Special Design Features of Baytown Vehicular Tunnel

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THE tunnel is 3,000 feet between portals, with open approaches 550 feet long on each end, carries two-way traffic on a roadway 22 feet wide between curbs with a minimum vertical clearance of 14 feet at the curb lines, and provides for the future widening of the ship channel to 700 feet and its deepening to 40 feet. Roadway grade from the midpoint to the future channel lines is 1 percent, and from there to the upper end of the open approaches the maximum grade is 5.83 percent.

The major part consists of nine sunken tube sections, six of 300 feet and three of about 250 feet length. They were constructed as circular steel shells 34 feet, 10 inches in diameter, with an interior lining of 30 inches of reinforced concrete placed while the shells were floating at the construction site. The tubes were sunk into a trench dredged across the channel, in which was placed a sand foundation course 3 feet thick. Steel screeds levelled this course to proper grade. The sections were joined and sealed under water, to permit entrance at the ends and removal of interior bulkheads.

Cut-and-cover sections and open approaches are reinforced-concrete structures, protected by outside multi-ply waterproofing. Part of the north cut-and-cover section was built into the ventilation building. The open approaches, ventilation building and cut-and-cover section between the north portal and the ventilation building are supported on piles.

To allow for differential settlement between pile-supported structures and parts resting directly on soil, a short length of each cut-and-cover tunnel was designed to form an articulated joint, which required development of connections which could transmit shear, permit deflection, yet be watertight. Joints between sunken tubes had to be designed to permit sufficient play during the sinking operation, but remain suitable for sealing from the outside by simple methods.

A method was developed to produce economically a satisfactory appearance of the exposed concrete surfaces of the open approaches. This was obtained by the use of simple, square-form panels made of rough-sawn lumber. Investigation of air flow indicated a longitudinal ventilation system, supplying fresh air through a duct below the roadway and exhaust of vitiated air through the portals, would be satisfactory. A fluorescent tunnel-lighting system with high intensity at the portals was designed. Investigations of suitable plastics for the covers were made, with Plexiglass as the final selection.

The drainage system was designed for maximum rainfall at the rate of 4 inches per hour and for a 10-minute downpour at 8 inches per hour. Deepwell pumps and booster pumps supply the fire main and hose outlets in the tunnel. Telephone and fire-alarm systems were provided.

● THE Baytown Vehicular Tunnel crosses the Houston Ship Channel near its junction with Galveston Bay, connecting the cities of Baytown and La Porte. It provides a more-direct route from the important refinery and petroleum production area of Baytown to the highly industrialized region of eastern Texas than is possible with the rather inadequate ferry service. The tunnel and its connecting highways were built as a federal-aid project under the jurisdiction of the Texas Highway Department, with participation by the Bureau of Public Roads. The construction cost of the tunnel and the hydraulic embankment of the approach highways was $8.6 million with an additional expenditure of $1,450,000 for highway pavement. The first contract was let in August 1949, and the tunnel was opened to traffic on September 22, 1953. It is operated as part of the Texas State Road System by the Highway Department.

The tunnel itself carries two lines of traffic and new highways extending from it across San Jacinto Bay in the south and Black Duck Bay in the north, are dual roadways, each 30 feet wide.

The Baytown Tunnel offered an unusually favorable opportunity for construction by the sunken-tube method, because both shores of the ship channel at this location were free from buildings of any sort. This permitted extension of the tube trench without obstruction beyond the channel lines as far as the water depth permitted floating of the sections into place. Since the welded steel shells of these tubes offer the best protection against leakage, it was logical to make the sunken tube part of the tunnel extend as great a distance as possible. This led to the adoption of a total of nine tube sections, six having a length of about 300 feet each, and three measuring approximately 250 feet, giving a total length of 2,558 feet of tunnel by sunken-tube construction. Short pieces of cut-and-cover construction extend the total length to 3,000 feet, portal to portal. Open approaches 550 feet long carry the roadway from the portals to an elevation of +19.0 feet, which is 4 feet above the highest hurricane tide on record. The solid balustrades around these approaches are 3 feet higher than this grade. This arrangement provides sufficient protection against flooding of the tunnel and makes the installation of flood gates unnecessary.

The profile of the tunnel was determined by the requirements of the proposed future widening of the channel to 700 feet and deepening to 40 feet, with provision for a minimum sand cover of 5 feet over the tunnel structure, even if the channel were over-dredged to a 45-foot depth.

