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TRANSPORTATION OF MAN AND MATERIALS 
THROUGH TUNNELS AND PIPES 

by 
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This work is dedicated to my loving parents.
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Chapter 1

INTRODUCTION

Extensive research throughout the world is being applied to mass transportation systems which will allow people to commute fast and safe and be able to handle large volumes of traffic as discussed by Wilson (1).*

In the field of transportation, it is recognized that pipelines represent the greatest growth potentials capable of increasing the living standards of the people. As the demands on pipeline and tube transportation are expanding rapidly throughout the world, it will be necessary to concentrate research efforts and monies toward this so that more economical pipes and tubes can be constructed, thereby providing the people with a pipeline or tube transportation system that has dependability, safety, acceptance, and efficiency with economy.

Bulk solids such as coal, ore, minerals, sand, and wood chips in slurry with water can be transported through pipelines. More recent developments have centered on the use of capsules or slugs. Capsules are packages of material enclosed within an envelope imper-

*Numbers in parentheses refer to references in the List of References, page 43.
vious to the surrounding fluid; slugs are more or less rigid bodies, either solid or formed of paste.

In general, the transportation system is made of a system of pipes and tubes of various sizes. Recently at Brigham Young University a project of constructing such a system for the transportation of men and material has been subject to investigation by Professor A. Wilson. It is proposed to use the component system of precast prestressed concrete to make the required economical tubes or pipes so that the man or material can travel or be transported either in the same or opposite directions at the same time as shown in Figure 1. The component method consists of making the inner as well as the outer cylinders in small sections and combining them into the required configurations, and then securing the components by circular prestressing.

These tubes can resist internal or external pressures of high magnitude and can be structurally installed to span long distances without the necessity of intermediate supports. This system can be effectively put into use in open or mountainous country.

Through this project, the author has tried to investigate the literature for deciding the economics of constructing tunnel lining or tubes in different situations. A vast variety of work is available for this and a selection of a suitable one is a difficult choice, but the author has briefly summarized the most suitable works pertaining to this system in this report.
Figure 1. Typical cross-section of tubes for transportation system
Chapter II

MASS TRANSPORTATION

There are two ways of reviewing the future of high speed ground transport of large numbers of passengers. The first is to consider what can be done to improve existing systems and the second is to consider what appears to constitute the optimum form of high speed ground systems.

The existing transportation system is a result of vast research and development of the past and continuous efforts are being put to improve it still further. The development of electrical traction for trains achieved the speed of more than 200 miles per hour (more than twice in normal service). The main source of difficulty in improvements is the presence of a large number of variables making the comprehensive solution rather complex. A simple four wheel wagon has seventeen degrees of freedom and to analyze its lateral motion alone requires simultaneous solution of seven sets of differential equations. The solutions to the mathematics of such analysis were, in practice, beyond the power of traditional methods. However, the rapid growth of electronic brains has made it possible to analyze such complex problems in a very short time. The result of this vast research has resulted in
modern high speed (with all passenger comforts) monorails, commuter trains, turbo-motor-trains, etc.

Still more revolutionary and affecting more people are the proposed mass transportation systems of the future: rocket-shaped vehicles flying through tubes or gliding on a thin film of air over elevated roadbeds, small auto-sized air buggies, riding cushions of air and guided along roadbeds, and special automobiles that enter magnetic highways, levitate six inches by magnetic repulsion, and dart away at 150 mph. Research and development projects are already underway in these directions (4).

At least three systems of flying through tubes are being seriously studied. Some vehicles in this system resemble a flying wing. Some skim silently along by use of a little-known phenomenon called the Coanda effect. As a result, rollway, hovertrain, gravity vacuum transit, and tube flight systems are on their way to replace the facilities of today, discussed earlier.

Flying through tubes (4): It is now considered feasible and perhaps economical to fly vehicles through tubes at speeds comparable with those of aircraft. For vehicles traveling at high speeds in a curving path, tubes have the advantage of providing support from all sides. They can also protect the vehicles from the whims of weather and from objects falling onto the roadway. The methods include evacuated tubes, Rensselaer Polytechnic Institute cushion trains, and Coanda vehicles
expected to run at 500 mph or at even greater speeds.

Air cushions over track (4): Until tube flying vehicles are perfected, improved air cushion techniques promise to provide a generation of air cushion vehicles to ride track beds on a thin layer of pressurized air at speeds between those of railroads and airlines.

Rollway (4): Rollway is an extremely wide train into which the passengers drive their cars, thus preserving the flexibility of personal transport with the high speed of rapid transit route. The hovertrain combines the advantages of air cushion support and linear electric propulsion. In the gravity vacuum transit, exceedingly high speeds would be reached by sloping the track down away from each station and maintaining almost one atmospheric pressure differential across the front and rear of the train. Tube flights use an air-filled tube and a vehicle lifted and guided by air pads which keep it centered in the tube; internal air flow provides the propulsion.

However, all the above transit devices of the rapid transit system must satisfy the basic qualities of a transportation system, which are:

1. Safety: absolutely fail safe, completely grade separated from everything.

2. Speed: faster door-to-door delivery for passengers, equal to or exceeding the automobile.

3. Convenience: frequent service with good delivery.

4. Attractiveness: clean, modern, well-lighted, well-
landscaped stations and parking lots, as well as the vehicles themselves.
Chapter 3

TRANSPORTATION OF MATERIALS

The transportation of solids has always been an important parameter in the transportation system. The mode of transportation has essentially remained unchanged though a switchover from ox-cart to modern high speed vehicles has been evolved out of centuries. Nearly all of these methods are batch processes requiring batch loading, manufactured vehicles, prepared tracks, vehicle crews, control systems, and a mobile vehicle which needs a power transmission system also. Usually the vehicles return unloaded to their point of departure. A standby capacity is also required to compensate for adverse environmental conditions. All these disadvantages are usually far less than the advantages of this ox-cart system which are its inherent qualities: flexibility, adaptability, and expandability. As such, this system is suitable to transport over short distances when routes are frequently varied. However, they are totally uneconomical when the path is fixed and capacity is not significantly changed.

