PCI DESIGN AWARD WINNER

Precast Prestressed Concrete Structure Provides Solution for Getty Center Tram Guideway

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To solve the problem of transporting visitors from an underground parking structure up a steep hillside to the new J. Paul Getty Museum (near Los Angeles, California), a people-mover system was devised. The design and construction of the guideway structure supporting this people-mover system posed several unique challenges to the designers and builders of the project. The answers to these challenges came in the innovative use of precast/prestressed concrete components combined with post-tensioning. This article presents the design features, precast concrete fabrication, and construction highlights of the project.

Precast and prestressed concrete played a prominent role in the design-construction of a 1080 m (3535 ft) long, curved, U-shaped tram guideway near the city of Los Angeles, California. This guideway structure supports a people-mover system, which rapidly transports visitors from an underground parking structure next to the San Diego Freeway to the main plaza outside the new J. Paul Getty Museum. Fig. 1 shows an aerial view of the tramway project alongside the San Diego Freeway (Interstate 405).

The Getty Center is a cultural complex dedicated to the visual arts and humanities. The facility will feature the new J. Paul Getty Museum, a scholarly research library, scientific laboratories for conservation of cultural property, and headquarters for the programs and administration of The J. Paul Getty Trust. The Center lies alongside Interstate 405 in the Sepulveda Pass between the San Fernando Valley

Fig. 1. The Getty Center Tram guideway winds up the Southern California hillside along the San Diego Freeway, and blends in beautifully with the site.

and the Los Angeles basin in Los Angeles, California (see Fig. 2).

The new museum will complement the existing museum at the Villa located on the Pacific Coast Highway in Malibu. The location of the Getty Center presented the logistical challenge of moving a large number of people from an entry point at an underground parking structure next to the San Diego Freeway to the arrival plaza of the Getty Center and to the new museum atop an adjacent hillside overlooking the Los Angeles basin.

The site has limited access — only one service road and a fire road with extremely steep grades. The site is also located in a secluded, quiet residential area of West Los Angeles. This resulted in restrictions on construction activities and on people-mover system configurations. With these problems confronting them, the Getty Trust decided that a people-mover system would be needed to shuttle Center visitors from the parking garage to the museum on a dedicated guideway.

SYSTEM PROCUREMENT

After a competition among vehicle system suppliers that included pricing, guideway aesthetics, vehicle and train appearance, pollution-free operating conditions, and low noise, Otis Transit Systems Inc. of Farmington, Connecticut, was chosen as the vehicle system supplier. The Otis system uses cable-driven, air-cushion supported vehicles.

The Otis contract was a design-build contract with the project contractor, Dinwiddie Construction Company (DCCo). Otis was to provide the vehicles, subsystems, and guideway design to DCCo; DCCo would then subcontract the guideway construction to a select shortlist of qualified bidders. With the added responsibility of guideway design, Otis contracted with BERGER/ABAM Engineers Inc. of Federal Way, Washington, to design the guideway structure.

THE PEOPLE-MOVER SYSTEM

The tram system guideway is single lane with a double-lane off-center bypass section. Two separate trains will operate in a shuttle configuration on

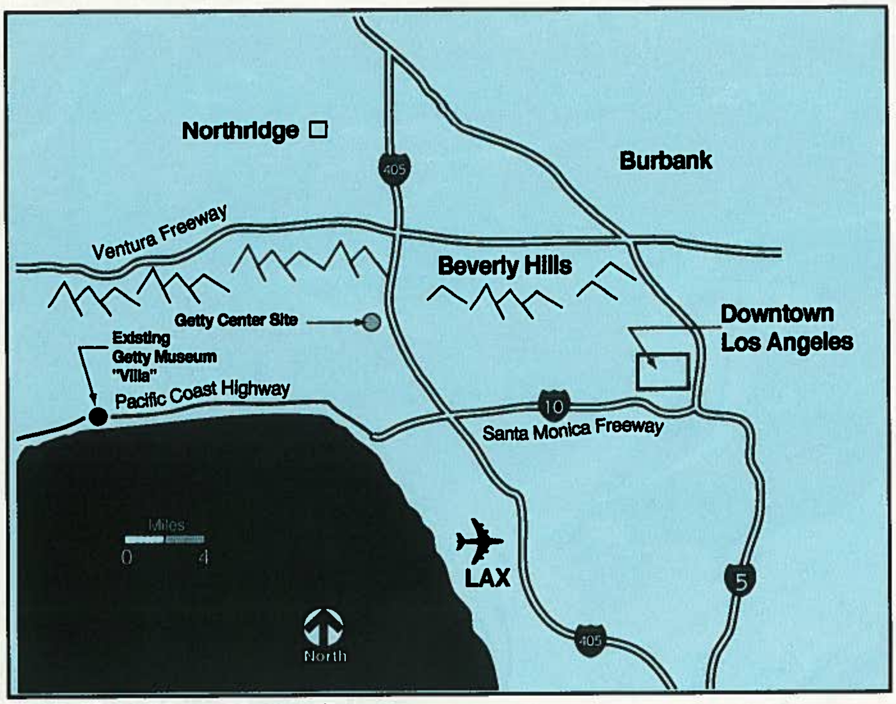


Fig. 2. Map of the guideway site.

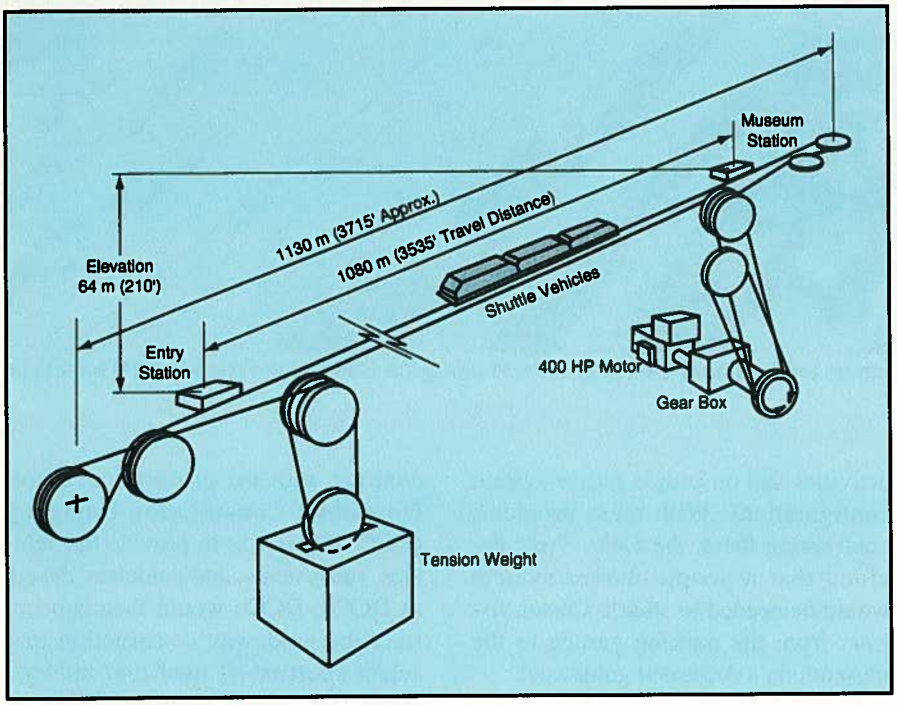


Fig. 3. Schematic of the cable drive system.

the guideway. Each train will be attached to a drive cable supported along the length of the guideway by a support sheave network. In turn, each cable will be driven by an elevator-type geared drive system located in a machine room outside and under the Museum Station. As illustrated in Fig. 3, a cable tension device (tension weight) is located at the entry station just outside of the station area.

