The work on Taiwan's high-speed rail line has involved a total of 39 km of bored tunnels and 8 km of cut-and-cover tunnels. Most of the tunnels are on the northern segment of the alignment, and their design and construction required a variety of techniques.

The emphasis in this article will be on the civil works component of the project delivery method. The civil works component will also operate the line. The system will be transferred to the government of Taiwan upon the expiration of the 35-year concession period. The system is designed for travel at 350 km/h, but the actual operating speed will initially be 300 km/h. The line will go into operation this October and will be fully operational in 2006.

Situated about 145 km off the southeast coast of the Chinese mainland, Taiwan is 393 km long and occupies approximately 35,758 km². Forested mountain ranges cover about 70 percent of the island and are prevalent on the eastern side. The plains for the most part are on the western side and are home to approximately 95 percent of the island's 23 million people.

The principal cities of Taiwan are Taipei, which is on the island's northern tip and has a population of 5.9 million; Kaohsiung, which has 2.6 million inhabitants and is the largest city on the island's southern seaboard and the world's third-busiest container port; and Taichung, roughly halfway between the other two, with 1.7 million inhabitants. Given the concentration of population on the island's western side, conventional intercity transportation options are proving unequal to demand, and the strain is leading to a deterioration in service. In view of the growing demand for intercity travel expected in the future, the government of Taiwan decided that high-speed rail, with its safety, energy efficiency, environmental friendliness, and minimal demands on real estate, would answer the need and make it possible to balance regional development. Day trips between any two points on the western side of the island would then be quite easy. Planning for the project began in earnest in late 1996, when the government opted for build/operate/transfer (BOT) as the project delivery method. The bureau set the project alignment and was responsible for surveying and for acquiring the right-of-way.

Under the BOT approach, the rail project is being constructed by the Taiwan High Speed Rail Corporation (THSRC), the private-sector company that will also operate the line. The system will be transferred to the government of Taiwan upon the expiration of the 35-year concession period, and was chosen to spare the government the financial burden of construction and to take full advantage of the efficiency and entrepreneurial spirit of the private sector in improving the island's infrastructure. This is Taiwan's first BOT rail project. In addition to being one of the most challenging infrastructure projects ever undertaken in Taiwan, it holds the record for being the world's largest (in dollar terms) private-sector-financed construction project. Total construction investment (excluding land acquisition and financing costs) is approximately U.S.$15 billion.

The THSRC has also been let for the main workshop (Yenchiao) and for four depots and maintenance bases (Liuchia, Taipao, Tsoying, and Hsinchu). The work includes the following:

- Advance work (site preparation, utility relocation, etc.
- Civil works;
- Stations;
- Depots and maintenance bases;
- Track work;
- Mechanical and electrical work for core systems (rolling stock, signaling, traction power, ancillary facilities, and telecommunications).

In addition to 12 design/build contracts for the civil and structural engineering work (involving Japanese, South Korean, German, Dutch, French, Italian, British, U.S., and Taiwanese firms), there are 2 systemwide turnkey contracts for core systems. One of those two is for design and procurement; the other is for integration, installation, and commissioning. Five contracts for track work have been awarded on the design/build basis, and six station contracts (Taoyuan, Hsinchu, Taichung, Chiayi, Tainan, and Tsoying) have been let using the traditional design/build method. Contracts have also been let for the main workshop (Yenchiao) and for four depots and maintenance bases (Liuchia, Taipao, Tsoying, and Wajhi).

The THSRC assembled a multinational project management team that, at last count, included staff from 40 countries and draws on the expertise of prominent international firms. One of these firms, Parsons Brinckerhoff International (PBI), has had a number of roles on the project, from independent checking of portions of the civil works design to actually designing all the yards and shops and supplying key individuals within the project management team.

The emphasis in this article will be on the civil works contracts, which encompass the total alignment (345 km).

The rail project is divided essentially into six major contract components, each involving one or more contracts:

- Advance work (site preparation, utility relocation, etc.);
- Civil works;
- Stations;
- Depots and maintenance bases;
- Track work;
- Mechanical and electrical work for core systems (rolling stock, signaling, traction power, ancillary facilities, and telecommunications).

By C. Michael Gillam, P.E., and Bradford F. Townsend, P.E.
• 39 km of bored tunnels with a finished cross-sectional area of 90 m²;
• 8 km of cut-and-cover tunnels (including a 2.8 km long tunnel on the approach to the station at Taoyuan);
• 351 km of prestressed concrete girder viaduct and steel through truss bridges;
• 32 km of cut-and-fill embankments.