Efforts and research have continuously been directed towards finding a new method of transporting solids under these adverse conditions when the conventional system is uneconomical. As a result, a
system involving the transportation of solids by pipeline using fluid as carriers has come up. Design studies have shown that the total cost of this form of transportation can be lower than those of conventional transport (3).

Such a system has many advantages: no vehicles are required, energy sources need not be transported, power transmission lines are not required, and the process can be continuously operated. Furthermore, traffic control and manpower requirements are minimal and no power is lost in transmission or in braking a wheeled vehicle. Independence of weather means that capital costs are not inflated to provide excess capacity, and capital savings can be made by minimization of stocks held at terminals.

The main disadvantage of pipeline transport has been its inflexibility. But the tendency is for both production units and consumer centers to enlarge, and bulk transport between such centers already follows fixed routes. It is, therefore, all the more surprising that the transport of solids by fluids should have been known for so long without finding more application.

This system has found extensive use in transportation of coal and it has been successfully applied to pipelines as long as 450 miles in the U. S. Also, transportation of coal to power stations has been put into use in Britain (3).

More recent developments have centered on the use of capsules
or slugs. Capsules are packages of material enclosed within an envelope impervious to the surrounding fluid; slugs are more or less rigid bodies, either solid or formed of paste. Each method has its own attractions for particular types of material. Capsules eliminate the need to prepare the solids beforehand and separate the carrier fluid at delivery; but the capsules themselves have to be filled, inserted into the pipe, recovered, emptied, and refurbished for further use, and this has yet to be done on a major scale. This concept has been studied extensively in Canada but no commercial example is yet in operation.
Chapter 4

METHODS OF LINING

The most important feature of any tunnel constructed is its lining. The main requirements for such linings are:

1. It should provide immediate bearing capacity against external earth and water pressure without detrimental deformation or leakage.

2. It must resist the impact stresses due to rough handling, transport, or erection operations.

3. It must resist the high axial stresses produced during the advancement.

4. It must resist to moisture and ground water effects of the segment itself and of its joints and watertightness as well as resistance to corrosive action.

5. It must be economical in construction and maintenance. (More expensive, stronger materials may compete successfully with cheaper materials of less strength when the difference in dimensions, erection, and durability is also considered.)

Linings may be single or double. Double layers are employed when the double tasks of resistance to external pressures and water-
tightness or aesthetic appearance cannot be obtained with a single layer.

Present practice is to apply cast-iron or reinforced concrete segments in the construction of larger diameter (railways and vehicular) tunnels (5). Whereas concrete blocks are given preference in the construction of smaller diameter (public utility) tunnels, fresh concrete is just beginning to compete with these materials.

Linings may be done with the following:

1. Cast iron lining
2. Structural steel lining segments
3. Concrete lining segments
4. Reinforced concrete lining segments
5. Prestressed concrete linings.

**Cast Iron Lining**

The permanent lining for a larger diameter tunnel is usually (for subaqueous tunnels almost exclusively) constructed of cast iron. Its main advantages are that it can be quickly erected and is at full strength to resist jacking pressures and external loads immediately upon erection. It is more watertight than other types of lining and, being relatively thin for its compressive strength, is not too heavy and is economical concerning the required area of excavation.

Cast iron lining for tunnels of a circular section is made up of successive segmented rings bolted to one another by means of
Figure 2. Cast iron lining ring with a segment unit
circumferential flanges which at the same time act as stiffening elements. The dimensions of the segments are determined by the weight limit required for easy handling and erection operations. The length of the segment is usually between five and seven feet, whereas width, i.e., the length of the single ring, is subject to several conditions (see Figure 2).

Figure 2 illustrates the section and plan of a lining segment ring of twenty feet external diameter tube with a detailed section of a single segment. The joints of the segments are staggered between adjacent rings in order to improve both watertightness and longitudinal flexural rigidity.

A full ring composed largely of equal segments (N) with the exception of the crown segments (K) where the contact faces of the flanges cannot be radially directed as this segment has to close the ring by being pushed in from inside. As a result, the contacting flanges of adjacent segments (A) must have also a corresponding special inclination on one side. The watertight bolted connections must be provided for, and this is effected by bituminous washers.

Cast iron satisfies well the requirements to tunnel lining. They do, however, require special protection against corrosion by soil. Tar or ferrofixol coating may be used.

The main disadvantage of cast iron lining is the heavy iron demand, i.e., 1.27 ton/ft for a twelve-foot diameter tunnel, and
7.35 ton/ft for a 28-foot diameter tunnel. Furthermore, the considerable weight of a single piece and the unaesthetic appearance of the bare surface may also be deprecated. The air is also contaminated by the dust which settles in its corners and recesses so that a smooth surface covering is frequently indispensable. Their application is restricted to lining station tunnels of very large diameter or of adjacent tubes lying close beside or above each other. The construction of such closely spaced tubes may be expected in the future.

**Structural Steel Lining Segments**

The same principle is used in fabricating steel segments from structural steel. These are fabricated from the usual rolled sections (plates) and welded to an appropriate form or from plates pressed to the required form—for smaller diameter tunnels. Due to its destructive effect, the use of welding must be kept to a minimum and pressing must be used wherever possible.

A great advantage of structural steel lining segments is that when all subsequent movements after placing have ceased, all joints may be closed with perfect watertightness by welded seams. In addition, experience shows that in dry clay a savings of 50 percent and in submerged silt a savings of 65 percent may be obtained in comparison with the use of cast iron segments (5).

To summarize its uses, structural steel segments are somewhat cheaper than cast iron segments, but they have two important
drawbacks:

1. They are highly sensitive to corrosion (except when corrosion-resistant steel is used, which involves considerable excess expenditure).

2. Their insufficient exactitude in their fabrication.

Concrete Segments Lining

Early attempts were made to develop some type of precast concrete blocks to avoid high costs of cast iron lining. The greatest difficulties encountered up to quite recent times have, again, been caused by the required perfect and uniform contact of adjacent block rings: Even when the considerable difficulties of exact casting could be overcome, there remained the inequalities of placing from the shield tail and the difference in level necessarily resulting in a distortion of the block ring. The big ram pressures produced by the propulsion of the shield have brought about bending pressures even with the slightest unevenness of contact which led to immediate cracking. The measure and structural importance of cracking can be considerably reduced by the use of reinforcement (which is an additional item of expenses) but spalling off at the edges and hair-cracking cannot be prevented by this measure.