The shuttle operation will be controlled by computerized equipment located in a control room next to the machine room. A schematic drawing of the cable drive system is shown in Fig. 3. Each train will be 27.4 m (90 ft) long and will consist of three, two-module vehicles, each with a length of 8.8 m (29 ft). Vehicles will be 2.24 m (7 ft 4 in.) wide and 2.90 m (9 ft 6 in.) high. Vehicle capacity will be 14 seated and 17 standing per vehicle or 93 per three-vehicle train.

THE GUIDEWAY DESIGN

Site Conditions

Site conditions imposed unique challenges on the guideway configuration and design. The Getty Trust dictated that guideway construction not scar the natural vegetation on the hillside. It was also important to position the guideway parallel to the access road that wound up the hillside to facilitate construction and minimize the visual impact of the guideway on views from the hillside on the opposite side of the San Diego Freeway. These conditions produced a guideway alignment consisting of nine curves, with horizontal radii of curvature varying from 38 to 305 m (125 to 1000 ft), that follows a profile with an average vertical grade of 7.2 percent (see Fig. 4).

The total length of the tramway is 1080 m (3535 ft). The rise in elevation from the parking garage station to the museum at the station is 64 m (210 ft). The aerial structure is 800 m (2580 ft) long flanked by either at-grade or pile-supported grade beam sections approaching the two passenger stations.

This 800 m (2580 ft) long structure is divided into 9 four- to six-span continuous units. The average span length is 20 m (63 ft); maximum span length is 26 m (86 ft). At some locations, the guideway is supported on columns over 13 m (42 ft) tall. At other locations, the guideway superstructure is supported directly on drilled pier caps without columns.

Vehicle System Interfaces

The guideway supports the vehicle on a smooth "flying" surface and supports the guide rail, sheave supports for the drive cable, power rails, and control subsystems. A U-shaped guideway with a horizontal bottom slab and vertical sidewalls was required to interface with the Otis vehicle system. Supports for a guidebeam for maintaining the lateral position of trains on the guideway, brackets to support the numerous rope sheaves re-

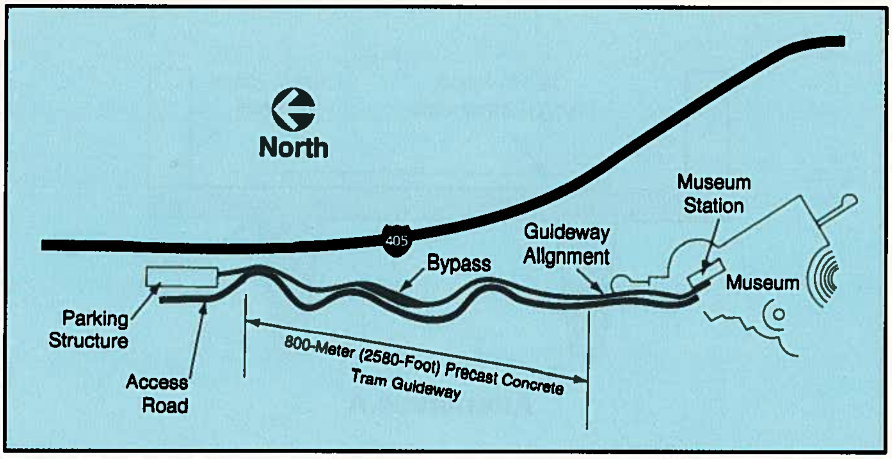


Fig. 4. The Getty Center site plan.

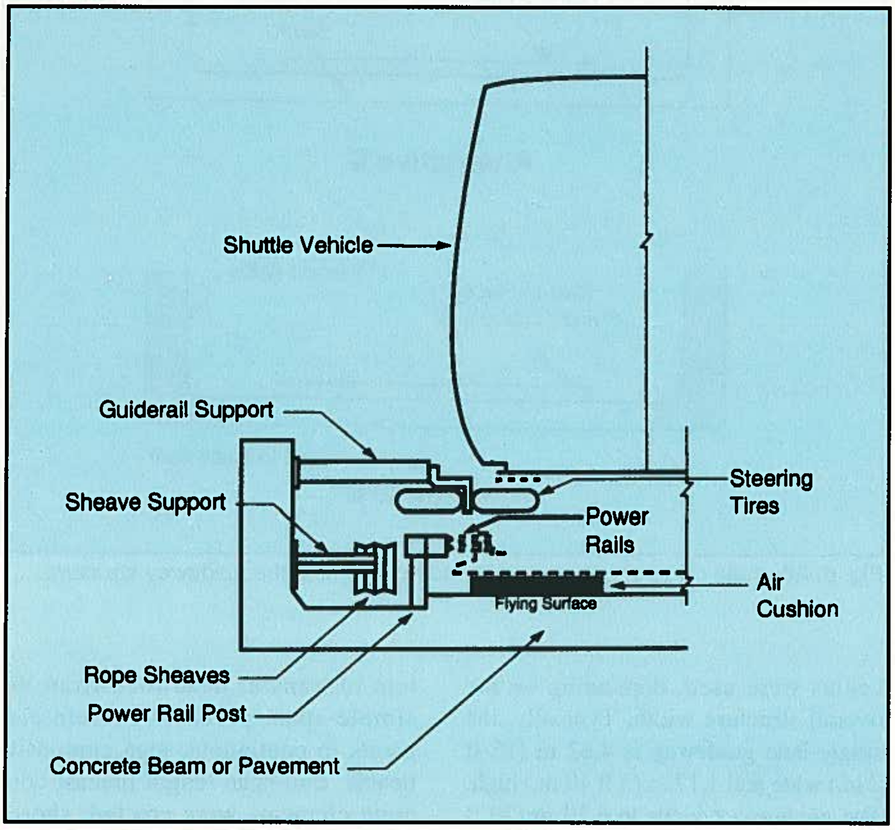


Fig. 5. The guideway/vehicle system interfaces.

quired to guide the propulsion cable around numerous turns, and the power rail for supplying electric power to the operating vehicles are secured to the guideway sidewalls and supporting slab (see Fig. 5).

Preliminary Design

The guideway designer's initial effort was to develop alternative guideway cross sections that would meet project design criteria. Alternate guideway cross sections included those sections shown in Fig. 6.

Alternative A — Precast concrete double tees spanning column to column. The stems of these double tees would be straight; the flanges of the double tees would be curved to make curved guideway sections. The sidewalls and flying surface would be cast-in-place concrete. Multiple double tees would be used in the bypass area.