From the deepest point at the center, the roadway rises at a 1-percent grade to the channel lines, where the grade changes to

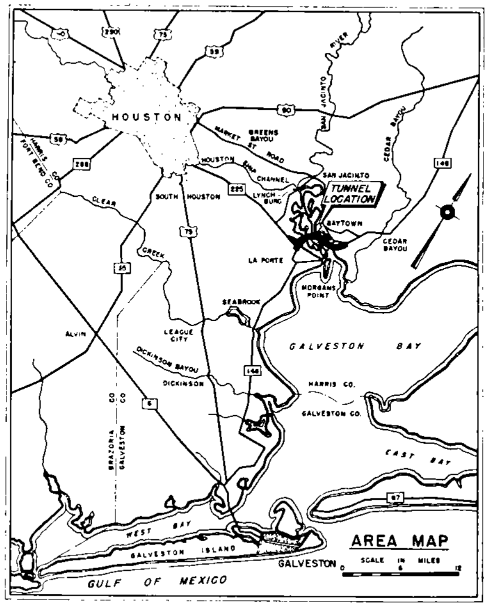


Figure 1.

5.83 percent, which is maintained to the end of the open approaches. The width of the roadway is 22 feet between curbs in the tunnel; this is increased in the open approaches by the addition of another lane on the off-going side. Thus, slow-moving vehicles can pull over to the outside lane as soon as they leave the tunnel to permit faster cars to pass. A minimum height of 14 feet is provided over the roadway at the curb lines, the critical points in the arch-shaped interior of the tunnel.

The soil conditions also were suitable for the proposed type of construction, since they permitted dredging of a trench across the channel with reasonable side slopes, and except for some accumulation of heavy sludge, this trench could be kept free of sediment without difficulty until the tubes were sunk. Under a 10-foot top layer of channel dredgings, there was encountered a 2-foot to 3-foot layer of organic material, then about 55 feet of silty sand, underlain by stiff clay.

Currents in the channel presented no problem, since they are normally low, due to the small tidal range. No severe hurricane tides occurred during the construction period. The only disturbances experienced were wave wash created by vessels ignoring the

