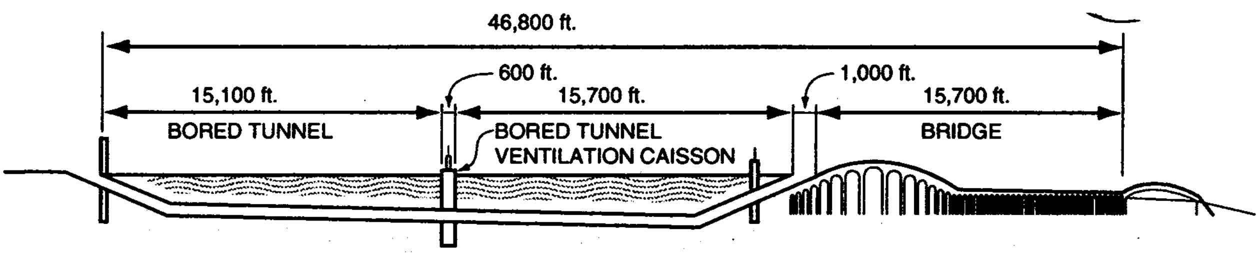

Fig. 2-11. Trans-Tokyo Bay Tunnel.

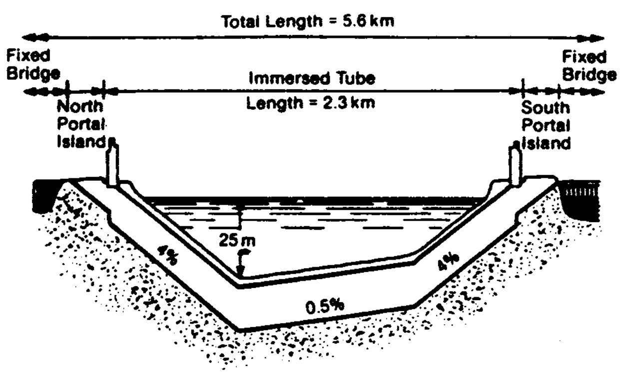

Fig. 2-12. Hampton Roads Bridge–Tunnel.

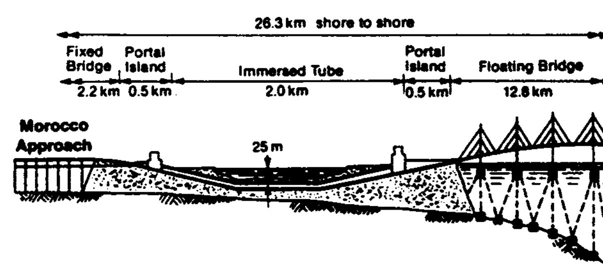

Fig. 2-13. Gibraltar Bridge–Tunnel (proposed). The Moroccan side is shown; the Spanish side is similar.

A different concept for a bridge–tunnel crossing was presented to the Madrid Colloquium on the proposed Gibraltar crossing in 1982 (Kuesel, 1982). Adapted to the particular site conditions of this project, the concept is shown in Figure 2-13. Two immersed tube tunnels, catering to separate European and African shipping channels, together with four portal islands, are provided in moderately deep water. The shallow-depth sections of the crossing adjacent to both shores are covered by fixed bridges, and the central deep gorge by a floating bridge structure.

As can be seen from this brief catalog of existing and proposed projects, the variety of solutions to undersea tunnel projects is matched only by the variety of site conditions to which they must be adapted. No one concept is superior for all conditions. For each new proposed project, the full range of possible alternatives should be considered in order to develop the best solution.

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Division of Responsibility between Resident Engineer and Contractor

Survey costs are small in comparison with the expenditures involved in tunnel driving. Nevertheless, if tunneling is held up because of faulty survey work or because of interference by the engineer's survey crew with driving operations, the resulting losses can be considerable. For this reason, specifications relating to tunnel driving accuracy should be written as a performance specification, and the contractor should have full responsibility for transferring line and grade from the primary surface control into the tunnel and for development of tunnel construction control procedures. If delays or rework are caused by errors in the basic survey data furnished by the engineer, or by unwarranted interference during the engineer's check survey operations, contractor claims for additional compensation are inevitable.

Before the start of construction, the engineer's surveyor performs all survey work such as preliminary surveys and primary control surveys on the surface. During construction, the engineer's survey responsibility should be limited to maintaining the basic survey network, monitoring existing structures, and checking results of the contractor's work. This includes making sure that underground survey control of adjoining contractors agrees at the contract interface. Check work should be done by the engineer's quality control surveyor on a defined schedule, with both field and office work completed and reviewed by the engineer as soon as practicable to detect any errors in the contractor's survey work, and to limit the impact on construction that such errors may cause. Any out-of-tolerance differences with the contractor's surveys or deviation from construction plans should be verified and brought to the contractor's attention without delay.