Another difficulty was revealed by the erection process when it was necessary to find some method of holding the upper blocks in position until the ring was keyed. Cast iron blocks were held in
position by bolting to the previous clean cuts and rings but concrete blocks should be held by some temporary props until the ring (arch) is completed. A further difficulty was presented when placing the key block. The first standard key block could not be placed until the shield had advanced another ring, i.e., the pressure distributing ring was correspondingly retracted. This required a longer tail on the shield in any case. A dummy key block of wood was placed temporarily in the uncompleted ring to assure stability during the push, which in turn necessitated that the top ram could not be used, so rendering steering more difficult. A more convenient method is to apply small cast in place concrete keys of rapid-hardening cement which becomes a permanent part of the lining.

The first successful development was the O'Rourke block. As shown in Figure 3, these segments, 2-1/2 feet wide and about 6-1/2 feet long, have two projections and/or recesses on both faces. Those on the forward face are depressed 1-1/4 in. and those on the rear edge project 1-1/2 in. The heads of the rams bear against an oak cushion in the recess. These blocks are erected to break joint a separation of 1/4 in. corresponding to the above difference between the depth of the recess and the height of projections between the faces. Thus, the concentrated and more uniform transmission of all jacking stresses through these restricted contact surfaces will be secured.

Another interesting feature of the system is the key-block
Figure 3. O'Rourke concrete blocks
which is in two pieces, the sections having an overall length equal to a typical block. After the last piece has been placed in position, a concrete pin is pushed into a groove to lock the two key pieces which may be erected separately from inside the ring. The blocks are placed by erector arms which are mounted on a trailer closely following the shield. At the front of this trailer is a frame carrying a series of telescopic steel beams which are designed to afford the required temporary support for all blocks in a new ring above the springline until the key is set and the ring is made self-supporting.

Gravel holes 1-1/2 in. in diameter are provided in some of the blocks for shooting gravel into the annular void left behind the tail of the shield and other holes are arranged for grouting the 1/4 in. interstice left between the faces of adjacent rings after sufficient time has been allowed for them to adjust themselves to rock pressure.

Considering that the bigger the dimensions of the lining segments, the more difficult it is to secure a uniform bearing for them. The use of smaller concrete blocks may be advised, particularly in the construction of relatively small diameter public utility tunnels. The system advised by Eroleyi and Vajda and successfully employed in the construction of subaqueous water supply tunnel at Kaposztasmegegrer under the river Danube is described in Reference 5.

The great development in recent decades in the improvement of concrete quality (careful grading, water control, steaming, vibration,
Figure 4. Trapezoidal concrete lining segments, Don-sea type

Figure 5. Trapezoidal concrete lining segments, T.M. blocks
etc.) has been largely responsible for the use of precast-concrete segments in general practice. This is well illustrated by the fact that a water-supply tunnel in London was built recently with 6 in. thick trapezoidal blocks of the Don-seg type (see Figure 4) and similar to the T. M. blocks (see Figure 5) (5).

These, however, have no flat sides, but have tongue and groove joints on all four sides. The primary function of the shield in the London water-supply tunnel was to cut a circular hole in the clay of an exact diameter. The protective function inherent to the shield was of secondary importance here. The most important requirement was to cut the hole for the precast lining of a fixed diameter very accurately. When the clay was exposed behind a shield, the pressure was released and the clay expanded. When the lining was erected and tightened, the clay became recompressed to some extent. It was important, therefore, to establish a correct relation between the shield diameter and the lining diameter, making proper allowance for the expansion of the clay and producing the required degree of compression in the ring and corresponding pressure against the clay. Each Don-seg ring was 21 in. wide and consisted of ten equal wedge-shaped segments weighing 300 lb. each. The longitudinal edges were coated with a bitumen paint. Alternate segments were placed in a ring with the wide end against the last assembled ring and the new ring was then tightened by using the shield jacks to wedge home the intermediate segments with their narrow ends towards the last assembled ring.
The segments were bearing tightly against the excavated clay face and became pre-tensioned through the passive resistance.

T.M. blocks are also trapezoidal in shape but are tongued and grooved on all four sides (Figure 5). They are laid up within the shield skin with their wide ends alternately to the front and to the rear; in effect, every other block constitutes a key block. The blocks F are laid first, joining tightly to the last ring, whereas blocks F are pushed by hand into the interstices. When pushing either the applied pressure distribution ring will push all the F elements into their positions at once or the separate jacks will do so, simultaneously bringing about a tight connection and solid bearing against the surrounding ground. In order to avoid bending in the block, only one jack bears against a block. All the tongues are coated with thick asphalt which acts as a cushion in the transmission of jack pressures and is squeezed into the joints where it acts as a water-seal. However, the bituminous coats do not comply with higher waterproofing requirements. In such cases, a concrete block lining must generally be subsequently completed by an additional inner waterproofing which must be capable of resisting water pressure. This inner lining may consist of a carefully prepared bituminous paper or P.V.C. sheets supported by an inner, cast in situ, monolithic reinforced concrete lining to resist water pressure, or a welded steel sheeting may be anchored to the outer block ring to ensure its resistance against external water pressure.
Figure 6. Cast in place concrete lining with anchored steel-sheet waterproofing.
(See Figure 6.) With adequate anchorage, the external concrete ring and the internal steel sheeting may be dimensioned as a composite structure to resist the united action of external rock and water pressure.

Some favorable results have been obtained recently by the application of the cast in situ fresh concrete linings. In this case, a rigid and resistant steel-formwork and shuttering has to be erected in the interior of the shield tail. The pressure distribution rings bear directly upon the annular space filled with green concrete and a push produces perfect compaction and light bearing against the excavated earth face. The erection employed, the removal and section length of steel formwork, as well as the number of units and the overlapping length with the tail skin must be in accordance with the setting time of the cement applied. The length of the shield tail may be shortened to reduce frictional resistances during propulsion. A rigid formwork and easily dismantled shuttering is another essential part of this construction, the use of which was given remarkable technical and economical results in Germany and recently also in the Soviet Union (the economy obtained is more than 50 percent). It is very probable that this method is suitable only in fairly cohesive ground.