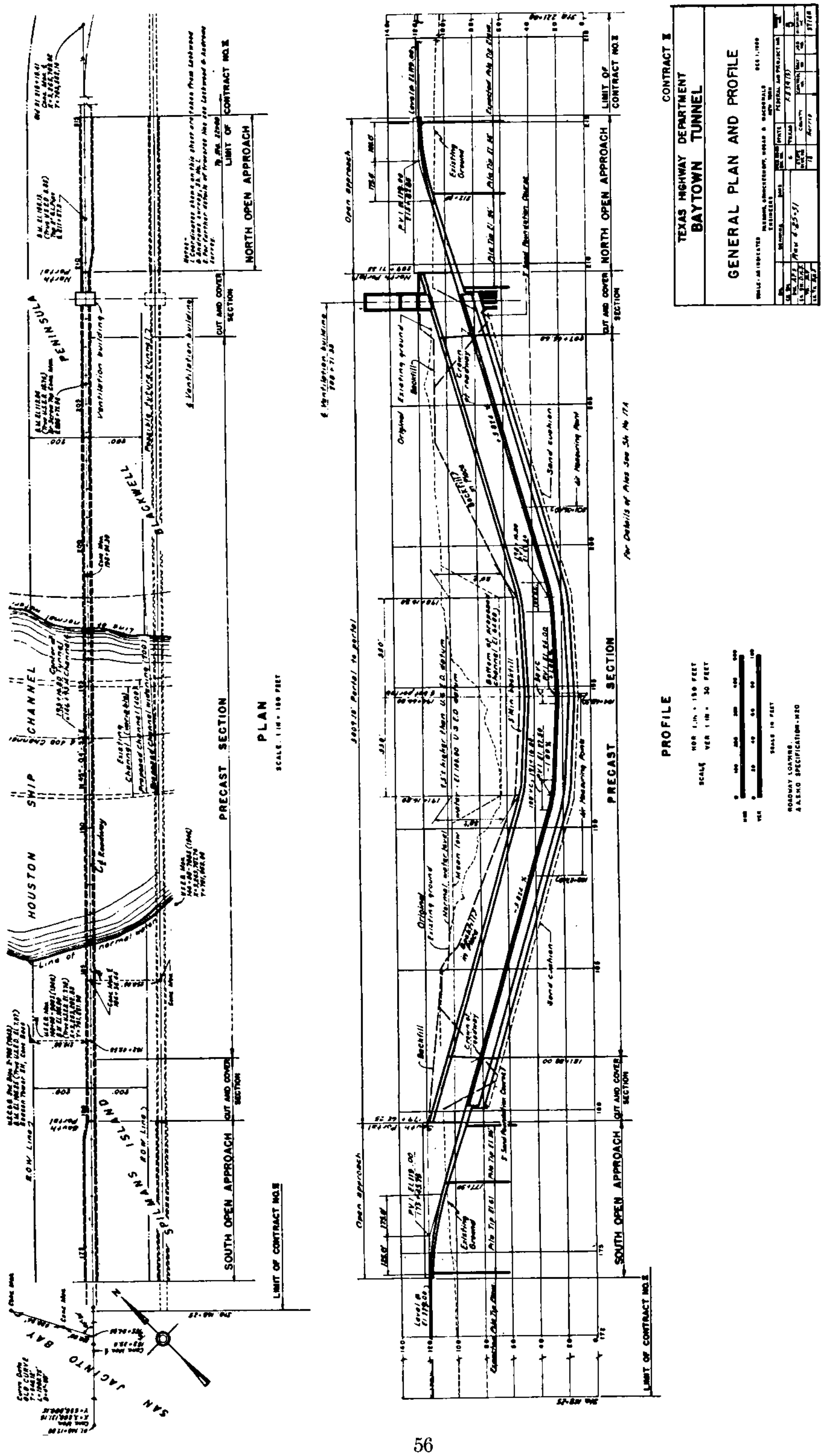

CONTRACT II
TEXAS HIGHWAY DEPARTMENT
BAYTOWN TUNNEL
GENERAL PLAN AND PROFILE
PLAN
PROFILE
NORTH OPEN APPROACH
CUT AND COVER SECTION
PRECAST SECTION
SOUTH OPEN APPROACH
LIMIT OF CONTRACT NO. II
HOUSTON SHIP CHANNEL
PENINSULA
BLACKWELL
SAN JACINTO BAY
Open approach
Ventilation building

Figure 2.