Both space and time for surveys are usually limited in tunneling projects. Although it is essential that the engineer's and contractor's surveyors maintain independence in their field and office operations, it may be feasible to combine forces when time and/or space are critically limited. This can be achieved by assembling a composite survey team and equally sharing the task of making survey measurements and observations, with each party independently recording all measurements and completing computations. If data collectors are used, the data log can be copied, or the original log can be used by both parties for their computations and preparation of plans.

Information concerning groundwater level as obtained from observation well readings is of vital importance for the contractor's tunneling operation. It is, therefore, reasonable to include installation of observation wells, maintenance of the wells, and periodic reading of water levels in the contractor's contractual obligation. Water level records should be made available to the engineer at the time of recording.

Level readings of surface settlement points, which serve as indication of construction problems at the tunnel heading, are not in the immediate practical interest of the contractor. As a matter of fact, the chance of inaccurate level readings during times when heading problems are encountered is greater than during normal operation. The contractor is preoccupied with the construction problems at the heading during times of trouble and, therefore, spends minimal time on required surface level readings. For this reason, surface levels over the tunnels should be run and evaluated by the quality control surveyor, and the results should be made available to the contractor. Installation and monitoring of special recording devices, such as subsurface settlement points, inclinometers, and strain gauges, should also be the quality control surveyor's responsibility.

TUNNEL GEOMETRY

Relationship of Centerline Track to Centerline Tunnel

On a rapid transit system, centerline of track and centerline of tunnel are normally not identical because of clearance requirements. Centerline of track is the basic control during layout of the system. During construction of the tunnel, however, it is desirable from a practical standpoint that the contractor's and the engineer's field personnel use centerline of tunnel rather than centerline of track as the basis of tunnel control.

The vertical and horizontal offset from centerline of track to centerline of tunnel varies with the superelevation of track. The resulting tunnel centerline is a curve of complex mathematical definition (Figure 3-14). Therefore, a tunnel centerline should be developed that is composed of tangent, circular, and transition spiral sections and approximates the complex theoretical tunnel centerline within a specified tolerance (0.25 in.). This centerline should be incorporated into the contract drawings of the tunnel contract, and all tunnel control should be based on this curve.

A computer printout listing coordinates of points, tangent bearing, and elevation of points and slope at 5-ft intervals on the tunnel centerline should also be incorporated into the contract documents. Since stationing of centerline tunnel and centerline track will not agree because of different curve radii, station equations between centerline tunnel and centerline track should be incorporated at the beginning and the end of each construction contract, at TS (tangent spiral) points, at SC (spiral curve) points, and at such points as vent shafts or cross passages. Stationing for tunnel centerline should start at station 0 + 00 for each tunnel contract. Stationing of track proceeds through the entire system, which, generally, is made up of several tunnel contracts.

If the rapid transit system has a natural center point from which several lines branch out in different directions, the station 0 + 00 should be assigned to this point. Stationing then proceeds to the outlying areas, and future extensions of the system can be added without upsetting the stationing sequence.

Working Line. The working line is the survey line used by the contractor's field personnel to establish shield or tunnel is driven, it is recommended that some additional vehicle clearance beyond the specified tolerance be incorporated into the tunnel design to absorb deviations of the magnitude outlined above. If clearance is not provided, realignment of the track or roadway centerline may be necessary to fit the as-built conditions.

SURVEY FOR CONSTRUCTION OF IMMERSED TUBES

Horizontal and Vertical Control

All tubes and bridges have different conditions for survey and construction control due to terrain, climatic conditions, reach of water crossing, vessel anchorage, vessel traffic, density of shoreline development, restrictions imposed by military reservations, parks, penal institutions, etc. Short tubes, less than a mile long, usually need three intervisible primary monuments at each end, with the tube centerline being defined, if possible, by the line between one centerline monument on each shore. Tubes longer than a mile may need additional monuments on islands, piers, bridge footings, or other sites near the tube centerline to serve as additional control during construction, when construction equipment may impede line of sight along centerline.

These monuments should be tied to National Geodetic Survey control stations or other primary monuments selected for the project, using dual-frequency GPS to attain 1:70,000 horizontal accuracy. Elevation of all monuments should be determined to Second Order Class 1 accuracy, based on NGS survey monuments whose historical record confirms little or no settlement. To ensure that the elevation of monuments at each end of the centerline is nominally correct, a level survey should be conducted between the two monuments by "Valley Crossing" methods, if site conditions permit. (This assumes that it is not feasible to conduct a level survey directly between end monuments.) The Valley Crossing method entails two calibrated level instruments or first-order theodolites sighting simultaneously in each direction to determine elevation difference between instruments.

If site conditions render Valley Crossing levels infeasible, closed level circuits should be run from each end monument to a temporary benchmark established on the shoreline. Then, during a windless period of slack tide, the elevation difference between the temporary benchmark and water surface should be measured simultaneously at both ends. This observation series should start one hour before predicted slack tide, and continue with measurements repeated at 15-min intervals until one hour after apparent slack tide. Unless the tube alignment crosses an area of excessive currents, elevation difference derived from the water transfer measurements should agree with direct level elevation of the TBMs within 0.2 ft. A third option to confirm the agreement in elevation between controlling end monuments is to determine the elevation (referred to the spheroid) of each end monument and each NGS benchmark using GPS survey and computational procedures. A disagreement larger than 0.3 ft in any of these procedures may indicate possible error in elevation of the primary benchmarks, or errors in leveling from the primary benchmarks to the controlling end monuments.