Reinforced-concrete Lining Segments

In order to increase strength and to reduce weight, concrete lining blocks are replaced chiefly in larger diameter tunnels by reinforced concrete lining segments. It can be stated authoritatively that
in the course of development over the last twenty years these principal requirements have been fairly well satisfied; the major problem still to be solved is to secure satisfactory watertightness both for joints and also for the concrete of thinner reinforced-concrete element itself. The solution of this problem has been sought in two directions:

1. Ribbed-type segments.
2. Slab-type segments.

The ribbed-type segment can be placed more readily and exactly and through the rigidity of its joints, it assures greater longitudinal rigidity in varying layers against differential settlements. Troubles have arisen, however, in watertightness at the ribs and at the connections. Both the roots and the bolted rims of the ribs are inclined to fissuration induced during fabrication or erection (bolt-tightening, caulking) process. The smaller structural thickness of their segment skin offers less resistance to water infiltration. In present practice, preference is given to the slab type in somewhat greater cover depths where a uniform pressure distribution may be expected, whereas in shallow depths the more rigid type of segments is used. In order to reduce the dangers of rib fissuration during shield propulsion as well as at bolt tightening, and to reduce the time necessary for placing the bolts, steel pins are used in Soviet practice in all axial joints and the circumferential bolted connections are somewhat modified. Only one row of connecting bolts is applied near the inside edge of ribs, not
piercing through the dovetail shaped recesses provided for swelling cement caulking. As to the watertight sealing of joints, experience has shown that swelling cement caulking frequently crumbles out when exposed to higher variations in temperature and to greater dynamic effects. Therefore, experiments are being carried out with various artificial resins and plastics (polymers, PVC, etc.) with a view to their use not only in the recess, but also for their insertion in the form of sheets between the contact surfaces. This latter application may also have a beneficial influence on the more uniform distribution of jack pressures upon the contact faces when the shield is advanced. The contact faces of slab-type segments are usually not planes but slightly convex or concave to ensure a hinge-like action. Watertightness is ensured by the insertion of plastic sheets and a seal of plastics or of swelling cement in the recesses arranged on the inside face. To reduce tolerances and to obtain greater exactitude, experiments are being carried out to fabricate the reinforced-concrete segments in the suitable squeeze moulding machines instead of casting them on vibrating platforms.

Precast-reinforced-concrete lining segments were first used in the construction of the Ilford line of the London underground (5). The whole design is perfectly similar to the cast-iron segments. Bolt holes were lined with a steel sleeve and wooden plate packing with inlaid bituminous sheeting was used between the contact surfaces for waterproofing.
Precast slab-type concrete lining was used in the construction of new Victoria line (5). In this, the segments are left completely unreinforced, a fact which is due both to the favorable strength characteristics of the London clay and also to the excellent quality of the concrete. In addition, no watersealing was necessary. Also, the construction of the Connerbuhl tunnel in Bern (Switzerland) was composed of four main precast segmental elements (5). The elements were designed with projecting collar flanges affording temporary support from the previous ring. The joints between the four main elements are arranged diametrically in the axis inclined at 45°, thus practically coinciding with the zero bending moment points. The backspace of the ring was grouted but thixotropic suspensions were forced behind the shield skin not so much for water sealing as for soil solidification, impregnation, and compaction. The application of thixotropic material is to anticipate the danger that grouting would increase friction resistance and render propulsion more difficult. In this way, the tunnel could be driven in the heavily water-logged soil with direct pumping only, without any excessive surface subsidence.

Prestressed Concrete Linings

The principal object of the prestressing in a prestressed tunnel lining is to reduce the thickness of the lining for a given internal or external pressure, to prevent and to control the incidence of cracks in the concrete. When over-burden is very shallow, prestressing
provides an alternative to cut-and-cover methods which might be difficult in built-up areas. Also, in a tunnel carrying water under pressure the bursting or internal pressure may exceed the external pressure due to the overburden, and in such a case prestressing by means of cables or bands will reduce the thickness of the lining. It is unnecessary to prestress in a homogeneous strong watertight rock.

Methods of prestressing linings include:

1. External cables
2. Bands or hoops.
3. Pressure grouting.

External cables. This method was introduced by Mary for concrete lining for pressure tunnel at Mareges (6). He introduced radial compression stress in the concrete lining of the pressure tunnel and assumed that the load was carried by the cables, the stresses in them being such that the stresses in the lining were compressive even when the gallery was filled with water at full pressure, and no advantage was taken of bulk resistance of the surrounding rock. The main disadvantage of this method was the great amount of friction which had to be overcome (see Figure 7).

Bands or hoops. This method of prestressing a tunnel was introduced by Freyssinet and used in the construction of sewer tunnels at two points in Paris (6). The reason for the use of hoops rather than
Figure 7. Inducing radial compression stress in concrete lining of pressure tunnel.
any other method of prestressing is the simplicity of placing and pre-stressing the constituent elements. The hoops, which give the necessary compression for the work to support the flexion due to the soil and the internal imposed pressure consists of special stainless steel plates having an ultimate tensile strength of 34.8 tons/sq. in. The tensioning is done by two jacks placed at the ends of the horizontal diameter. Under the effect of pressure from the jack a joint opened at the point where the jack is placed; the pressure will increase until the required extension of the steel hoop is obtained and pieces of concrete of the required thickness are introduced into the joint and the jacks are then removed. The circumferential compressive stress thus obtained will not exceed 430 lb/sq. in.