Alternative B — Cast-in-place U-section. This section would use the necessary elements to interface with the Otis vehicle system as structural elements. Added structure beneath the supporting slab would generally be eliminated. In the bypass area, a structure to stiffen the cross section would be added beneath the supporting slab.

Alternative C — Precast concrete L-beams spanning from column to column with a cast-in-place connecting slab to form the above U-section. Precast concrete stem beams extending below the supporting slab would be used in the bypass area. Precast concrete beam components would be designed to support the weight of the connecting slab and associated formwork and construction loads without auxiliary supports. This alternative minimized the amount of cast-in-place shoring and minimized the pick weights of precast concrete elements.

Alternative C was chosen by the Getty Trust, the project architect, and the project contractor because of cost, aesthetics, and constructability factors.

Design Criteria

The site for the guideway was within the jurisdiction of the City of Los Angeles, so the Los Angeles Department of Building and Safety was the approving authority. Early discussions with the Department of Building and Safety indicated that the Department would be comparing the design for the guideway with the Los Angeles Uniform Building Code (LAUBC). The concerns of the Department centered on the seismic design of the guideway structure.

This review process presented a dilemma to the design team because the guideway structure was more like a bridge than a building. The LAUBC grouped this type of structure into the category of "Other" structures. Guideway design engineers thought it was essential to introduce the latest research regarding bridge seismic behavior and safety into the design of this structure. Therefore, prior to beginning the final design process, a Getty Center People-Mover Guideway Structural Design Specification was submitted to the Department for approval as an acceptable analysis/design method. This specification combined provisions of the LAUBC and California Department of Transportation (CALTRANS) Bridge Design Specification.

Seismic design provisions of the Structural Design Specification stated the following:

- Internal seismic forces would be computed using response spectrum analysis methods.
- A site-specific response spectra would be used with a return period of 1000 years. A two-thirds vertical response would also be imposed on the structure.
- Design methods of the CALTRANS Bridge Design Specification would be used for reinforced and precast concrete components. The CALTRANS methods for seismic design of reinforced concrete components use ultimate loads and ultimate component design capacities.
- A minimum design base shear force would also be imposed on guideway columns. This minimum force would be computed per the LAUBC, based on rules for "Other" structures in the code.
- Effects of vehicle live load would be scaled from results of response spectrum analysis with only dead load mass to account for the added mass. This was done because the vehicle will be "secured" to the guideway.

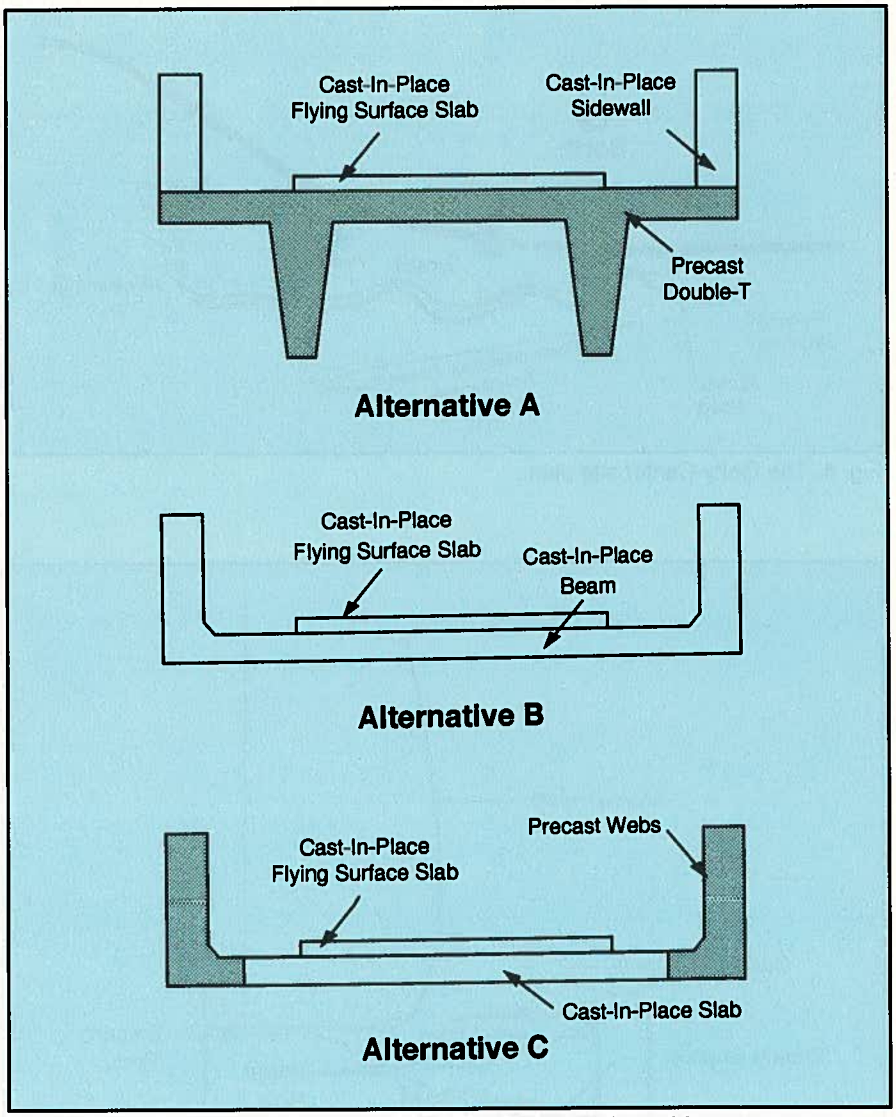


Fig. 6. Alternate cross sections considered in designing the guideway structure.

Superstructure Design

The single-lane tram guideway superstructure was made from two L-shaped precast, prestressed concrete web beams connected with a cast-in-place slab. Web beams were designed to support the weight of the slab and its formwork. Web beams were prestressed at the plant to support their own weight and simple-span applied loads.

The guideway design specified that W30 beams would be used to tie the precast concrete web beams together during casting of the connecting slab. Spans were later post-tensioned into four- to six-span continuous structure units.

Flanged rectangular precast concrete stem beams, extending below the slab, were used to stiffen the superstructure in the bypass area. One or two stem beams were used, depending on the overall structure width. Typically, the single-lane guideway is 4.62 m (15 ft 2 in.) wide and 1.17 m (3 ft 10 in.) high. The guideway widens to 6.20 m (20 ft 4 in.) in the bypass area (see Fig. 7).

Spliced girder construction was used in the design to extend the span length of the 1.17 m (3 ft 10 in.) deep channel section to 26 m (86 ft) over a slide area along the tram alignment. Two adjacent beam elements were erected on a shore tower, joined with a cast-in-place closure pour. The elements were then post-tensioned in the field to make up the 26 m (86 ft) span. The shore tower was removed after the span was integrated into a continuous span unit.

Three other long bypass spans were designed to use a touch shoring system to transfer dead load from the simple-span, precast concrete elements to continuous span composite beams. Full-span-length precast concrete elements were erected; shores were installed to just contact the bottom of these elements. Decks and closure pours between elements were cast. Touch shores were removed after the spans were integrated into continuous span units.

