilation sections, if its length requires; each section being served by one fresh air duct and one exhaust duct which ascend vertically at the shafts to the blowers and exhaust fans located in ventilation buildings. If the tunnel is smaller the number of ventilation sections may be adjusted to its length. The exhaust air ducts lead to air tight rooms in which the exhaust fans are placed, and the vitiated air is discharged to the outside atmosphere above the roof of the

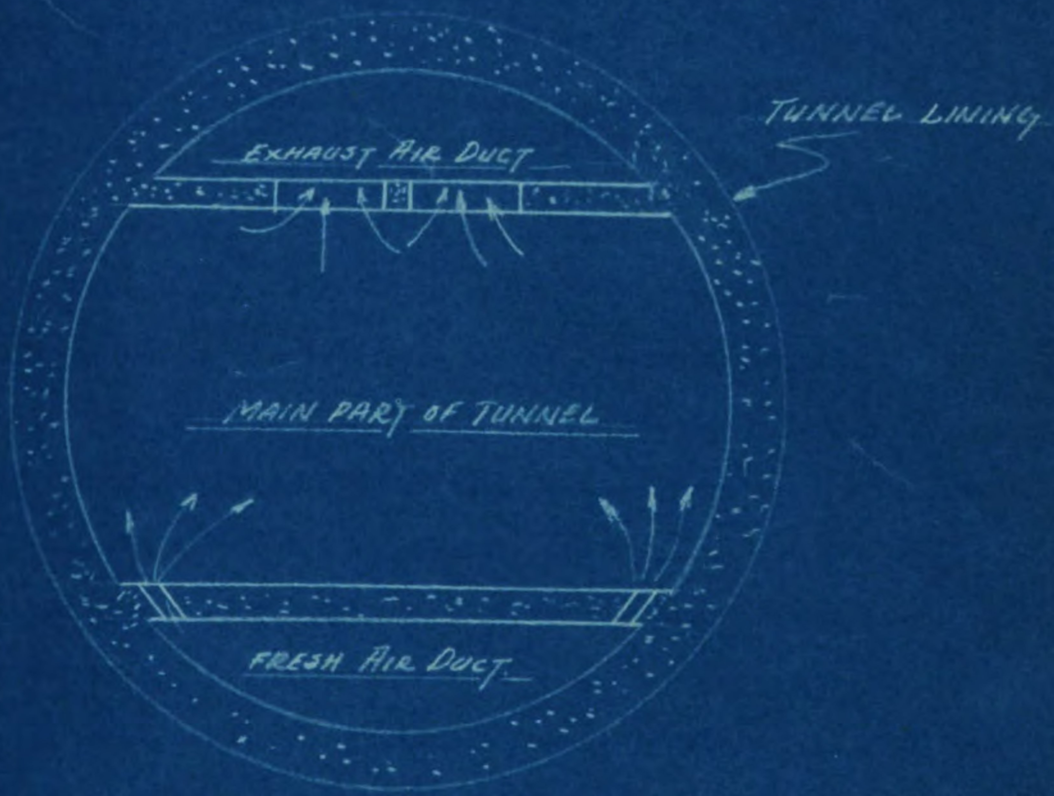


FIG. 21 - VENTILATION SYSTEM

building.

The chief advantages of this method of ventilation is the practically complete elimination of longitudinal air currents. It is felt that a longitudinal flow of air in the main tunnel space presents an undue hazard if the tunnel is one used by a large volume of traffic and the velocity of flow is such as would rapidly spread smode or other fumes. The chief disadvantages are the higher initial and operating costs.

In the design of the various parts of the duct systmes particular attention must be directed to the improvements in details of construction and the reduction of resistance losses. All elbows must be of liberal radii and where conditions warrant it they should be supplied with splitting vanes. Changes in area and shape should be as gradual as possible, especially in expanding ducts. The areas of the exhaust ducts at the points where they enter the exhaust fan rooms should be large in order that the expansion loss at those points may be as small as possible. Access to all tunnel ducts are provided for by manholes in the lower sections and hatches in the upper sections. Figure 21 shows cross-section of a typical tunnel with ventilation layout.

C - Labor

Having citied the construction phase let us turn to the labor side of the situation at hand that confronts both the contractor and the worker on tunneling projects. As labor and construction go hand in hand it is necessary to regard these phases with equal importance.