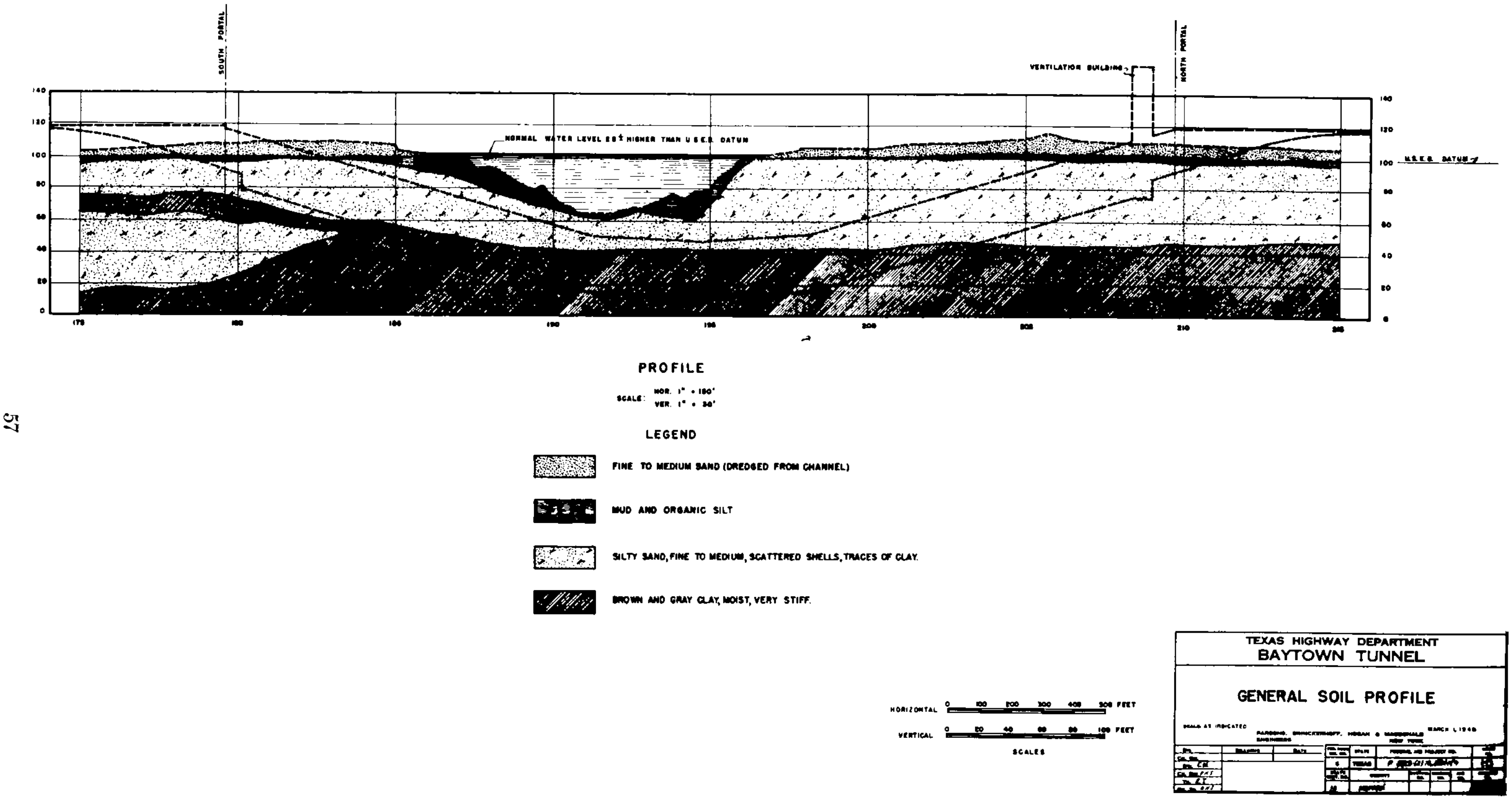

SOUTH PORTAL
NORTH PORTAL
VENTILATION BUILDING
NORMAL WATER LEVEL 2.3± HIGHER THAN U.S.E.D. DATUM
U.S.E.D. DATUM
PROFILE
SCALE: HOR. 1" = 150'
VER. 1" = 30'
LEGEND
FINE TO MEDIUM SAND (DREDGED FROM CHANNEL)
MUD AND ORGANIC SILT
SILTY SAND, FINE TO MEDIUM, SCATTERED SHELLS, TRACES OF CLAY.
BROWN AND GRAY CLAY, MOIST, VERY STIFF.
HORIZONTAL
VERTICAL
SCALES
TEXAS HIGHWAY DEPARTMENT
BAYTOWN TUNNEL
GENERAL SOIL PROFILE

Figure 3.

slow-down order in the narrow channel, which on several occasions seriously buffeted floating sections being made ready for sinking, and, in one instance, tore one tube loose from its moorings.

SUNKEN-TUBE SECTIONS

Each sunken tube consists of a welded circular steel shell, about 35 feet in diameter, made of ½-inch plate, and stiffened by interior rings of 6-inch T sections welded to the shell and spaced 5 feet 7½ inches on centers. These tubes were built from subassemblies on shipways. All splices and connections were made by the arc-welding process. The ends of the tubes were closed with square, steel dam plates, which were welded to the shell and supported by heavy steel beams. Before launching, all seams were tested for tightness by a compressed-air stream and soap solution. Access to the interior was provided by means of several hatchways in the top of the shell. These water-tight tubes were launched and towed from Orange, Texas, to the construction site on the south side of the channel.

While the tubes were floating in a basin dredged in the south channel shore, the 30-inch reinforced-concrete lining and the road-way slab were placed in successive pours. As the sections were slightly buoyant without the interior tile finish, curbs, sidewalk, and roadway pavement, they had to be ballasted for sinking. Sand was placed in the tubes through stacks attached to the hatches while they were suspended from the sinking barges. The hatches were then sealed inside the stacks and the latter removed, after which the section was ready for the sinking operation.

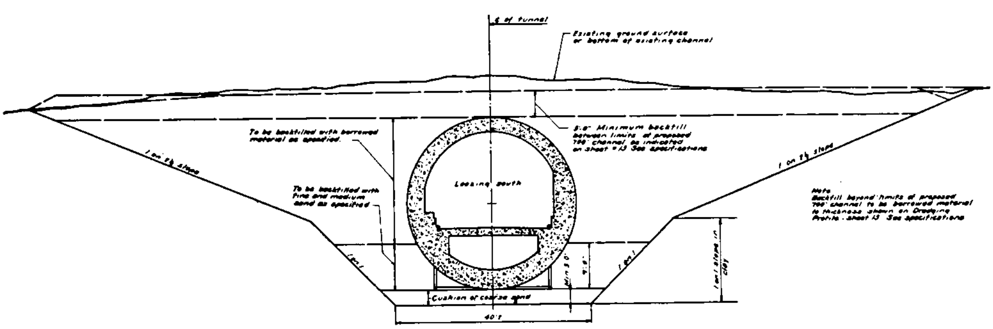
To set the tubes to the correct grade, a layer of coarse sand was placed to a minimum thickness of 3 feet in the bottom of the trench, which had been dredged across the channel. This foundation course was leveled by a screed made of large steel beams, suspended from a carriage supported on a special float. The latter was anchored over the trench against vertical and horizontal movements from wind and tide, and the tracks for the carriage were set parallel to the desired grade. The movement of the screed back and fourth graded the foundation course with such accuracy that the deviation from the correct slope in the entire length of a 300-foot tube in no case exceeded 3 inches. The sinking of the tube was regulated by steam winches on the two sinking barges from which it was suspended and controlled by instruments from the shore, using sighting masts attached to each end of the section as targets. The maximum error in horizontal alignment achieved was less than 1 inch in either direction.

Five horizontal steel saddles welded to the underside of each tube kept it upright on the foundation until the trench had been backfilled with well-graded sand to a depth of 11 feet. The rest of the backfill and cover over the tubes consisted of silty sand dredged from the channel.

Each section had to be designed for the following loading conditions:

Shell on Shipways. Due to the continuous support by the blocking, the ring and longitudinal bending stresses in the shells assembled on the ways are very low.

Shell During Launching. A cylindrical structure of this type would inherently be



TYPICAL TRENCH SECTION FOR TYPE S

SCALE: 1/8" = 1'-0"

Figure 4.

more suitable for side launching, but outside of the Great Lakes district, there are few launching ways of this type available. The fabricator therefore elected end launching, for which temporary longitudinal stiffener beams had to be welded to the top of the tube. This reduced the compression stresses, which might have caused buckling of the shell plate at the moment when the section was supported by buoyancy at the outer end and on the fore-poppet at the inboard end, while sliding off the ways.