Inserts to support the vehicle guideposts and supports for the rope sheaves were cast directly into precast concrete L-beams. Over 10,000 threaded inserts were to be cast into these precast concrete components to a tolerance of 3 mm ($^1/_8$ in.). The design required formwork adjustments to offset predicted deflections and cambers as small as 12 mm ($^1/_2$ in.).

Substructure Design

The guideway substructure generally consists of 1.07 m (3 ft 6 in.) diameter round columns supported on 1.22 m (4 ft) diameter shafts. The columns support a cross-head element to absorb shear forces from precast concrete web beam superstructure elements (see Fig. 8). The shaft and column use a common reinforcing steel cage to achieve ductility requirements with a minimum amount of reinforcing steel. Foundation shafts are generally designed to resist horizontal shear and moment forces associated with hinging (yielding) of the base column section.

In the bypass area, dual columns and shafts are used. These columns are connected with a cross-head element to transfer shears from precast concrete L and stem beams to supporting columns. Careful attention was paid during the design phase to the ductility requirements of the joints between cross-heads and columns.

In areas where the guideway is supported close to the ground without columns, multiple shafts are used. Shaft moments and shears were designed to resist the maximum elastic seismic shears and moments from response spectrum analysis. The guideway superstructure is connected to the substructure through bearings and large steel bar lugs that were cast directly into the cross-head elements (see Fig. 9).

The completed tram. guideway structure survived the January 17, 1994, 6.8 magnitude Northridge earthquake without damage (see Fig. 10). During the earthquake, measured horizontal accelerations within 20 miles (32 km) of the epicenter ranged from 0.24*g* to 1.82*g*. The Getty site is 10 miles (16 km) from the epicenter of the earthquake.

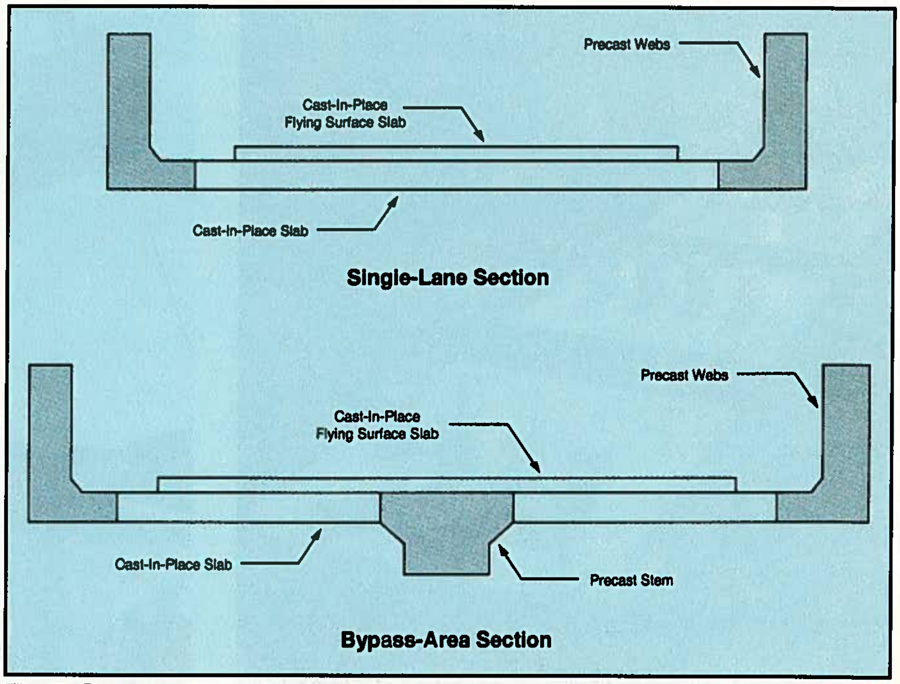


Fig. 7. Cross section of the superstructure.

THE GUIDEWAY CONSTRUCTION

Initial guideway construction documents were issued to a select shortlist of qualified bidders in the summer of 1992. Final guideway construction documents were bid in September and October 1992. A. T. Curd Constructors of Glendale, California, was selected to be the guideway construction subcontractor.

Site Logistics and Planning

The site conditions were the major factor driving construction sequences and methods. The guideway alignment roughly follows the contours of a steep hillside, passing over several environmentally sensitive areas that could not be disrupted by construction activities. While the vertical gradient of the guideway along its final path of travel is approximately a constant 7 percent, the slopes and cross slopes of the hillside at the foundations are as steep as 1:1 in some locations. Creating access for drilling 1.22 m (48 in.) diameter-deep caissons and erecting large precast concrete elements was of primary importance.

A series of narrow access roads was planned to provide access for caisson drilling. These roads were limited to areas where partial canyon fills were already planned; hence, regrading and revegetation after construction was a feasible alternative. It was not possible, however, to construct a road wide enough to allow a suitable erection crane to travel around cross-heads that topped support columns. Several sections of the alignment were over sensitive areas that could not be disturbed with access roads, so all construction had to be reached over the top with large cranes.

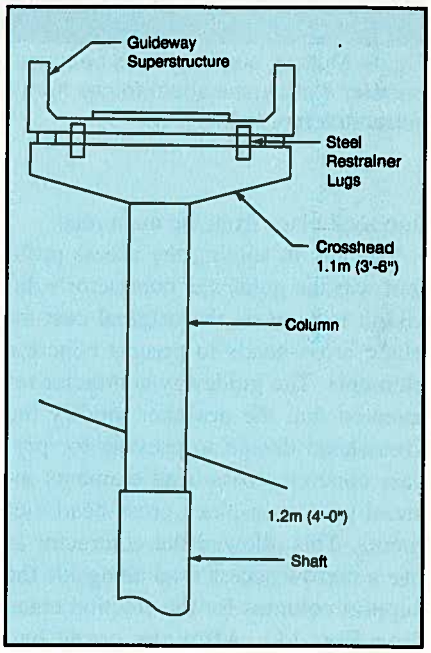


Fig. 8. Typical guideway substructure.

Erection of precast concrete elements from the nearby parallel permanent roadway had several drawbacks. This road was the only access to the top of the hill where the main building construction was underway. Constant, heavy construction traffic needed to be maintained almost the entire day. Only brief time windows were available to block this road with precast component erection activities. Also, the size and number of erection cranes required would be significantly larger if erec-

Fig. 9. Multiple steel lugs and bearings were required to transfer earthquake shear forces from the guideway superstructure to this pier.

Fig. 10. Nine horizontal curves make up the guideway alignment. The structure survived the nearby Northridge earthquake (January 17, 1994) without damage.

tion took place from the main road.

The key to solving the access problem was the guideway contractor's decision to convert the original cast-in-place cross-heads to precast concrete elements. The guideway contractor requested that the designer modify the cross-head design to provide for precast concrete cross-head elements instead of cast-in-place cross-head elements. This allowed the contractor to use a narrow access road alongside the support columns for the erection crane (see Fig. 11). After the crane had passed by the support column, the cross-heads were erected just before the beams (see Fig. 12).