The northern section of the alignment, between Taipei and Taichung, is generally mountainous, and construction here has relied on tunnels, viaducts, bridges, and embankments. This region required a variety of design and construction techniques for both the tunnels and the viaducts. The stretches of alignment between tunnel segments are on viaducts, with short lengths in cuts or on embankments.

The southern section, between Taichung and Kaoshiung, is constructed on an alluvial plain, and nearly all of the alignment is on viaducts and bridges. The deep alluvial or colluvial materials here are often overlain by soft clay that varies in thickness, conditions mandating deep foundations. The viaducts in this section are generally designed and erected as simply supported single-cell box girders of prestressed reinforced concrete.

The total length of the civil works for the guideway being constructed by the thsr is about 330 km. (This does not include the structural works between the Nankang and Panchiao stations within Taipei, which have been undertaken by the Ministry of Transportation and Communications [MOTC] through the Taipei Railway Underground Project Office and are to be fitted out by the thsr.) The civil works include the following:

• Two terminal stations, in Taipei and Kaoshiung (Taoying), and six intermediate stations (Nankang, Xinyi, Hsinchu, Taichung, Chiayi, and Tainan) will be part of initial operations. These terminal stations (Miaoli, Chungli, and Yulin) and a second station in Kaoshiung are to be added after operations commence.

• Depots and storage yards will be available in the north (Hsinchu), center (Wuji), and south (Taoying).

• Bases for civil infrastructure and electrical and mechanical maintenance facilities are located in the north at Liuchia and in the south at Taipao.

• The main workshop for assembly, overhaul, repair, and maintenance of rolling stock is near Wenchau, at the southern end of the line.

• The control center for operations is located in the station at Taoyuan.

This section is designed to attract ridership by placing the emphasis on efficiency and functionality. The stations are generally just outside the major urban areas, which allowed for tailored development of the adjacent land.

The thsr project will have double tracks for the main line plus side tracks at the station diversions. The 1,435 mm standard track gauge at 4.5 m track centers will permit operation at speeds up to 350 km/h. The line will normally operate 18 hours a day. Express trains from Taipei to Kaoshiung (with a three-minute stop in Taichung) will make the trip in 90 minutes, whereas trains stopping at the six intermediate stations will take 120 minutes.

The project required approximately 48 separate double-track tunnels, the total length of the tunnels being 47 km. The tunnels are generally shallow with low groundwater levels. The geological conditions were generally known in advance, and the formations encountered were relatively homogeneous for the entire length. The shallow tunnels made multifaceted drives possible in constructing additional shafts and adits, which was a boon in adhering to the construction schedule.

The thsr selected Taiwan Shinkansen Corporation and Taiwan Shinkansen International Engineering Corporation to design, manufacture, and commission the core electrical and mechanical systems for the line. These two firms are made up of shareholders from the famous Japanese “bullet train” technology and come 40 years after the inauguration of the Tokaido Shinkansen Line, which links Tokyo and Osaka. Thirty 12-car trains will be supplied by Kawasaki, Hitachi, and Nippon Sharyo. (The T in the model type denotes Taiwan, the rolling stock being custom made for the Taiwanese market.) The trains will initially operate at a maximum speed of 300 km/h, and each cost approximately US$40 million. Each train can seat 989 passengers, a figure that includes 66 in business class. Standard passengers will be seated five abreast, three on one side of the center aisle and two on the other. The cars will have restrooms, vending machines, and telephones. The first-class section will have 48 by 2010.

Each contract is administered by an employer’s representa-
tive (mr), who focuses on contract compliance, conducts limited design reviews, and in general monitors and audits the contractor’s contract compliance with an emphasis on quality and safety. In the case of the civil works contracts, each contractor employed a contractor’s independent checking engineer, who was responsible for assessing and evaluating the contractor’s design and certifying that the design met the thsr’s requirements. The role of the mr changed with respect to quality management in the design and construction processes. For design, the mr focused on monitoring the contractor’s quality assurance procedures, reviewed the contractor’s designs for contract compliance, and facilitated the contractor’s interac-
tions with the other parties having a bearing on design. For construction, the mr carried out random inspections and monitored and audited the contractor’s quality control measures.

In addition, the thsr appointed a joint venture to serve as an independent checking engineer (ctc) and independent site engineer (nite). In those capacities the joint venture monitored, audited, and spot-checked the design, construction, and commissioning of the project or collateral work.