**Pressure grouting.** This method was also introduced by Freyssinet in which a thin precast concrete lining, made of planks and segments, is prestressed by injecting a colloidal mortar into the space left between the precast lining and excavation (6). By a special study of the joints and segments and also of the resistance of the ground, it is possible to obtain very high injection pressures which result in high prestress in the precast lining and expulsion of excess water through the joints, giving a very strong inside cover to the lining. The value of the water/cement ratio must be adjusted to suit the condition of the joints and of the ground. The space behind the precast slabs can be packed with dry aggregate if a thick lining is needed.
There are many advantages to this process:

1. Reduction of lining thickness.

2. Very good surface of concrete as a result of precasting.

3. Maintenance of the ground in similar condition to that which existed before tunneling, and no danger of cracking due to hydraulic pressures.

4. No need for traveling formwork for lining.

5. Colloidal grout can be pumped many miles through small pipes.

6. It is possible to concrete in the presence of water—the colloidal grout is not affected by it.

7. No need for conventional-type grouting behind the lining.

So far this method has never been used on a very large scale.

The Kieser method of prestressing makes use of the pressure produced by forcing grout behind annular rings of precast concrete blocks. These blocks are masoned against a rough concrete lining covering the rock surface. The precast blocks are provided with a small circular groove running along the outside of the concrete lining. Grout is forced into these grooves, compressing the cylinder formed by the precast blocks. The consequent prestressing should be greater than the stresses created by the water pressure inside the pressure tunnel.

The grouting of galleries in unsound or broken rock with no
cohesion constitutes a special problem. With no cohesion and with zero stress around the parameter of the gallery, equilibrium cannot exist, and the rock would collapse under its own weight. A radial compressive stress must, therefore, be applied if equilibrium is to be maintained. This stress can be applied by supporting ribs, by bolts, or by a concrete lining in conjunction with grouting.

Component System

The proposed transportation system is to be made of prestressed concrete and constructed by a component method. To illustrate, the procedure of construction for a transportation system (Figure 8) is described in detail.

The half section of the inner pipes and the external pipe can be constructed by conventional methods of fabrication. For this purpose, semicircular formwork of suitable dimensions is made. The prestressing tendons are placed in position and pretensioned to a desired degree. The wiremesh is tied with the tendons which serves the purpose of additional reinforcement. The concrete is poured in with the help of semicircular "slip-formwork" and the sections are taken out after seven days. Similarly, the second half of the inner pipe is constructed and finally, the two halves of the inner pipes are attached back-to-back and joined by epoxy cement.

For the outer pipe, the longitudinal prestressing is done in the same way as discussed above. After the construction of the two
(a) Half cross-section of outer pipe

(b) Half cross-section of inner pipes

(c) Combined cross-section of the transportation system

Figure 8. Typical cross-section of proposed component system of pipe transportation.
outer halves, they are placed enclosing the inner pipes and cemented by epoxy and finally prestressed circumferentially. The circular prestressing is done by simply winding prestressed wires around a concrete core and covering the wires with air-applied mortar. Thus the pre-tensioned prestressed pipe system is to be completed except for a protection against the corrosion due to the entry of water. For this purpose, a gunnite cover, i.e., a coat of pneumatic mortar of a suitable thickness, is provided around the pipe and prestressing wires for protection. Thus the transportation system is ready to be properly supported if passing through an open area or to be buried underground.
Chapter 5

ECONOMICS

The economics of tunneling are basically governed by the design method employed in the construction. After deciding the appropriate design construction schemes are carefully chalked out so that the men and materials required in the design are deployed to the maximum advantage. Although this sequence in designing the tunnel for economy both in use and construction appears logical, economy in the techniques to be adopted in tunneling and the methods of carrying them out during the construction of a tunnel impinge on its design.

Sometimes, while constructing small and medium size tunnels, it may be found that the overall cost can be reduced if the tunnel is made larger than the ultimate size required, simply to provide room to maneuver equipment and men to the best advantage. Thus the economics of tunnel design for a specific purpose is inseparable from the considerations of the methods to be employed during its construction. A similar situation arises in designing the lining to be installed in the tunnel. Sometimes a continuous monolithic concrete lining is cheaper than conventionally cheap brick linings because of modern mechanized methods of casting the monolithic lining in place result in economy.
The locality of the tunnel in relation to the working population also affects the problem. In some parts of the world, such as India, the local labor is so cheap and plentiful that it is not economical to use highly sophisticated modern techniques needing few but highly paid skilled people. For maximum overall economy a tunnel must be designed for economy both in use and construction, the one being adjusted in relation to the other as necessary to assure the maximum overall economy for the scheme as a whole.

As in all engineering enterprises, the final choice is a compromise between various intermediate and long term economy factors. To summarize, the three major interlocking factors to be taken into account when designing and constructing a tunnel are:

1. The most appropriate design of the tunnel as such for its main economic purpose.

2. The variations of this design that are desirable to achieve economy in construction and the effects these alterations have upon the prime economic purpose of the tunnel.

3. The overall economic advantage in driving the tunnel at a greater or reduced speed than the original purpose and the effects that this variation will have on the overall cost of the project.

The experience and the judgment cannot be separated from the economical aspect of tunnel design and construction. The three interlocking facets of economy must, however, be taken into account
as providing a background against which the border economy implications can be judged.

Design in Relation to Economics

The starting point in design of a tunnel is its purpose, e.g., if the tunnel is to be used for conveying water or air, the internal rubbing area of the tunnel should be at a minimum. If it is to be used for sewage or drainage when the flow through it varies, the total rubbing surface at any given depth of the contents should be minimum. Possibly an egg-shaped tunnel would offer certain economy in use, particularly when conveying sewage or sludge which may contain solids that can be held in suspension if the velocity of flow is maintained above a critical limit. On the other hand, the bending stresses in odd-shaped linings may involve additional strengthening of the lining and additional cost which would offset advantages in use. Thus, the balance can be arrived at.

In the tunnels to be used for transportation purposes, and particularly if locomotives are to be employed, a rectangular cross-section or a horseshoe section providing at least a reasonably leveled floor is necessary. Even so, if considerable strata pressures have to be resisted the economy of a circular cross-section into which an artificial flow may be introduced is usually explored during design and planning.
Economics of Construction

After calculating the tunnel dimensions and lining requirements tentatively, research is directed into the proposed methods of construction of the tunnel. The possible variations in cross-sectional dimensions or in the horizon of the tunnel in rock may be considered in relation to the cost of the construction. Sometimes considerable economy in the cost of construction may be arrived at by altering the cross-sectional dimensions suited most to the case under consideration. Thus the designers must have an opportunity to reconsider their proposals in the light of the constructional economic data. In practice, however, it is not easy to consider these before the major aspects of design have taken a good shape without which the engineers have very little information.