The guideway was divided into five general areas for overall construction sequencing in the following order:

1. The first 16 spans of elevated guideway at the uphill end

2. The last 11 spans of elevated guideway at the downhill end

3. The 14 spans of elevated guideway in the bypass area

4. The on-grade guideway adjacent to the entry station

5. The on-grade guideway between the south abutment and the museum station

Foundation and Column Construction

Work at the site began with construction of the temporary access roads. These roads were generally a series of short spurs off of the main road, in most areas only wide enough for crane travel without outriggers. Special outrigger pads were created on the slopes at the points where the crane needed to set up. A few of the road areas required shoring to create a large enough flat area. Several sections of the access roads had 20 percent gradients.

Deep caisson drilling followed the road construction. Drilling was accomplished with conventional earth augers and rock cutting buckets. Drilling was much more difficult than originally anticipated. There was significant time spent coring through fractured rock layers. The bottoms of all of the caissons were cleaned out by hand. This required long continuous casings to be installed temporarily in each hole during cleanout operations. These casings had to be transported up and down the access roads during drilling.

Five caisson locations could be accessed only by foot (see Fig. 13). Drilling with conventional equipment was impossible. Instead of hand excavating these shafts, the contractor used a special long reach drilling apparatus. A small remote-operated diesel auger was suspended over the side of the hill from a large truck crane located on the access road directly uphill from the drilling location.

Continuous spiral-tied reinforcing cages were installed in the cleaned holes (see Fig. 14). The cages were continuous from the bottom of the hole to top of the cross-head. Caisson depths ranged up to approximately 24 m (80 ft) and column heights varied up to 13 m (42 ft). Some of the resulting reinforcing cages were nearly 30 m (100 ft) long. All of the caisson cages were fabricated off-site due to space restrictions on site.

A critical aspect of the cage installation was orientation of the vertical re-

Fig. 11. The erection crane was able to back out a narrower access road without cross-heads atop the columns. A precast concrete cross-head is being rigged for erection.

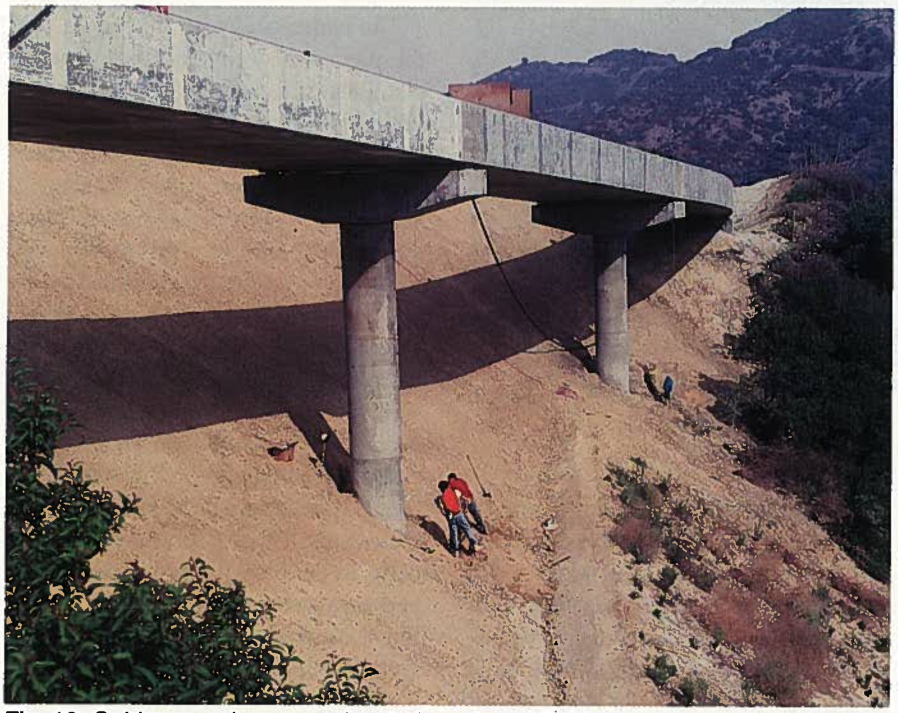


Fig. 12. Guideway columns are located on steep hillsides.

inforcing bar pattern. Because the cage was continuous to the top of the cross-head, the reinforcing bar protruding above the top of the caissons had to be in the correct pattern. The pattern had to be in the correct horizontal location and at the correct azimuth orientation; the top of the reinforcing bar, as much as 13 m (42 ft) above ground level, had to be at the correct elevation. The tolerances were much tighter than normal for drilled caisson construction, so the contractor used special double templates for fabrication and installation of the caisson/column cages.

The columns were cast in place using 1.07 m (42 in.) diameter steel forms. A special double reinforcing bar template was used on the top of each column form to ensure accurate alignment of each vertical dowel passing into the precast concrete cross-heads (see Fig. 15).

The typical reinforcing bar pattern included 16 vertical #9, #10, or #11 bars. These dowels matched up with a set of vertical corrugated sleeves cast into the cross-heads. After erection and alignment of the cross-head, these sleeves were filled with a high strength grout. At the bypass areas, larger cross-heads were supported by two columns. These had to be aligned as a matched set when the columns were poured because they shared a common cross-head piece.

At some locations, the terrain elevation matches the elevation of the bottom of the guideway (see Fig. 16). In these locations, precast guideway beams were supported directly on cast-in-place pile caps at grade level. These pile caps were constructed concurrently with the cast-in-place columns in each area.

Cross-head and Superstructure Construction

A significant contribution was a full-scale mock-up that was constructed in the precast manufacturing yard prior to production. The mock-up verified architectural details and construction means and methods (see Fig. 17).

Precast concrete erection followed the columns. Most of the erection was accomplished with a single 160-t (180 ton) conventional truck crane. Several picks, however, required a 225-t (250 ton) crane or both of the cranes working together. Cross-heads were erected on the station ahead, reinforcing bar sleeves were grouted, and web and stem beams followed on the cross-heads.

Special lifting frames were required for the beam elements to prevent them

Fig. 13. Some column locations were only accessible by foot.

Fig. 14. Reinforcing steel cages for drilled shaft foundations and columns were over 30 m (100 ft) long.

from rolling over. The lengths and curvatures of many of the elements resulted in the center of gravity of the component being located outside the center of gravity of the available lifting points. The lifting frames allowed the crane connection point to be offset from the cross section of the beam. The frames were configured to automatically compensate for any of the curvature conditions encountered without readjustment (see Fig. 18).

Special heavy diagonal braces and lateral clamps were also fabricated to transmit the torsional force from the precast concrete beam end to the cross-head. After two parallel webs were erected, they were tied together with 0.76 m (30 in.) deep, wide flange beams in the transverse direction. These large beams served to hold the web pairs in correct horizontal and vertical alignment with each other (see Fig. 19). After installation of the web beams, diagonal braces could then be removed and used again on the next span.

Other special erection and bracing hardware was devised by the contractor to keep the beams from moving downhill in the longitudinal direction prior to connection to the permanent bearings and steel lugs through cast-in-place closures. Temporary vertical bearing pads and support shelves were also required because the precast concrete webs and stems had minimal physical overlap above the top of the cross-heads. The ends of the precast concrete sections were joined over the cross-heads by cast-in-place closures; closures included the permanent slide and fixed bearings and lateral restrainer lugs (see Figs. 20 and 21).