As a further measure, the thsr has retained the services of an independent validation and verification (tv&v) engineer. The tv&v will verify and validate—by a thorough examination and auditing of contract records and of the nite and ctc reports, as well as by spot-checking—that the permanent works designed and constructed meet the requirements of the thsr project with respect to function, quality, and safety. The tv&v will provide the thsr with the overall certification and recom-

mendation for licensing to revenue operations.

With high-speed operation in mind, the alignment has been designed to be as straight as possible. Viaducts and bridges are used in the plains, while tunnels, cuts, and embankments are used on the mountainous terrain because of the gradient limit. Although the alignment had to be designed for ultimate operation at 350 km/h, speeds will, as mentioned above, initially be limited to 300 km/h. This requirement is met throughout the line, except for a few small sections in Kaos-
shiung and Taipei that were built within the existing railway infrastructure or are parallel to the existing railway.

The minimum horizontal radius of curvature was set at 6,250 m. Only one exception was allowed where, because of a constraint, the radius was reduced to 5,556 m within a radius of 25,000 m. This resulted in a minimum horizontal radius of curvature of 7,500 m. The steepest grade is a 3.5 percent grade, and the steepest curve is a 1,600 m radius. These grades and radii are included in the mountainous terrain on the northern half of the railway. In many cases, an effective vertical radius of curvature was as low as 19,000 m.

Curves with large radii and long tangents were used to the greatest extent practicable, but a few other points had to be considered in view of the high speeds involved. The spiral type is referred to as a half-sine spiral because the changes in radius and cant follow a sine curve rather than a straight line so as to avoid sudden changes in the lateral rate of change in the rate of change of the lateral rate of change. This resulted in a sharp curve at high speeds. Track centers and tunnel clearances were determined by aerodynamic considerations; consequently, the track centers were set at 4.5 m. Platform tracks and other tracks parallel to the main line were set at centers of not less than 6.60 m from the nearest high-speed track.

High-speed operations with all station platforms being on parallel platforms tracks rather than on the main line required the use of high-speed turnovers. To prevent the turnovers from limiting speeds into and out of stations, the turnovers were designed for speeds up to about 160 km/h on the diverging track in four locations. To avoid excessive jolts into and out of these turnovers, long, large-radius turnovers with spiral switch points and spiral adjacent to the cross-end were used. The platforms on the main line all have power-operated swing noise reductions. Each platform has a maximum of 50,000 m² and none exceed 1.2 percent. In keeping with normal civil engineering practices in Taiwan, vertical curves between grades are parabolic but are determined by calculating the vertical acceleration equivalent radius. The desirable limit for vertical acceleration was 0.20 m/s², equivalent to about 2 percent of gravity, which gives a calculated radius of curvature of 49,000 m at 350 km/h. However, since this resulted in impractically long vertical curves in certain cases, an effective vertical radius of 25,000 m was used in many locations, and in a few isolated locations the figure is as low as 19,000 m.

Through steel trusses were used to carry the twin tracks over certain roadways and water courses. Of particular note is the crossing of the river south of the Taichung station, where three parallel Warren truss bridges were built.
risk was adopted for the project, and the division of seismic zones was based upon a hazard analysis. The maximum peak ground accelerations for the various zones, although they are different, are equivalent to the same earthquake intensity. There are four zones, and the maximum peak ground acceleration would equate to a seismic event intensity of between 7 and 8 on the Richter scale. This criterion is equal to that used in designing nuclear power plants in Taiwan.

The six stations were designed by different architectural teams using concepts and designs tailored to achieve efficiency and functionality and adapted to the particular needs of each site. Passengers using the stations will be able to purchase tickets and obtain travel information and will find taxis, parking facilities, and shopping outlets. They will also be able to make connections with buses and urban rail systems.

In general, “station areas” will include both “station land,” used for the station proper, peripheral passenger transfer facilities, parking areas, and other transportation facilities, and “enterprise development land,” used for such subsidiary commercial enterprises as hotels, stores, banks, conference centers, restaurants, and recreational and entertainment venues. According to the construction and operation agreement signed by the MRT and the MRTA, the former will have the right to use the transportation facility land for 35 years and the enterprise development land for 50 years.

The station at Hsinchu is notable for its innovative design, its shimmering roof suggesting an airborne leaf, perhaps a nod to the windy conditions that often prevail in Hsinchu. The city is renowned as a high-tech center, and the station incorporates glass, metal, and exposed concrete in a highly imaginative way. The effect is made more dramatic and engaging by the display of both modern and traditional works of art. The architectural design of the elevated one-story station, with its parabolic space frame roof clad with metal sheeting, is striking.