Economics of Driving the Tunnel

Once the section and shape of the tunnel have been decided upon, the maximum economy of driving is to be considered critically. It comes from an optimum combination of the following variables:

1. The current rates of wages in relation to the overhead charges on plant and equipment required to reduce manpower to a minimum.

2. The speed of driving the tunnel, which determines the extent to which over-crowding with loss of individual operating efficiency is advisable.
3. The nature of the strata to be penetrated in relation to the speed of penetration, which determines the pattern of blasting and particularly the extent to which overbreak as a result of heavy blasting is economically acceptable.

4. The length of the tunnel, which determines the length of the working shift at the tunnel face and therefore the number of shifts per twenty-four hours.

The costs of tunnel driving are also affected to some extent by the methods adopted for ventilating and servicing the working heads. The cost of a lining may be as much as a third of the cost of the tunnel.

To summarize, for maximum overall economy in tunneling, a balance between many conflicting requirements has to be found. When planning for economical driving and tunnel construction, many variables such as the kind of strata to be pierced, the cost of driving through the strata, the purpose of the tunnel, the various sizes of the tunnel, the subsequent costs of different kinds of lining, and so on, have to be considered in the early stages of design and the results plotted as a series of euteclics in order to arrive at an indication of the optimum pattern for maximum economy.
Chapter 6

CONCLUSIONS

The following conclusions may be derived from this study:

1. More research efforts and monies should be provided for the mass transportation of man and materials through tunnels and pipes.

2. The future high speed ground system which is under research and on the development stage must satisfy the basic qualities of transportation, such as safety, speed, convenience, and attractiveness.

3. Transportation of solid materials through pipes is more economical than the conventional methods so that more research is needed for construction of economical sections of pipe.

4. The application of cast in situ concrete lining is very probable with a rigid formwork and easily dismantled shuttering in fairly cohesive ground only. (Precast component systems on open ground will also be more economical.)

5. With the use of reinforcements in concrete lining, it is possible to reduce the weight, increase the strength, and construction of larger diameter tunnels will be ultimately economical.
6. The recent methods of prestressing the tunnels or pipes allowing the use of less steel and less concrete offer economy in construction.
LIST OF REFERENCES
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APPENDIX
METHODS OF CONSTRUCTION

The method of construction largely depends upon the type of tunnel, the topography of the region, and the economics of the project.

The tunnels may thus be classified according to their purposes, locations, and geological situations. The following two main groups of tunnels may be distinguished:

(A) Traffic tunnels

1. Railway tunnels
2. Highway tunnels
3. Pedestrian tunnels
4. Navigation tunnels

(B) Conveyance tunnels

1. Hydroelectric power station tunnels
2. Water supply tunnels
3. Tunnels for intake and conduits of public utilities
4. Sewer tunnels
5. Transportation tunnels in industrial plants

In addition, the location and position related to the terrain and alignment are important classification criteria which have a decisive influence on the tunnel selection, method of construction, the design, and the acting forces.
Railway Tunnels

The recent problems of mass transportation in large congested areas of big cities have led to the development of underground railways. Although essentially these are similar to conventional railway tunnels, they constitute a different group because of basic differences of location, construction materials, methods, and purpose. The conventional railway tunnels are of horseshoe sections while the underground railway tunnels are usually circular, rectangular, or polygonal in cross-section, depending upon whether shallow cut and cover or deeply located tunnels are concerned.

In principle, the underground railway tunnels distinguish themselves from conventional railway tunnels because of the following special requirements:

1. Increased safety requirements due to the large amount and high speed of traffic (freedom of displacement and deformation of track and tunnel lining).

2. Careful water sealing.

3. Highest standards of cleanliness and ventilation.

Highway Tunnels

Highway tunnels can be classified broadly into these groups:

1. Tunnels constructed on motorways, or modern main traffic routes, may be of the same type as railroad tunnels.

2. Interconnection tunnels, underpassing minor hills in the
interior of a town, differ mainly in dimensions from the former group.

3. The third group of highway tunnels is those which have to pass under water courses and are generally encountered in urban areas.

Pedestrian Tunnels

In principle, these belong to the group of highway tunnels but because of their smaller cross-section, short radii of curvature, and steep permissible gradients, together with the possibilities of providing vertical shafts instead of ramps for their access, their construction and design are very much different from conventional highway tunnels. This justifies their discussion as a separate group. Usually they are constructed in congested traffic areas in central business districts of big cities to enable pedestrians to cross the path without disturbing the traffic.

Navigation Tunnels

The navigation tunnels deserve special consideration in design and construction because of their inherent deviation from conventional tunnels. These are constructed to facilitate the navigation from one river system to another river system and other similar situations.

Conveyance Tunnels

Conveyance tunnels are essentially pipes used for carrying
fluids or solids using fluids as a carrier. They are used in hydro-electric power plants, water supply and sanitary schemes, industries, and public utility schemes.

**Hydroelectric plant tunnels.** The water directed for utilization in hydroelectric stations is conveyed from the raised reservoir to the adjacent valley where the power house is generally located. The conduits carrying water have to be installed using tunneling techniques.

**Water supply tunnels.** These are used for conveyance of domestic water from springs, reservoirs, or river diversions to the storage tank of a city water works. These have to pass through the varying strata soil and thus problems of settlement also come into play.

**Sewer tunnels.** These are constructed for the removal of domestic sewage and have to be designed such that sewage flows are under the action of gravity. Good internal watersealing is provided to protect the walls against the corrosion due to chemical agents contained in sewage. Owing to considerable variation in sewage volume, cross-sections of special shapes are used and brick lining is provided in the interior surfaces.