In rock tunneling jobs the labor problem is relatively simple. The men are handled in the same manner as in surface construction work and their are relatively few dangers to be encountered. For this reason the author shall only deal with those problems that exist in the construction of tunnel in pressures higher than that of normal atmosphereic.

In the past years, that is in the period previous to the great war, men worked under high air pressures, up to fivty pounds per square inch for periods for periods as long as ten or twelve hours. Most every sandhog had in this time contracted at least one bad case of some compressed air desease. The term sandhog meaning men who labor under compressed air. The contractors and authorities merely took for granted that if work of this type was to progress there would have to be made a maximum amount of sacrifises by the personnel. They neither sought to correct or to reduce these falicies. These men were at this period receiving the common laboring wage of twenty-five or thrity cents per hour.

Today through added scientific research and greater medical knowledge, compressed air workers are able to labor with the feel- of little chance of contracting the deseases; unless through carelessness on their own part. They also receive wages high above those of the present common laborer and on certain jobs their wages rank on a par with those of the average college professor. It is not a peculiar instance for a sandhog to earn as much as one hundred dollars per week for as low as ten to twelve hours of actual work. These high wages may be accounted for by the fact that his mortality rating ranks high in the upper bracket.

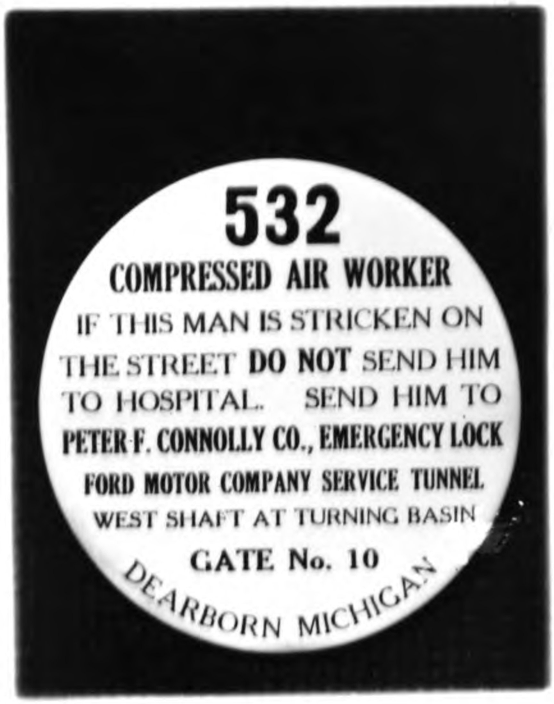
The most familiar desease to the compressed air worker is the bends, this desease is often called the " Diver's Palsy ", " Compressed Air Sickness", or"Caisson Disease ". The bends a painful form of paralysis, is caused by the worker taking on a great deal of nitrogen into his blood stream when he comes into normal pressures; this forms bubbles in the veins and may result in permanant crippling or death. Even the most modern methods of decompression have not entirely obliviated this danger.

There are several different manifestations of this illness, depending upon the position of the nitrogen bubbles.

The bends is formed by the pressure of the bubbles in the joints or limbs. In general this symtom may be looked upon as a nondangerous type. Another form,the chokes, is caused by bubbles in the blood vessels of the lungs giving rise to form of suffocation. The staggers or vertigo is caused by bubbles in the brain or middle ear. Both of the latter types are extremely dangerous.

Various experiments with helium, which like nitrogen is an inactive gas and is less soluble in the blood stream, have been; suggested; but they have proved impractical due to the large requirement of air needed in the construction of a tunnel. It might be proposed to have an individual supply chamber for each workman; but it is doubtful that this system would be very much more effective than the present methods now employed.

The solution of the whole problem seems to lie in the fact that the decompression period must be properly controlled so as



Typical badge worn by compressed air workers on tunnel jobs.

to assure complete expelence of the foreign matter from the blood stream and tissue. One method that might be emphasised for the treatment after a quick decompression, is the recompression followed by decompression in the presence of pure oxygen; this method should however be only used in the case of rare necessity. The period of exposure also can be analysed to avoid compressed air diseases. It is found that the symtoms of compressed air disease can be completely releived by the immediate return of the victim to pressures equal to those that he has been previously exposed. For this reason a special air lock, called a medical lock, should be on hand on all high air jobs.