Shell Floating During Concreting. During the placing of the concrete lining and roadway slab, while the section was floating in the water its immersion increased, resulting in continuously changing stresses. By limiting the size of the pours, the increments of increase in pressure were controlled to keep the ring stresses in the section and the bending stresses in the shell plates within permissible ranges. Longitudinal bending stresses were limited by starting the pours at the quarter points of the section and proceeding uniformly toward the ends and the center. Ring and transverse bending stresses were calculated under the assumption that the rings were cut at the top. A maximum calculated stress of 26,000 psi. in the stiffening rings was reached during the second pour. As the lining began to participate and stiffen the shell, the bending stresses were reduced until a practically moment-free condition was obtained at the moment when the tube was awash. A circular section whose weight is equal to its buoyancy and is distributed equally around its circumference is free of transverse bending moments when fully submerged.

Tubes in Final Location. As tubes are sunk, they are subjected to increased compression but not bending stresses, until the backfill is placed. This condition is closely approximated by the tubes before ballasting. Even when considering the effect of the roadway and ballast during and immediately after sinking, the stresses in the section are considerably below those of the design condition described below.

Tubes in Place and Backfilled. Backfilling of the trench by sand and silty sand will create vertical and horizontal pressures on the structure. Following standard practice, it has been assumed that the overburden over the tube produces uniform vertical pressure on the top of the tube, and that the active side pressure varies in linear proportion from the top of the tube to the bottom and is equal at any point to the vertical pressure above that point multiplied by a coefficient. The latter may vary between 0.27 and 0.50, depending upon the degree of consolidation of the fill.

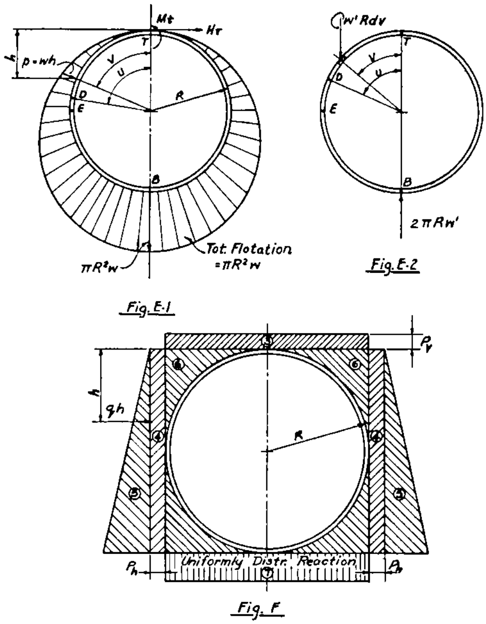


Figure 5.

With the freshly placed fill, which has a low angle of repose, the larger coefficient is the governing factor, and the lateral pressure is at its maximum. Since the moments created by it are opposed to those caused by the vertical load, this condition is not critical.

As the fill consolidates, the angle of friction increases, the side pressure decreases, and the coefficient falls off to the lower value. This permits a greater effect of the moments produced by the fill resting directly on the tunnel and results in the critical design loading of the section. In order to avoid excessive use of reinforcing steel, the plans limited the maximum height of backfill over the tunnel to about 30 feet for the two end sections at each shore. For the tubes under the deep water, this fill did not exceed 20 feet.

Once the fill has completed its consolidation, which may take considerable time, the material can be considered as an elastic continuum.

This will permit extending the fill for an additional height of 5 to 7 feet, if desired in the future, without increasing the stresses in the tubes.

In order to calculate the stresses for the design condition, the loading was divided into separate components. Stress coefficients developed for large horizontal pipe lines by James M. Paris were applied to these loading areas, the combination of which gave the actual design stresses. These reached the following maximum values:

Concrete compression	1,175 psi.
Compression steel	11,750
Tension steel	20,700

Weights of materials assumed were as follows:

Moist earth above water	110 lb. per cu. ft.
Submerged earth	62
Water	63

Design stresses for sustained loading conditions were within AASHO specifications. For design purposes, the steel shell plate was not considered a part of the structural tunnel section.

An important factor in the sunken-tube construction is the design of a joint which allows ample clearance for the sinking operations and, at the same time, lends itself to efficient sealing from the outside. Gasketed joints have been used but have not generally proven satisfactory. The design for the Baytown Tunnel called for a circular steel collar 31 feet in diameter extending 4 feet from each dam plate at the ends of the sections. The tubes are set with a normal clearance of 6 inches between adjacent collars. From the lower half of the collar on the tube already in place a hood plate projects 15 inches to form a cradle for the collar of the next tube to be sunk. This, in turn, carries a similar hood on its upper half. These hoods have an inside radius 1 inch larger than that of the collars, which provides adequate play when the tubes are sunk. Cast steel lugs riveted to the lower and upper hoods have matching holes, one round and one elongated, through which divers insert 5-inch-diameter steel pins to connect adjacent sections after they have been lined up. The annular space between the collar and hood plates can easily be caulked by the divers to hold back the tremie concrete with which the joint is sealed from the outside. The outer forms for this concrete are provided by the sand foundation at the bottom, into which the dam plates penetrate, and by curved steel closure plates attached to the vertical edges of the dam plates, by matching sheet pile interlocks welded to the dam and closure plates. The latter slide easily into place after the tubes have been pinned together. The tremie concrete seals the joints sufficiently to permit draining them from the inside and removal of the bulkheads. A steel ring is later welded to interior stiffeners located on each side of the joint to form a continuous, completely watertight steel shell. Placing of the concrete lining then completes the joint.