The formwork for the cast-in-place deck was supported by hangers attached to the precast concrete beam elements. After the decks were placed, groups of individual spans were post-tensioned together to form a series of multispan bridge structures (see Fig. 22). The on-grade guideway has a cross section matching the elevated guideway; however, the sidewalls are cast-in-place concrete rather than precast concrete.

Flying Surface Construction

The entire guideway, including both the precast and cast-in-place concrete elements, is topped by a superflat concrete flying surface upon which the air-supported vehicle glides. The tolerances for smoothness and flatness for this surface are critical because they affect the vehicle ride quality and wear life of the air-cushion pads.

There was considerable concern about the ability to achieve high-tolerance flatwork at such a demanding site, where concrete was placed on a 7 percent grade, and where the geometrically correct shape of the flying surface is a helix, not a flat plane, in all of the curves. There was also some difficulty in defining the proper tolerances and measurement methods to achieve the desired surface. The contractor, together with the vehicle system supplier and a superflat floor consultant, took as-built measurements from an existing installation, analyzed the data, and devised a measuring scheme and tolerances to be used to control the quality of the flying surface.

Concrete placement on the flying surface was successful due to a number of special quality control measures. These measures included tight control of the concrete mix proportions and timing of deliveries, high precision formwork measuring and leveling tools, special wet finishing techniques, prompt and thorough wet curing, and immediate measurement and reporting of results so daily corrections could be made (see Figs. 23 and 24).

PRECAST CONCRETE FABRICATION

The structural solution to the design challenges was largely due to the efficient use of precast concrete components. In total, 134 components were used as follows:

- L-shaped web beams
- Flanged rectangular stem beams
- Single-lane cross-heads
- Bypass single column cross-heads
- Bypass dual column cross-heads

Table 1 shows the shape, number and principal dimensions of the precast concrete components.

Precast Concrete Cross-heads

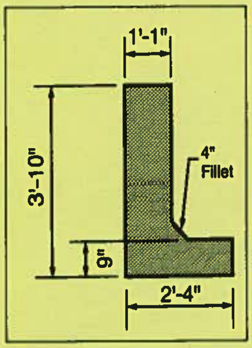
As previously noted, a key concept in solving this project's construction difficulties was casting the precast concrete cross-heads. Typical precast cross-heads were 4.67 m (15 ft 4 in.) wide and weighed 140 kN (31,000 lbs); bypass cross-heads measured up to 7.82 m (25 ft 8 in.) and weighed 350 kN (80,000 lbs). Forming cross-heads was straightforward, using standard steel forms similar to those used for cast-in-place cross-heads on top of the columns. Tying the reinforcing bars was more complicated because the ductility requirements called for a series of closed, interlocking, progressively tapered welded loops requiring a systematic placement sequence that took a few tries to figure out.

The real challenge, however, and the key to the successful use of the precast concrete cross-heads was the templating system devised to ensure that they would meet with a cast-in-place column in the field. The connection detail was designed to fit the cross-head over the extended column vertical steel, 16 bars in a 0.9 m (3 ft) diameter circle.

Fig. 15. Precise jigs were used to ensure that reinforcing steel protruding from the tops of cast-in-place concrete columns aligned properly with mating sleeves in precast concrete cross-heads.

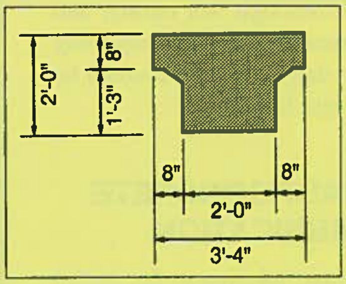
Fig. 16. At some locations, the guideway profile was nearly at ground level. At these locations, the guideway superstructure was supported directly on cast-in-place pile caps.

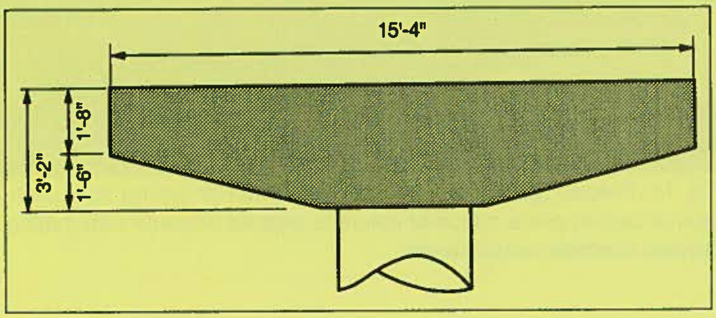
Table 1. Breakdown of precast and prestressed concrete components used in tram guideway.



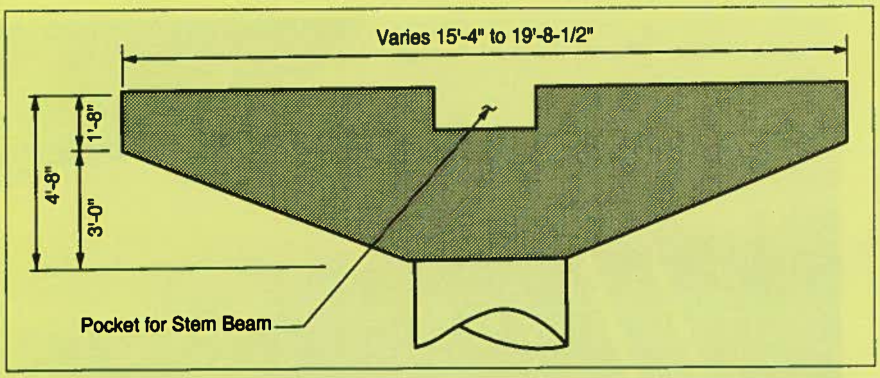
L-shaped precast prestressed web beams: 84 components
Minimum length — 13.9 m (45 ft 6 in.)
Maximum length — 22.1 m (72 ft 6 in.)

Flanged rectangular stem beams: 19 components
Minimum length — 13.9 m (45 ft 6 in.)
Maximum length — 21.5 m (70 ft 6 in.)