A widely used measure of the time of decompression is to remain in decompression for a period of one minute for each pound of air pressure the worker has been exposed to, up and inclusive of forty pounds; above forty pounds of air pressure two minutes in decompression for each existing pound of air pressure is advised. A few men have worked in pressures above sixty pounds, but this is at present considered dangerous from a physical standpoint.

A suitable tag or badge, see picture, identifing the worker must at all times be worn, for it has been found that the bends do not necessaryily attack the worker immediately after decompression; but might stricken him on his way home from work. On the badge are the company's by whom he is employed address and information as to his care, this is necessary for only at the company's medical lock can he receive the proper treatment.

The present laws recognized by the various sandhog unions are these drawn up by the New York State Labor Commission. They are as follows:

Pressures lbs. per square in.	1st period of work in compressed air		Rest period		2nd period of work in compressed air		Total period of actual work	
	Hr.	Min	Hr.	Min.	Hr.	Min.	Hr.	Min.
0 to 20	4	00	0	30	4	00	8	00
21 to 29	3	00	1	00	3	00	6	00
30 to 34	2	00	2	00	2	00	4	00
35 to 39	1	30	3	00	1	30	3	00
40 to 44	1	00	4	00	1	00	2	00
45 to 49	0	45	5	00	0	45	1	30

Also as the pressure increases so do the wages.

Several general rules for the safeguarding of the health of the sandhog should be stated as they have not been covered specifically in the past pages,

(A) Use a recording gauge to show the rate of decompression on each man lock.

(B) Test all gauges once a day.

(C) Use a good competent man as lock tender.

(D) See that the decompression of each man is recorded.

(E) Keep the tunnel and locks in an absolutly sanitary condition.

(F) Allow no smoking in compressed air.

(G) Allow no animals (other than men) in compressed air.

(H) Give each man an individual clothes locker.

(I) Provide a drying room for wet tunnel clothing.

(J) Provide hot and cold shower baths.

(K) Provide wash basins with hot and cold water.

In order to keep the cases of compressed air disease at a minumim certain precautions must be taken. These may be summarized as

(A) Examination of each man.

(B) Limitation of the hours of work.

(C) Slow decompression.

(D) Avoidance of chill during decompression.

(E) Making the men stay near the work for a period after decompression.