CUT-AND-COVER SECTIONS

After completion of the sunken-tube portion of the tunnel, dikes were backfilled over the end sections to a height sufficient to permit excavation and unwatering of the trench for the construction of the cut-and-cover sections in the dry. These sections have a length of 220 feet each and were designed as reinforced-concrete arches. Loads and design stresses were similar to those assumed for the sunken tubes. Waterproofing of four-ply membrane was applied to the outside of the structures and was protected with 4 inches of concrete.

The fact that these sections contained transitions from structures resting directly on the subsoil to parts supported on piles posed the problem of allowing for possible differential settlement. On the north side, the ventilation building straddles the tunnel and contains part of the cut-and-cover section, the whole unit resting on piles, as do both open approaches and the cut-and-cover section between the ventilation building and the north portal.

The parts of the cut-and-cover sections adjacent to the pile-supported structures were designed to function as articulated members by building into them two flexible joints about 30 feet apart. At each of these members the longitudinal reinforcing bars of the bottom slab were crossed vertically and grooves were formed in the top and bottom of the slab to leave only 8 inches of solid concrete. This permitted the connection to act as a hinge while transferring shear and served to prevent longitudinal movement.

The sidewalls and arch at these points were cut through completely to form open joints, which were sealed with double water stops and filled with plastic filler. One waterstop was made of 24-ounce copper, shaped to permit longitudinal movement, the other was a Gates rubber waterstop with dumbbell-shaped cross section. Similar waterstops were built into the bottom slab at the hinge points. Joints were also provided in the roadway slab at these locations. At the ventilation building, the upgrade end of the articulated part of the cut-and-cover tunnel is carried on a cylindrical socket type support which permits rotation.

TUNNEL FINISH

It may seem incongruous to finish the approximately 150,000 sq. ft. of interior tunnel surface with a material which requires that about eight pieces must be set for every square foot, or about 1.2 million tiles altogether. But ceramic tiles are still the material which best combines durability with the basic requirements of a good tunnel finish—good light reflecting quality without glare and an easily cleaned surface. The entire tunnel was finished with off-white ceramic tile, with the exception of the vertical face below the service walk and the edge on the opposite side, which were surfaced with tan-colored terra-cotta tile.

The roadway slab was covered with a separate concrete wearing course at least 3 inches in thickness, reinforced with steel-wire mesh. This concrete also served the purpose of equalizing slight irregularities in the grade of the roadway slab, particularly at the joints of the sunken tubes.

OPEN APPROACHES

The open approaches are U-shaped reinforced-concrete structure supported on concrete piles. During the construction stage, with the ground water lowered to foundation level, the entire weight of the structure had to be supported on the piles. On the other hand, extreme high water creates enough buoyancy to overcome the full weight of the open approaches, causing them to uplift. The piles were therefore tied into the bottom slab, so they could act as anchors under these conditions.

The section was designed for the two basic loading conditions mentioned, using similar weights and earth-pressure coefficients as those given for the sunken tubes.

The satisfactory treatment of the high concrete walls of the open approaches created an architectural problem. Smooth surfaces require either rubbing or meticulous and expensive form work and, even then, present a monotonous appearance on which all later streaking, from any cause, is conspicuous. Furthermore, rubbing destroys the hard concrete surface and reduces its resistance to weathering. Square form panels made of striated plywood were first considered. In these the grain of the plywood is raised by sand-blasting or edging to give a pattern to the concrete surface. Tests were made with this method on the Elizabeth River Tunnel, which was built during the same period, but the results were not entirely satisfactory. Even with great care in oiling the panels and in stripping the forms, enough concrete stuck in the grooves to obliterate the pattern after a few usages. The expense of the plywood and its scarcity made the replacement of forms every few pours impractical. Next, some 4-foot-square panels of regular form lumber were made and set so that the boards would run vertically and horizontally in alternate panels. This was further improved by using boards cut on a very rough saw, resulting in a coarser surface. As a last refinement, V-shaped battens were nailed over the panel joints. The result was highly satisfactory on both the Baytown Tunnel and the Elizabeth River Tunnel, and this method is recommended whenever a better appearance of concrete surfaces is to be achieved with a small increase in the cost of forms. The same panels were used over and over again without loss of texture.