The design and construction of the viaducts generally relied on bored, cast-in-place pile foundations and spread footings supporting single columns of reinforced concrete. The prestressed-concrete single-cell box girder viaduct was erected using a variety of techniques, among them movable scaffolding and advanced shoring, the full-span precast launching method, the free cantilever method, the balanced-cantilever method, and the full support method.

In addition, the project includes a number of through steel truss and composite long-span bridges. With the exception of those steel and composite bridges, the spans of the bridge and viaduct structures are generally shorter than would be found on equivalent road structures, among them movable scaffolding, and advanced shoring, the full-span precast launching method, the free cantilever method, the balanced-cantilever method, and the full support method.

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The project required a total of approximately 1.39 million m³ of drilled piles 1.5 to 2 m in diameter. For the piles, 50 m in length, as many as 82 were put in place each day. In constructing the bridges and viaducts, the peak rate achieved was 18.6 km per month. The work with the single-cell box girders of prestress, prestressed concrete typically resulted in producing one box girder per casting bed per day. This allowed for a peak launching rate of 303 spans (9.1 km) per month, or approximately 10 spans per day.

Through steel trusses were used to carry the train tracks over certain roadways and water courses. Of particular note is the crossing of the river south of the Taichung station, where three parallel Warren truss bridges were built. Each truss comprises three continuous spans, the lengths being (from north to south) 150, 120, and 140 m. The members are welded box sections of rectangular shapes. Some parts of the spans were fabricated in Japan, others in Kaohsiung. The bridge sections were assembled on-site using high-strength bolts. A sophisticated erection scheme devised to assemble the first two spans of the bridge in the center on temporary supports and launch the bridge to the south abutment using a 108 m long cantilever. The entire bridge was moved sideways into its final position to the right side (looking south) to allow erection of the next truss. The procedure was then repeated for the next truss, which was launched and moved to the left side (looking north). The third truss was then erected and launched between the two previously erected and placed trusses with a maximum launching tolerance of approximately ±150 mm from the centerline. The bridges were supported on two of the biggest post bearings (per span support per truss) ever manufactured, the maximum vertical capacity (ultimate limit state) being approximately 70,000 kN. To resist any horizontal seismic forces, mechanical shear keys with capacities in the range of 30,000 kN were required. To ensure uniform distribution of longitudinal seismic forces among the piers supporting the spans, a series of shock-transmitting units, each with a maximum capacity of 10,000 kN, have been installed.

Since the train alignment is along the densely populated west coast of the island, the tunnel did not pass through mountain ranges with high overburden and unknown geological and hydrological conditions. The tunnels were generally shallow and the geological conditions were visible along much of the alignment. Typically, the formations encountered involved cohesive and cohesionless soils of marine deposition, gravel and sedimentary rock; or a combination of soil, gravel, and rock. Excessive hydrostatic conditions caused a few problems in construction, primarily in the tunnel in Huksou, which was driven under a head of 70 m.

The tunnels were typically advanced using an approach that relies on sequential excavation and support since this method was seen as most suitable for the tunnel sizes and geometries. The schedule benefited from the use of available construction adds, even though this approach was quite labor intensive. However, the flexibility in adjusting to changing geological conditions offered by sequential excavation and support made this method the most effective way of adhering to the construction schedule. It minimized the time and cost consequences of unattended occurrences and allowed contractors to take appropriate action in the event of failure.

An excavation diameter approaching 15 m, resulting in an excavation area ranging from 135 to 155 m², was required to allow for the finished geometry that would house the double-track main line. The finished tunnel cross-sectional area is typically at least 90 m² to accommodate the aerodynamic aspects of high-speed train travel. This cross-sectional area is dictated by the health and safety requirements that must be met when trains pass one another in the confined space of a tunnel at high speed. The cross-sectional area of the standard 13.50 m diameter double-track tunnel is approximately 92.15 m² above the track slab, thus allowing room for construction tolerances.

Some of the tunnels have the potential to develop a sonic boom at the portals. Accordingly, some portals required an enlarged pressure relief structure 20 m long with a cross-sectional area equivalent to a 150 percent increase of the tunnel finished cross-sectional area for pressure wave dissipation.

Most of the mined tunnels were constructed as drained tunnels. In a few specified areas where harm to the environment was a concern, the tunnels had to be designed as undrained. The final liner, which is 400 to 600 mm thick, is
typically a reinforced-concrete shell designed to support the opening without the benefit of the temporary liner. All tunnels are designed with the internal drainage systems and niches required by the core system contractor, typically not exceeding 250 m. Emergency egress from the main tunnel is required for all tunnels in which the portal-to-portal distance exceeds 3,000 m.