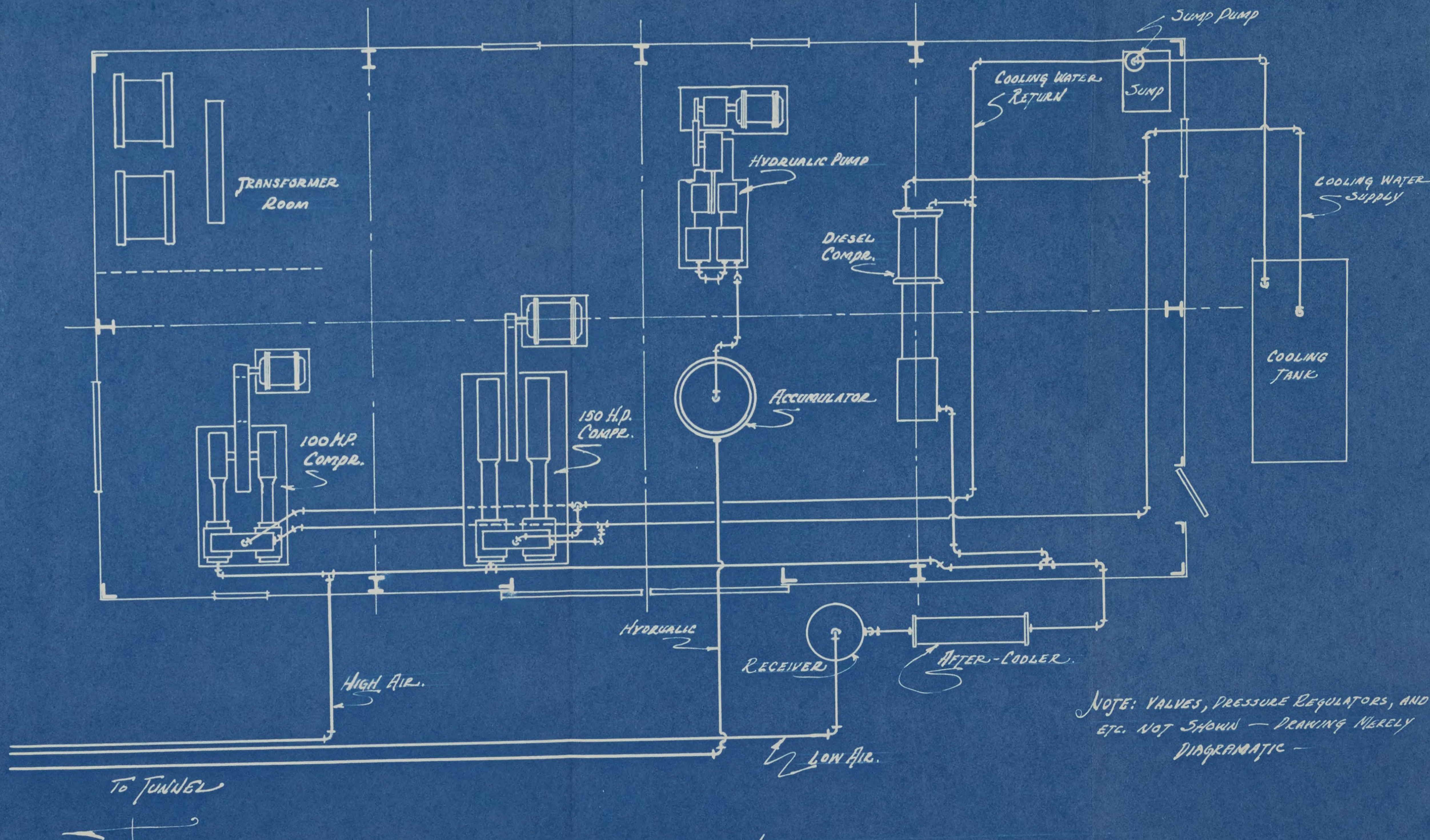
With all these disadvantages and there are many more, whenever there is a high air job the sandhog will leave whatever else he may be doing and go below to toil beneath the surface; for air jobs are few and far between andthay pay exceedingly well.

D - Power

Compressed air is, of course, vital to the undertaking whether it be a rock tunnel or a high air tunnel. A reliable compressor plant should be installed by the contractor to carry on his work in the prescribed manner. This brings us to the thrid important phase of this paper.

The equipment involved in the construction of high air tunnels includes transformers, compressors, coòling apparatus, general piping and hydraulic pumps and accumulators.

The compressors are of two types; the large two stage compressors to develope the high pressure air for the pneumatic tools and equipment used in the tunnel operations, and the single stage compressors to develope the low pressure air used in the tunnel itself. Often times only two stage compressors are used, the high pressure are reduced by means of a pressure reducing valve. The high air pressures are maintained at pressures ranging between 75 and 100 pounds per square inch and are piped directly to the tunnel machinery. In the case of the low pressure air, which must be more carefully regulated as to temperatures and pressures for it is this air that the men breath; it is first cooled in a series of aftercoolers to a desirable temperature and them piped to a receiving tank where the pressure is regulated before going to the tunnel. Once the tunnel is completly filled with air the load on the compressors is greatly reduced , but suitable arrangements must be made so that if leaking becomes to apparent air can be supplied in large quantities. An average capacity for low air compressors on the average tunnel job runs in the range of 4000 cfm., while in the qase of the high air compressors where the demand on them is not so large 1000 to 2500 cfm. is deemed sufficient.



Typical Powerhouse Layout

Also installed in the compressor plant is the hydraulic equipment, this consists of the hydraulic pumps and the hydraulic accumulators. The pumps of course furnish the needed pressure to drive the shield jacks, the accumulators stabilize the pressure and feed the water to the pipe lines at a uniform rate. The water is carried to the shield in two one and one-half inch extra heavy lead pipes each designed to withstand a pressure of 8000 pounds per square inch.

The transformers in the plant are merely used to reduce the existing primary line voltage to a voltage suitable to drive the compressor, pumps and accessory equipment motors.

In rock tunneling or tunnels constructed under normal air pressures the low air compressors are not needed. But additional high air pressure compressors must be furnished to supply the increase of load due to the great number of pneumatic drills used in the operations.