VENTILATION BUILDING

As previously mentioned, the single ventilation building is directly over the north cut-and-cover tunnel and forms a part of it. It rests on a concrete mat supported on timber piles. The entire structure, including the part above ground, is of reinforced concrete. The exterior finish consists of Cordova limestone veneer, black glazed brick and aluminum louvers for the air intake areas. The building houses the ventilation fans; fire pump; drainage sump and pumps for the north approach; electrical switch-gear, transformers, and controls; emergency power generator; heating plant; locker rooms for the attendants; and an elevator operating from the service-walk level of the tunnel to the fan-control room. A hatch in the second floor permits lowering of any large unit, such as a fan motor or rotor, onto a truck which can enter the ground floor.

SERVICE BUILDINGS

A service building adjacent to the ventilation building houses a crash truck, tunnel washing truck, and other service vehicles used for tunnel and highway maintenance. A smaller building at the south open approach provides shelter for a second crash truck and its crew.

TUNNEL VENTILATION

Prior to the building of the Holland Tunnel under the Hudson River (the first underwater tunnel for automobile traffic), extensive tests were made by the tunnel authority, the U. S. Bureau of Mines, and the University of Illinois to determine the maximum permissible carbon-monoxide contamination of air breathed by humans, the nature and quantities of exhaust gases emitted by automobile engines, and the flow of air in concrete ducts. The ventilation system designed on the basis of these tests gave such satisfactory results that the same fundamentals are still used today. Supplementary tests of engine exhaust gases made in the early 1930's showed little deviation from the earlier results. Improvements in modern automobile engines have undoubtedly raised their efficiency, as a result of more-complete combustion, which also lowers the carbon-monoxide content of the exhaust. This condition is influenced to a large degree by the state of maintenance and does not warrant a material change in the ventilation provided. In practically all tunnels in operation it was found that the air requirements are largely determined by the necessity to maintain proper visibility and reduce haze, resulting in a CO contamination of the tunnel air of less than half of the maximum of four parts per 10,000 permissible. The increased use of diesel engines in trucks and buses aggravates the haze condition but, at the same time, somewhat reduces the CO emission. The use of haze detectors was investigated, but no commercially available devices were found to be satisfactory for the very low densities involved, without requiring an unreasonable amount of maintenance. The eyes of the tunnel guards are today still the most reliable instruments for this purpose. However, some progress made in this field of late offers promise for tunnel applications.

Most of the earlier automobile tunnels were of a length requiring transverse ventilation, in which fresh air is supplied through a duct under the roadway and at openings spaced at regular intervals along each curb and the vitiated air is exhausted through vents in the ceiling into an air duct carrying it to the exhaust fans. Shorter tunnels, such as the one at Baytown, can be provided with a simpler system giving longitudinal air movement. Supply fans located in the ventilation building on the north side furnish fresh air to the duct under the roadway, from which it enters the vehicle space through flues located about 15 feet apart on both sides.

The vitiated air flows along the roadway space and leaves the tunnel through the portals. The length to which this system can be extended is limited by air velocities in the supply duct and in the vehicle space. Under maximum conditions, the latter reaches about 12 mph. in the Baytown Tunnel, which is in no way objectionable. Local wind conditions may slightly unbalance the air flow to the two portals, but this has no serious effect, since the proper amount of fresh air is supplied to each foot of tunnel. The flue openings are adjusted in width to distribute the air supply evenly over the entire length.

The maximum air quantity is required when both lanes are congested with slow-moving vehicles, as may happen in the event of unusually heavy truck traffic or stoppage for any reason. This calls for 600,000 cfm., supplied by two fans running at high speed. A third fan, of the same size, is available as a standby. Each of the fans is driven by a high-speed electric motor to which a smaller two-speed motor is connected through an overrunning coupling. The fans can be operated, therefore, at full, half, or quarter speed, giving ample flexibility in adjusting the air supply to the traffic requirements. It is interesting to note that in all existing tunnels the fan power averaged over the year amounts to only about 7 per cent of the maximum needed for the design conditions. It is of great importance, however, to have available the calculated air quantities in the few instances when they are needed. The fans are of the centrifugal, nonoverloading, double-inlet type, with backward-curved blades.

Two carbon-monoxide analyzers take continuous samples from two locations in the tunnel about 110 feet from each portal, and print a record of the CO content. Should the contamination reach 3 parts in 10,000, an automatic alarm will ring.

Serious consideration was given to automatic control of the fans through the CO detectors, but it was decided that unattended operation of a facility of this nature would be unwise, and since an operator should be on duty at all times, the automatic feature would be a detriment rather than a boon.

ELECTRICAL SYSTEM

Electric power is brought to the tunnel by overhead pole lines from both sides of the channel, thus insuring a reliable supply. However, this area is occasionally visited by hurricanes which could readily damage both of these lines simultaneously, leaving the tunnel without power. For such an emergency, a 150-kilowatt diesel-engine-driven generator has been installed in the ventilation building. While this is not sufficiently large to supply the maximum amount of air, which requires 300 horsepower for each of two fans, it will be adequate to maintain traffic through the tunnel with minimum ventilation and lighting. Two sets of transformers change the incoming primary power from 11,000 volts to 480 volts, which is used in the motors. Additional transformers supply proper power to the lighting systems.