**Public utility tunnels.** These are pipes carrying power and telephone cables, gas, water, and other important public utilities. They are buried underground below water courses, roadways, railroad
tracks, blocks of houses, etc., in city areas so as to provide for continuous inspection, maintenance, and repair of occasional damage.

**Industrial pipes.** These are pipes carrying solid materials with fluid as carrier. The flow is mainly by gravitational force alone. They have been extensively used for transportation of coal, slurry, and other minerals from natural deposits to refineries and power plants.

**Construction Methods**

The construction of tunnels is governed by a number of factors such as location, geological and hydrological conditions, purpose of the tunnel, shape, size, and overall economy of the project. A compromise of these factors has to be arrived at for an optimum design. Basically, the construction of tunnels requires schematic execution of the following operations:

1. Excavation.
2. Support.
3. Transportation.
4. Lining, sealing, draining, and ventilation.

As tunneling constitutes an important area in many major projects like construction of railroads, highways, water supply and sanitary schemes, etc., it has developed into a highly systematic and scientific field of specialization. Essentially, the various tunneling systems can be grouped into the following five categories:
1. Full face tunneling without temporary supports.
2. Mining or classical methods.
3. Combined underground and open surface cut-and-cover methods.
4. Precast element and caisson sinking methods.
5. Shield driving methods.

The choice of a particular method of construction depends largely on the type of rock or ground to be excavated. In other words, the method applied while working with solid rocks will not serve the purpose when soft strata are encountered. In general, the first method is limited solely to solid rocks whereas the methods belonging to the second group can also be successfully applied in this situation. In loose and firable rocks and in cohesive or granular soils all the methods given above can be used with the sole exception of the first method. In exceptionally soft and loose ground, the methods given under four and five will afford good results.

**Full face tunneling without supports.** This is the most simple method of tunneling and can be used in slightly fissured rocks of very high strength. Before applying this method one must: make absolutely sure that the temporary supports can be omitted. It consists in the repetition of the following cycles of operations:

1. Drilling shot-holes into the tunnel phase.
2. Loading and firing of shot-holes.
3. Mucking out—clearing and disposal of debris.

4. Supplementary operations consisting of contour trimming, breaking down of loosened rock layers, and lining or coaling for operational purposes, if necessary.

The usual practice is to drill all the shot-holes required for excavating the full cross-sectional area of the tunnel in such a number and suitable pattern so as to achieve an adequate advancement with minimum use of explosives. A suitable plan for efficient mucking has to be developed in advance. The improvement in rock tunneling in the last two or three decades comes from the improvement in drills and drill steel, use of delay exploders in blasting, and development of economical and reliable mechanical muckers.

In large section tunnels and very hard rocks were no timbering is necessary, the central heading (drift) method can be used advantageously. From this central heading radial holes at right angles to the axis of the tunnel are drilled to the contours of full size section and then blasted, thus enlarging the remainder of the tunnel section in one single round. Recently, a multi-phase tunneling system with a separate parallel heading has been developed in connection with the center loading method. Here intermediate tunnel faces are made of a raiing, the advantages of not only one or two faces of attack but an unlimited number.

*Full face tunneling with supports.* The full face tunneling
method undoubtedly is the most economical tunneling system. However, as stated earlier, it needs rocks of very high strength to be applied and cannot be used when the rocks cannot support the loads coming. Therefore, it is desirable to extend its field of application by all practical means to rocks which fall in the second category. To summarize the supports, provide the following:

1. Protection against the fall of loosened rock fragments while, at the same time, no resistance is offered against the displacement of the surrounding virgin rock disturbed by the excavation.

2. Support against all loosened rock masses without preventing further loosening of the virgin rock.

3. Support partially stabilizing the excavated cavity by preventing rock displacement beyond a certain extent.

4. A perfectly rigid and powerful support preventing any movement of the surrounding rock.

5. An opportunity for the consolidation of the surrounding rocks with a view to relieving the permanent tunnel lining.

The temporary support may be provided by the following:

1. Prefabricated steel construction with subsequent independent permanent tunnel lining.

2. Temporary support by reinforcement like rigid steel structures followed by its successive concreting.

3. Anchoring of the intermediate roof layers by rock bolts to
upper lying layers of higher load-bearing capacity (roof bolting) with a subsequent decorative coating.

Mining method. It has been found that as the cross-sectional dimensions of the tunnel become smaller, it is easier work because natural bridge-action of the rock takes place. Therefore, it has been a long-established procedure to excavate the tunnel section in parts rather than attacking the full cross-section. These smaller parts are termed "headings" or "drifts." These headings are always adopted while working with moderately firm rocks and ground. The methods falling under this category are called classical or mining methods.

It must be noted that tunnel construction in parts implies the subsequent and repeated erection, dismantling, and removal of various temporary supports. This procedure requires not only much surplus work and a considerable additional consumption of supporting material, but gives rise also to additional roof subsidence and repeated loosening of over-lying rock, which results in increased rock pressure.

The modern tunneling practice uses "solid pressure grouting" of the voids left behind the over break line and lining as against the loose back packing applied with mining methods. The advantages of pressure grouting are: provision of complete back-filling, better supports for surrounding rocks on all sides of tunnel and substantially increased strength, load bearing capacity, and modulus of elasticity of the rock. It is particularly suitable for water supply or pressure
pipes where watertightness is an important aspect of tunnel construction.

Headings are mainly used for working and haulage purposes. In addition, headings are also important in geological explorations, direction control, and for various service liner and for drainage. The modern practice of tunnel construction is to construct a subsidiary tunnel running parallel to the intended proposed tunnel called a pilot tunnel. The pilot tunnel is usually started at both tunnel adits. These pilot headings serve not only for setting out the tunnel and the exploration of soil and hydraulic conditions, but also constitute an integral part of tunnel construction from the very beginning. They provide excellent panage for mucking out and help in successive enlargement of the excavation and lining of the final tunnel section. The most remarkable advantage of a pilot heading is that it reveals the geological profile through the whole length of the tunnel and also provides the best points of attack for excavation at any location of the tunnel. The important by-products are that haulage track, ventilation duct, electric compressed-air, and other service lines are all installed in the pilot heading. It also provides for the collection and drainage of ground water from the working places (adits).