Mapping. 1 in. = 40 ft or 50 ft photogrammetric maps with 2-ft contour intervals are prepared over the terminal sites, and hydrographic surveys of a 2,000-ft wide corridor centered on the tube alignment are conducted along cross sections at nominal 200-ft intervals.

Subbottom, electromagnetic toning, magnetometer, and sonar side scan surveys are conducted at this time if needed to locate pipelines, cables, and the like. Surveys may also be needed to position rigs for geotechnical surveys and borings.

The foregoing photogrammetric mapping and hydrographic survey data is composited into mylar map sheets covering the project corridor at 1 in. = 100 ft or other suitable scale with coordinate grid, monument locations, hydrographic spot elevations and/or contours, boring locations, notations indicating horizontal and vertical datum, monument coordinates and elevations, scale bar, date of survey, north arrow, etc.

Shipyard Survey of Tube Sections. As the final horizontal alignment of a tube being laid is solely governed by the tube geometry and the relationship of its inboard end with the outboard end of the adjoining tube in place, a mathematical model of key points on each constructed tube section is needed to determine fit and angular relationship between the ends of adjoining tube sections. This model is constructed by first establishing a precise reference baseline in the concrete ways of the shipyard, affixing temporary survey targets to key points on the tube (before launching), and conducting a survey to determine local *XYZ* coordinates of each key point relative to the shipyard baseline. This survey can be done either by triangulation or by Total Station survey using reflective targets at the tube key points. In both cases, the reference baseline monuments serve as origin for coordinates and elevations. Each key point is observed from at least two baseline monuments, reading three sets of horizontal and vertical angles using a 1-sec theodolite or Total Station. Height of instrument should be measured to 0.001 ft at each instrument setup (Figure 3-30).

The *XYZ* coordinates derived from this survey describe the relationship between key points on an inclined model, because the tube is in an inclined attitude on the ways. These coordinates are then rotated to describe the model as it would be when the tube is laid on its design slope. The key point coordinates of the inboard end of the tube can then be compared with the outboard end coordinates of the adjoining tube in place. With this data (especially coordinates of the two key points on the lateral axis of the tubes), the final location of the outboard end of the tube to be laid can be projected, and shims for the joint can be designed if needed.

During steel construction of the tube in the shipyard ways, the contractor's surveyors will conduct surveys and layout out-tube centerline and other points controlling construction.

contractor made four notches on the top shaft ring, two each on the tunnel centerline and two on its perpendicular. Wires with flagging were then stretched between the notches, and an optical plumb bob set near the ends of each wire to transfer the centerline and its perpendicular to the tunnel floor. The benchmark was transferred down using a 300-ft steel tape. The starting station was established as the perpendicular, and the centerline was transferred to the shaft wall above the tunnel crown. The tunnel grade was transferred to the tunnel wall, 5 ft above the invert, to three pairs of tunnel spads. This enabled tunnel workers to do line and grade control with strings and plumb-bobs. The transfer of control from the surface into the tunnel was accomplished using a theodolite and a Leica engineer's level adapted for vertical sighting (auto plumbing).

The tunnel boring machine was guided by a laser beam mounted on the tunnel wall. Transparent targets were mounted about 45 ft apart on the front and rear of the machine. The use of double targets allowed the operator to check the position and attitude of the machine as it bored though the rock.

A procedure was developed to negotiate curves in the mining process using prisms and chord offsets. The curve was divided into 100-ft segments. This produced a small series of small curve portions, except for the beginning and end of the curve. Prisms were set for the 100-ft segments, and the chord offsets computed. Tapes were placed on each of the targets, and the operator kept the laser on the offset mark while mining the curve. Distortions caused by radial offset in the laser are compensated for in the laser adjustment, as it was moved and adjusted every 500 ft.

A Total Station and engineer's level were used to extend the tunnel traverse monuments through the tunnel. A north-seeking gyro was used at 1,250-ft intervals to check the line of the tunnel. As the mining proceeded past dropshaft sites, checks of shaft locations developed from the tunnel traverse were compared with the coordinates of the dropshaft sites developed from monuments at the surface. Adjustments to the tunnel monuments were made as needed using the compass rule.

The contract specifications stipulated the tolerances allowed in the tunneling process. One contract stated that an error of only 24 in. would be allowed in the lateral alignment over a tunnel length of 9.3 miles. The contractor was able to maintain tunneling accuracies well within the specifications. On a recently completed project, the largest error was 2.5 in. over a distance of 4,000 ft of tunnel. Since the tunnel accuracy was checked at dropshaft sites, the alignment was corrected before proceeding. Most tunneling deviations were attributed to the guiding of the boring machine or variations in the rock rather than the accuracy of the surveys.

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