All electrical controls are located in the control room of the ventilation building, in dead-front, metal enclosures. The CO recorders are mounted in separate cabinets next to the electrical controls.

The tunnel is lighted by two continuous lines of fluorescent lamps mounted in the top of the arch. In order to limit outage of lamps in case of circuit failure, the power for these lights is furnished by two three-phase circuits. The fluorescent lamps are of the instant start, slimline type, 72 inches long. They are protected by transparent Plexiglass covers, provided with gaskets and compression fittings to make watertight enclosures. Fourteen two-lamp fixtures are connected to an emergency circuit which, in case of power failure, will automatically be switched to an auxiliary source. This consists of a storage battery with sufficient capacity to operate the lights until the emergency diesel generator is put into service. The direct current of the battery is converted to alternating current by a motor-generator which is kept idling at all times by a small alternating-current motor.

In order to reduce the contrast between daylight and the tunnel interior, the lighting intensity at the portals is increased for a distance of about 300 feet by four additional rows of fluorescent lamps. These can be switched in pairs to adjust the amount of light to prevailing outside conditions.

The lighting intensity at roadway level is 35 footcandles in the portal sections and 10 footcandles in the interior (by actual measurement after completion of the tunnel). Under service conditions, these values will be somewhat reduced, but should not fall below 30 and 6 footcandles, respectively.

FIRE PROTECTION AND DRAINAGE

Fire-hose outlets are spaced about 250 feet apart in niches on both sides of the roadway. These are connected to a 6-inch water main running the entire length of the tunnel. Water for fire protection and general use in the buildings is supplied by two 500 gpm. deep-well pumps with a discharge pressure of 40 psi., which is maintained in the system by a pneumatic tank. In case of fire, the pressure is raised to 125 psi. by two booster pumps located in the ventilation building.

Chemical fire extinguishers are mounted in each of the hydrant niches.

Three transverse interceptors in each approach collect the precipitation falling into the open approaches. One of these is located about midway on the open approach, the second in front of the tunnel portal, and the third about 20 feet inside the tunnel. Pipelines carry the water from the interceptors to sump chambers, located in the basement of the ventilation building on the north side and under the roadway pavement at the end of the air duct on the south side. Three electrically driven, automatically controlled pumps discharge the contents of each sump overboard into the ship channel. Sump and pump capacity are based upon a continuous rainfall of 4 inches per hour, and a 10-minute downpour at a rate of 8 inches per hour, with one of the three pumps acting as standby. A sump at the mid-point collects any water entering the tunnel drainage system, which is discharged by electric pumps to one of the main sumps.

TRAFFIC-CONTROL SYSTEM

Traffic lights are mounted at intervals of about 400 feet over each roadway lane. Control stations along the service walk permit setting all signals in either direction from the portal to any point in the tunnel on amber or red, leaving the off-going signals from this point to the other portal on green.

FIRE-ALARM SYSTEM

Fire alarm stations along the tunnel service walk can be used by the guards to actuate signals in the two crash truck stations and in the ventilation control room.

SERVICE TELEPHONE

A sound-powered service telephone system with stations in the tunnel along the service walk, in the ventilation control room, and in the crash truck stations provides intercommunication between these points for tunnel guards, crash-truck crews, and main operator. Outside telephone service is brought into the main control room.

ENGINEERING AND CONSTRUCTION

For the Texas Highway Department, D. C. Greer, state highway engineer; R. B. Alexander, bridge engineer; and J. Douglas, district engineer in Houston, exercised general supervision over the project. J. M. Page represented the Bureau of Public Roads. Parsons, Brinckerhoff, Hall & Macdonald was in charge of design and construction of the tunnel. Brown & Root, Inc. of Houston was the contractor for the sunken-tube tunnel. Farnsworth & Chambers, Inc., also of Houston, was the contractor for the remainder of the tunnel project.

Theory of Corrosion and Prevention of Paint Failures

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THIS paper discusses: (1) simplified presentation of the theory of corrosion of structural steel, outlining the electrical nature of corrosion, the electromotive series for metals and causes of difference in potential, galvanic cells and their action, mill scale (its composition, structure, why it accelerates corrosion), and mill-scale lifting; (2) the action of paint in preventing corrosion by inhibitors of corrosion, mechanical barriers, and sacrificial action of paint pigments; and (3) causes and prevention of paint failures—the types that occur in paint films on structural steel and methods of eliminating such failures.

●CORROSION has been defined as the destruction of a metal by chemical or electrochemical reaction with its environment (*13*). Two general types of corrosion occur: direct chemical oxidation and electrochemical. In direct oxidation, corrosion occurs by chemical reaction of metal with a gas. In the case of iron, iron plus oxygen forms iron oxide:

$$Fe + \tfrac{1}{2}O_2 \rightarrow FeO \qquad (1)$$

Since there are various forms of iron oxide, the corrosion products should be specified.