Besides the compressor plant an additional shop should be erected for the repair of machinery, the sharpening of drill bits, and the plumbing equipment storage space. It should be equiped with drill presses, lathes, saws, planers, hammers,and pipe threading and cutting apparatus.

E - Uses of Tunnels

The scope and importance of tunnels are rapidly growing as the years increase and our cities grow in population and wealth. The author has entitled his closing paragraph "Uses of Tunnels", for tunnels are showing an ever increasing service to the progress of mankind. Whether it be the lowly sewer or the highly finished highway tunnel all must be looked upon as a vital part of this great civilization. As the years grow on a need for rapid transportation of articles, food, people, supplies and power will exist, but the tunnel will not heed the beckoning call of progress for it will again serve as it has from the beginning of time.

If the author has brought to mind in this paper the difficulties and tasks that must be overcome by the contractor and his personnel and the service to humanity that the tunnel confers upon the reader, he will feel justifiable repaid indeed.

John Massey

Photographs of various operations in
the construction of a tunnel.

Photographs of the progression of work on the construct-

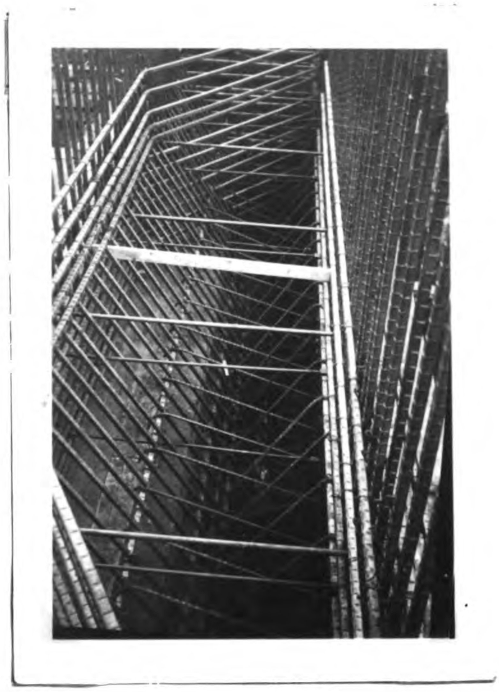
of the caisson shaft of a tunnel.

Breaking ground for the cutting edge of the caisson.

Same as above.
Reinforcing steel to be used in construction in the forground - concrete forms shown in rialroad car.

Cutting edge in place - erecting of the wooden forms taking place by carpenters.

Forms at completion of construction.



Reinforcing placed in cutting edge.
Note complicated and heavy design due to large forces exerted by the great head of earth at bottom of the shaft.

Loading pig-iron in tunnel opening in shaft to balance the weight of opposite side.

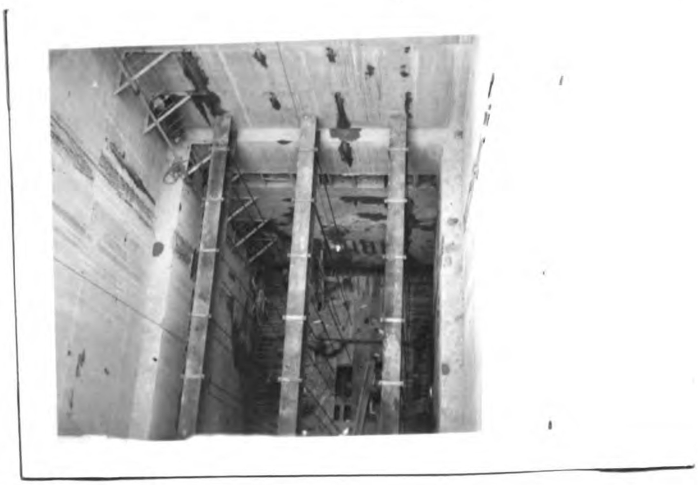
Caisson in operation of being sunk.
Note that the shaft is tipping to left this
is counteracted by the large wooden "kickers"
which force the shaft in the opposite direction.
Power house in rear- left. Concrete forms not as
yet stripped.

Mucking at bottom of shaft.

Looking down into shaft after it has completed
its decension.
Reinforcing for lower deck bent out from shaft wall.

Beginning of the operation of unloading
pig-iron from tunnel opening after the shaft
has been shouldered to
hard pan.

Looking up from the bottom of the shaft.



Forms for the poring of the lower deck
being placed into position.