Various types of supporting structures are used for supporting the over burden in the tunnel:

1. Timber headings: Timber headings are usually trapezoidal
because this shape is suitable for resisting both vertical and lateral pressures. The timbering consists of bents spaced at 3' to 4-1/2'
with timber logging supported on them.

2. Headings with steel supports: Here sheet-steel piles are used as legs supporting reinforced concrete bolts. The stronger legs have to be used here because of wider spacing of steel ribs. It must be noted, however, that the legs of these ribs may not be placed directly on the floor because of their comparatively small contact surface, but concrete blocks, reinforced concrete plates, or iron-covered-hardwood blocks must be inserted.

3. Precast reinforced concrete supports: The use of reinforced concrete sets combined with leggings either of reinforced concrete planks or wooden bolts economizes use of timber and steel. The advantage of such a system are: long service life and relatively high strength gained for comparatively little reinforcement.

"Cut-and-cover" method. While tunneling in loose ground and under water courses, the most commonly employed method is the combined "cut-and-cover" tunneling. The public utilities tunnels, serves, and shallow underground-railroad tunnels (commonly called subways) are often built with the cut-and-cover method. This is usually cheaper and easier to work with than tunneling up to depths of thirty-five feet in open trenches. The sides of the open trenches are supported with sheet piling or by simple timber bracing. The dewatering is usually effected
by draining ten sumps or by lowering the water table depending upon nature and the stratification of the ground.

The possible advantages of the cut-and-cover method are:

1. The haulage of excavated and constructional material is entirely above ground, giving obvious economy in time, distance, and hence cost.

2. The system is near the ground surface and passenger access quick and easy, eliminating the need for installing elevators or escalators which are costly.

3. The possibility is provided through running between the underground rapid transit and modern surface traffic system.

The possibilities of disadvantages with the cut-and-cover method are:

1. Interference with streets and property.

2. The route of cut-and-cover subways are restricted and streets where the facility is required may often be the ones where the closing of the roadway or diversion of traffic is least desired.

3. The cost of diverting and maintaining the services (like telephone cables, power cables, sewers, water mains, gas mains, hydraulic power mains, etc.) which are generally laid beneath the road surfaces can be very high.

4. The underpinning or the removal or reconstruction of buildings which may lie in the proposed alignment is sometimes very expensive. Severe disruptions may come up to the businesses carried on in
such buildings.

5. Rapid changes in the gradient of the ground through which a cut-and-cover subway is proposed may necessitate deep and expensive excavations.

6. The noise and vibration created by the rapid transit may be seriously objectionable in some cases.

When the traffic does not permit an open cut in the entire width, the pavement is taken up, necessarily at night, and replaced by a temporary deck under the cover of which the subway building may proceed. Where wide cutting would be objectionable, side walls and interior supports are build first in trenches, bore holes, or pits, and roofed after which the core is removed, and the bottom, insulation, and interior coating is placed. After the deck has hardened, the pavement may be replaced and surface re-established. The interference with street traffic is thus restricted to a minimum, i.e., the time required to place the deck, and a reasonable transfer of the enclosed public utility conduits is also made possible.

**Tunneling by sinking caissons.** This method is excellent while tunneling at a shallow depth below the ground surface or under river beds. It consists of sinking adjoining tunnel units as caissons from the surface, or, in the case of sub-aqueous tunnels, by launching and sinking pre-fabricated caissons in a previously dredged trench in a river bed. Basically there are two methods in this system.
1. Sinking caissons in the form of working chambers: Caissons used for this purpose may be constructed so that the working chamber is arranged separately underneath the pre-fabricated caisson or subsequently within the watertight enclosure of the established tunnel section. Sometimes, the inner space of the working chamber itself is converted later to the tunnel proper. Because of the higher elevation of such tunnels resulting from a much smaller cover depth, the length of approaches can be kept to a minimum.

The method is mainly used for the construction of sub-aqueous tunnels when the river bed is made of loose, permeable, silty layers to a considerable depth in which drainage by either direct pumping or compressed air would be impossible due to the hazards of blowing out with the latter and of boiling up with the former.

2. Floating caisson method: Public utility tunnels have been constructed in large numbers by pre-fabricated tunnel sections in dry docks or on launching ways, floating them to the site, and sinking them into a dredged trench with a suitably prepared and leveled sand bed. Afterwards, the sections are joined together into a continuous tunnel. The sinking operations are controlled by floating derricks or other means.

The internal pavements and coatings, ducts, etc., of the tunnel can all be prepared in the pre-fabricated units when in the dry docks or when floating, with the exception of the joint sections. The uniformity
and evenness of the subgrade of immersed units can be secured by subsequent hydraulic filling underneath or be more rigid end supports such as sub-aqueous bearing plates on pile groups, supporting the pile bed.

**Shield tunneling.** The tunnel shield is a moving metal casing which is driven in advance of the permanent tunnel lining to support the ground surrounding the tunnel-bore and afford protection for construction of the permanent lining without any temporary support or timbering.

In fact, the shield is a rigid cylinder open at both ends, providing facilities at its front for the excavation of ground materials and its rear for the erection of the pre-fabricated lining. Thus, the shield is always forced ahead by steps keeping pace with the progress of excavation and erection work to the extent that the excavated hole should be well supported until the permanent lining is constructed. A full cycle of shield tunneling comprises the following items:

1. Excavation and temporary support of the front face at an appropriate depth.

2. Advancing the shield, taking support from the previously erected lining.

3. Placing another course or ring of the permanent lining.

As the only face left unsupported during the working cycle is at the front, the amount of advance and of unsupported face area must
always be carefully adjusted to the actual soil and ground water conditions.

Shield tunneling offers four essential advantages:

1. The tunnel sections can advance with its full dimensions.
2. It offers a moving but constant support to the advance tunnel.
3. The omission of any temporary support is compensated for by the immediate installation of the permanent lining.
4. By speeding up construction work, it prevents the development of higher rock loads.

The limitations of this method are found in hard rock where excavation must be effected by blasting, thereby making it necessary to exclude it partly because of the sensitivity of its inherent missionary and partly because of the loss of its steerability.