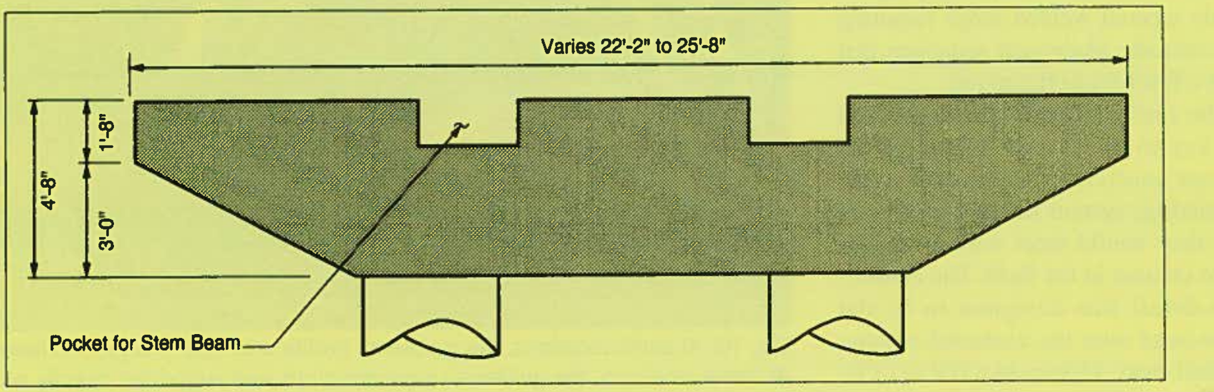


Single-lane cross-heads: 19 components
Width of cross-head — 1.5 m (5 ft)



Bypass single-column cross-heads: 7 components
Width of cross-head — 1.5 m (5 ft)

Bypass dual-column cross-heads: 5 components
Width of cross-head — 1.5 m (5 ft)



In order to clear cross-head reinforcing, sleeves were limited to 40 mm (1.5 in.) diameter corrugated tubes for #11 bars, leaving very little clearance per sleeve. The fabricator of the miscellaneous metal components devised a precise jig that remained in his shop. All templates for the project, both field and shop, were made against that master template to guard against progressive creep in dimensions.

For the cross-heads, a template in the form's baseplate matched the inside diameter of the corrugated sleeves. A similar template at the top, with "handles" that would support it from the form sides, aligned the sleeves vertically and in plan. PVC pipes inside the corrugated sleeves acted as stiffeners. In the field, all cross-heads fit and aligned correctly.

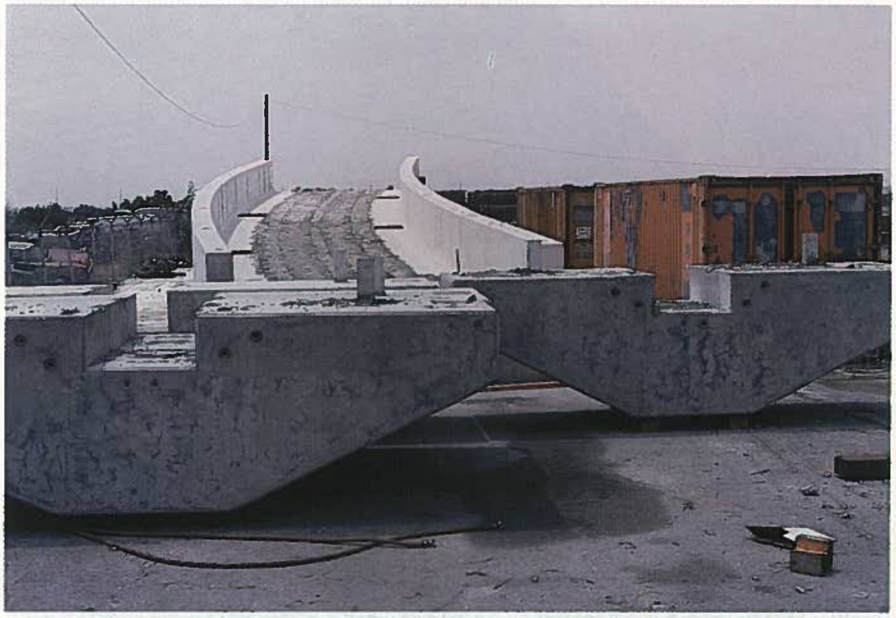


Fig. 17. Prior to production, a full-scale mock-up was constructed at the precast manufacturing yard.

Precast Concrete Web and Stem Beams

The L-shaped precast concrete beam sections, or webs, ranged from 11.6 to 22.0 m (38 to 72 ft 4 in.) long, with corresponding weights of 132 to 250 kN (29,500 to 55,800 lbs). Geometry was complex, as even an 11.6 m (38 ft) beam might include a tangent, spiral, and constant radius alignment. Radiuses were 64, 69, 75, and 305 m (210, 225, 245, and 1000 ft) each with spiral transitions into and out of the tangent or straight sections.

The necessary alignment came from a profile grade line (PGL) at the center of the flying surface. In two locations, the PGL also required a vertical curve (VC). The design allowed the webs to "chord" between cross-heads and compensate for the VC with the cast-in-place flying surface. The embedments, however, needed to follow the PGL, which meant that at these two locations, embedments were not a constant height relative to the web section.

Fig. 18. Special lifting frames were fabricated to allow picking outside the center of the web beam cross section.

Web form layout was clearly a major challenge. The entire structure was drawn in three dimensions using AutoCAD 12.0. The individual beam sections were cut out on the computer, and rotated into a horizontal, casting position, which resulted in a twisted shape relative to the beam centerpoint. Horizontal and vertical offsets were then calculated from control lines that could be used in the plant for form layout and control.

The forms had to be able to twist to match the required shape. The form pallet was built with 0.6 m (2 ft) on center back-to-back channels 2.4 m (8 ft) long resting on screw jacks set into a longitudinal track (see Fig. 9). To make a flexible base over the double channels, flat 0.6 x 1.8 m (2 x 6 ft) timber sleepers with a 19 mm (3/4 in.) plywood sub-base and 13 mm (1/2 in.) high density overlay (HDO) plywood were laid down for the casting surface.

Setting the table was a two-step process. First, each double channel was "aimed" at the center of curvature by sliding the screw jacks perpendicular to the channels. Thus, for example at the outside of a curve, the center-to-center dimension might be 620 mm (2.034 ft) and the inside 595 mm

Fig. 19. W30 steel sections were used to tie the web beams securely together after erection.

Fig. 20. In the bypass area, stem beams were used to stiffen the section.

(1.952 ft). Screw jacks were then adjusted vertically so that one end might be plus 4 mm (0.013 ft) and the other minus 4 mm (0.013 ft). Each shop drawing had these dimensions calculated in tabular form, so that layout could be done with a simple tape and level approach. This combination of radial and vertical adjustment of the beams set the correct warp to the pallet.

Beam sides were controlled by building a series of 90-degree frames of glued and screwed plywood over 0.6 x 1.8 m (2 x 6 ft) timber (see Fig. 26). Side forms, like the pallet, were flat 0.6 x 1.8 m (2 x 6 ft) planks sheathed with 19 and 13 mm ($^3/_4$ and $^1/_2$ in.) HDO plywood. Again, this created a flexible form that would not deflect between supports but was limber enough to follow curves and spirals accurately.

The 90-degree frames were bolted down to the double channels so that the beam sides were always perpendicular to the twisting pallet below. A casting sequence was developed in a database of all components, sorted by curves and lengths, to minimize minor and major form reconfigurations. Templates for embedments consisted of plates with the exact, tight eight-hole pattern set through oversize holes in the form sides, so complete embedment assemblies could be shifted to cope with the layout differences caused by the horizontal and vertical curves.

Two forms were built. The typical production cycle started at 3 a.m. with a small stripping crew, pulling forms and yarding a beam into the storage area. There was sufficient mild reinforcing steel in the design to allow stripping and handling without prestressing. Meanwhile, the form was cleaned and oiled, and ready for the form setting and reinforcing bar crews at 6 a.m. At the same time, the stripping crew went over to the other form, and became the concrete placing crew. They would be "poured out" and ready to go home by lunchtime.