Looking down into shaft to the complete
lower deck. Holes in slab for the air
locks to be placed when loose
waterbearing hard pan
ic struck.

Lowering of workman and inspector
down into shaft. Signalman in background.

Hauling muck from the bottom of the shaft
under the lower deck.

Lowering men to bottom of shaft.

Architectual inspector under lower deck of shaft.

Photographs of the progress of the sheild to
its final resting place at
the bottom of the shaft.

Sheild to be used in the tunnel
Construction.

Shield being lifted from barge that it was
brought to the site of the job.in.

Shield being placed in flat car which
will haul it to the shaft
opening.

Same as above.

Shield at shaft site - preliminary work
under operation.
Note erector arm and shield jacks. Barrels
containing segment bolts in for-
ground.

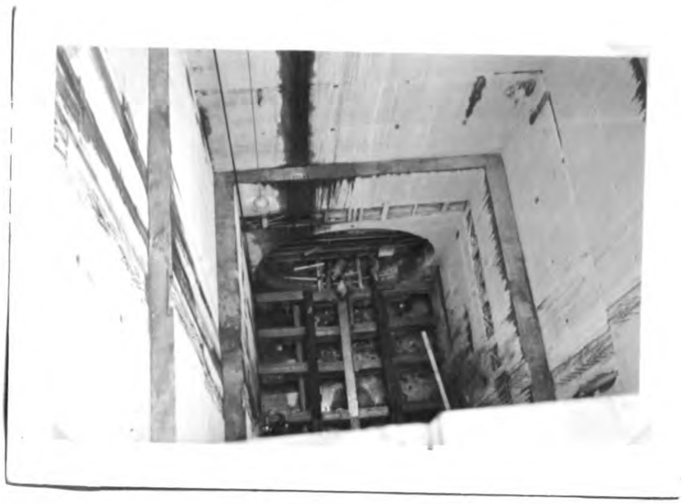
Shield being picked up before lowering to
bottom of shaft.
A heavy railroad crane for wrecking
work is being used because of the
enormous weight of the shield.

Lifting the shield.
Note air locks to be used in upper deck of shaft directing through opening in shield.

Same as above.

Lowering the shield down into shaft.
Cutting edge of shield
facing forward.

Same as above.

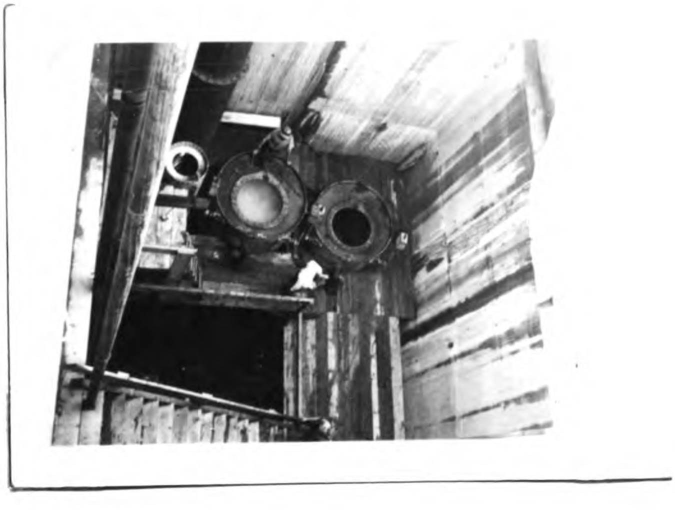


Setting of the wooden cradle for
the shield at bottom of shaft
and in front of the tunnel
opening.

From this point on the shield is
literally on its own, that is, it
must receive all its motivating
force from its jacks.

Photographs of the preliminary tunnel operations made before the main holing through.

Air locks in position in the lower deck. The largest lock in diameter is the muck lock, the small lock into which the workman is lowering an object is the pipe or timber lock, and the long shaft in the background leads from the man lock which is on the surface.



A veiw with the muck lock open, note the fog caused from the compression heated air.

A veiw of men fitting the pipes to supply air and water to the tunnel.

Erection of the first tunnel segments.

These pictures where obtained by the author while he was in the employment of the P. F. Connolly Co. who constructed the Ford service tunnel at Dearborn, Michigan under the turning basin of the Rouge River. The photos follow the construction until I took leave to return to school in the fall of 1936.

John Massey

ROOM USE ONLY