There are 42 mined tunnels on the project, their lengths ranging from 92 to 7,360 m. The overburden reaches 115 m, and the water tables are medium to high. Typically 40 to 50 of the approximately 80 tunnel drive faces were being excavated at any given time during the project. The 42 mined tunnels have a total length of 39,050 m.

For completion of the works, the THSRC required that the contractors prepare a baseline critical path program supported by what are called time-chaining schedules. These schedules made it possible to see how the linear tunneling operations were interacting with other schedules and with access to the site. In this way robust plans to execute the construction could be formulated. The tunnel excavation totaled approximately 5.5 million m³, which, allowing for a bulking factor, meant that roughly 7.3 million m³ of tunnel spoil had to be handled. These estimated volumes do not include the work associated with the ancillary adits and shafts.

Tunnel excavation began in November 2000 and all tunnel headings were essentially completed by July 2002, 21 months later. This was achieved at an approximate average project rate of 77.6 m per day, or approximately 2 m per day per drive face. Rates of as much as 12 m per day were achieved on some drives on occasion. Accordingly, approximately 40,160 m³ of sprayed concrete lining (shotcrete) was placed per month to support the tunnel heading excavations. The excavation of the drive was typically advanced in three stages: heading, bench, and invert.

To maintain the project schedule, work on the permanent reinforced-concrete lining began in November 2001 and continued through March 2004 for the main drives. In some cases, more forms were ordered by the contractors to meet the schedule. This resulted in casting approximately 1.1 million m³ of reinforced-concrete tunnel lining. An average casting rate of 67,530 m³ per month was achieved during the prime execution of the work. This resulted in an approximate pour of one 12 m long block per day on some contracts where the contractor had an efficient forming system.

In general, tunnel excavation and lining installation followed the proposed and approved schedules, which were based on the overall project programming requirements to meet specified completion dates so that the track work contracts could commence. The THSRC reduced the risk of program overrun by adopting a milestone performance strategy that relies on material (cableing). The projections are integral with a concrete base (roadbed) that supports the ca mortar. Installation was “bottom up,” the roadbed progressing at a rate of approximately 50 m of single track per day on up to 20 separate fronts, allowing 1 km of track roadbed to be constructed per day. Laying the precast slabs, pumping in the ca mortar, and pouring the caaling typically progressed at a rate that made it possible to complete 400 m of single track per day. The rail fastenings, ca mortar, and caaling were supplied from Japan, with the precast-concrete units manufactured locally at three factories.

The twin track forms comprise a rail fastening system with a bolted spring clip attached to a twin-block concrete sleeper with an exposed lattice reinforcement. The sleepers are concreted into slab sections that are typically 7,500 mm long and underlain by a 150 mm thick concrete protection layer installed across the width of the civil works structure. The protection layer and the slab are separated by a sheet of foil (thin rubber membrane) and held in place by “camplasts” (tapered rectangular concrete upstands) integrally concreted to the protection layer and surrounded on all four sides by flat rubber bearings. The camplasts are arranged along the track centerline, and a typical (7,500 mm long) track slab has four camplasts. Installation is “top down” once the concrete protection layer and the camplasts have been poured. Concreting of the track slabs progressed at a rate of approximately 100 m of single track per day. The rail fastenings and the initial batches of sleepers were supplied from Germany, with the remaining sleepers produced locally.

The high-speed turnouts for the main line were supplied by a German firm and are based on designs and geometries that are standard in Germany. However, the turnouts were based on a standard Japanese turnout design for thsr60 but were adapted for thsr geometry. Several types of high-speed turnouts were used, depending on the prevailing line speed, including four 10,000/4,000 m transition turnouts with components over 50 m in length and an overall installed length of 131 m. Delivering these components caused a number of shipping and inland transportation problems. The turnouts for the two depots, two maintenance bases, and the main workshop were supplied by a Japanese firm but were adapted for thsr turnout geometry.

The programming and management of the private-sector-financed thsr project are a significant accomplishment in that the infrastructure created will provide a solid underpinning for future economic growth in Taiwan. As mentioned previously, the project also represents the debut of the bullet train outside of Japan. Record rates in erecting the guideway and constructing the tunnels were achieved. The success of this project has in part been due to the cooperation shown by the various parties involved—the contractors, the designers, and management personnel from the THSRC. The technical, contracting, and management lessons learned on this mammoth project are sure to be of benefit to the future in projects in other parts of the world.

As mentioned previously, the project is scheduled for completion later this year, and the thsr is rapidly making the transition from construction organization to railway operator.

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