The cleaned form pallet would be reconfigured if necessary, then the reinforcing bar crew would set the pretied cage, the post-tensioning ducts, and the stressing heads where applicable. They would then pre-tie the following day's cages. The form crew then buttoned-up the forms, located embedments, and checked details before the end of the shift. The form would thus be ready for concrete placement the next morning.

After any necessary dry finish took place, the beams were sent to the post-tensioning area. Every Monday, the post-tensioning subcontractor did the first stage, simple-span post-tension-

Fig. 21. Stem beams in the bypass area were set into notches cast into the precast concrete cross-heads.

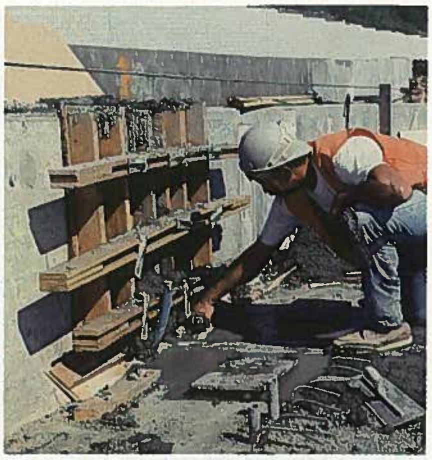


Fig. 22. After precast concrete beams were erected, closure pours were cast to make the precast units into four- to six-span continuous beam units.

ing and grouting, in the yard. This schedule allowed the weekend cure even on Friday's casting, met early strength requirements without overly aggressive mix designs and heating systems, and gave the post-tensioning subcontractor at least five beams for a full day's work cycle. The balance of the prestressing was done in the field.

The small "T" beams that supported the deck at the wide, bypass locations were dubbed "stems." Although of complex shape, as these poured into the deck, the tolerances were less challenging than the webs. A similar bed system was used (see Fig. 25).

In all, over 500 shop drawings were prepared to detail the 134 precast concrete components. Putting the effort into details, especially into a simplified layout system, paid dividends in the production cycle and achieved good dimensional tolerances. No inserts cast directly into the precast concrete units had to be reworked because of out-of-tolerance positioning.

Fig. 23. Reinforcing steel placed in the flying surface at the Entry Station.

CONCLUDING REMARKS

The J. Paul Getty Trust is constructing a world-class art facility and is demanding the highest quality in design and construction. The tramway ride quality, passenger comfort, and durability were important requirements that necessitated the complex design and close tolerances.

The construction of the Getty Center guideway was a model of cooperation between owner, designers, and builders. Direct lines of communication were established early to facilitate a response to questions and to ensure that design intent was being followed and that guideway requirements for the vehicle system were being achieved.

Use of precast, prestressed concrete made the construction feasible and cost effective. The resulting finished product is a graceful and dramatic structure suspended along the hillside that will provide an exciting, welcoming experience for visitors to the J. Paul Getty Museum.

The project won an award in the 1994 PCI Design Awards Program. The citation of the jury read: "This project really fits the site and environmental conditions, and through the innovative use of precast/prestressed concrete elements provides an extremely efficient solution to a difficult transportation problem."

It is expected that the people-mover tramway system (see Fig. 27) will be operational by the end of 1995.

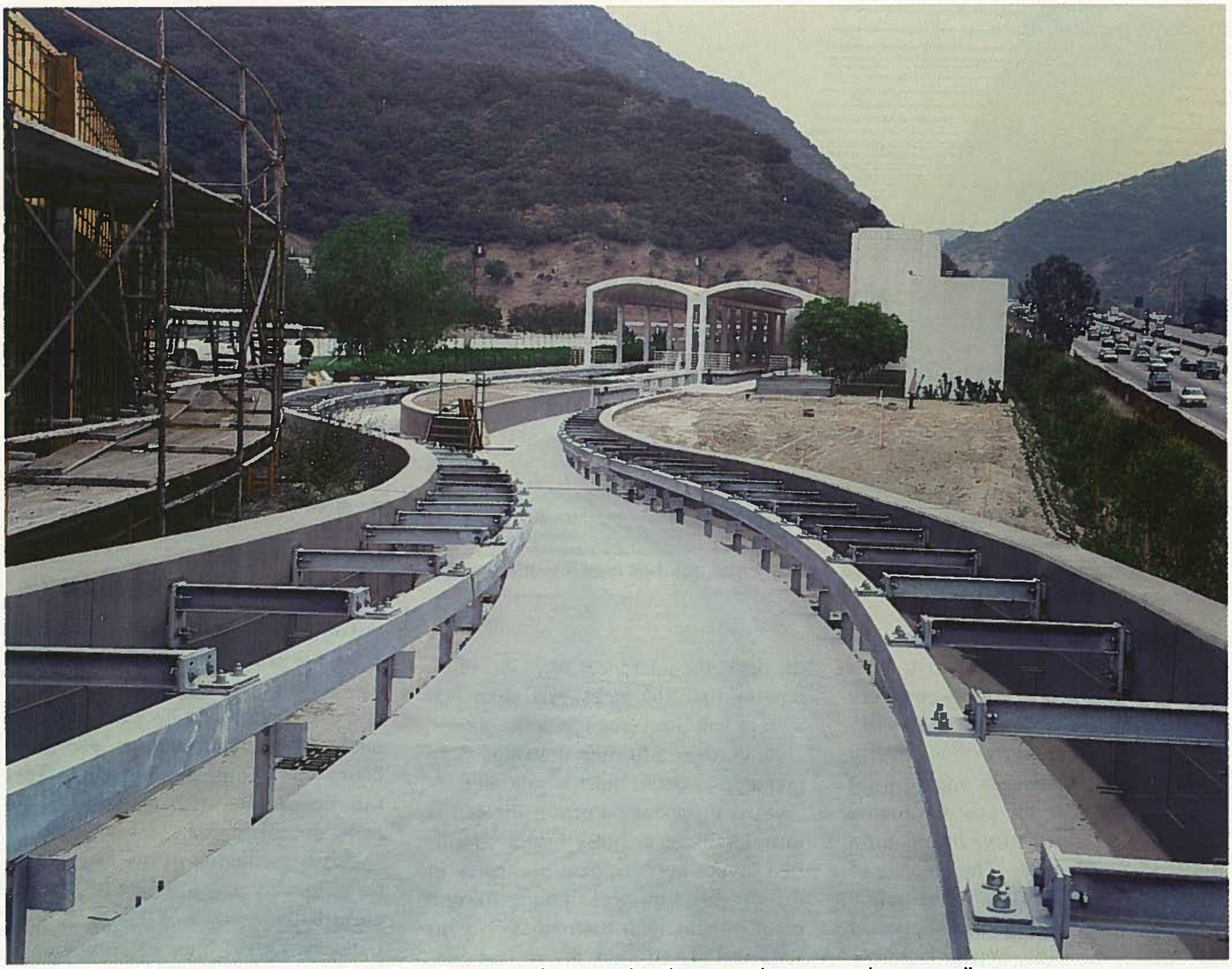


Fig. 24. The flying surface and steel guide rails are ready to receive the rope sheaves and power rails.

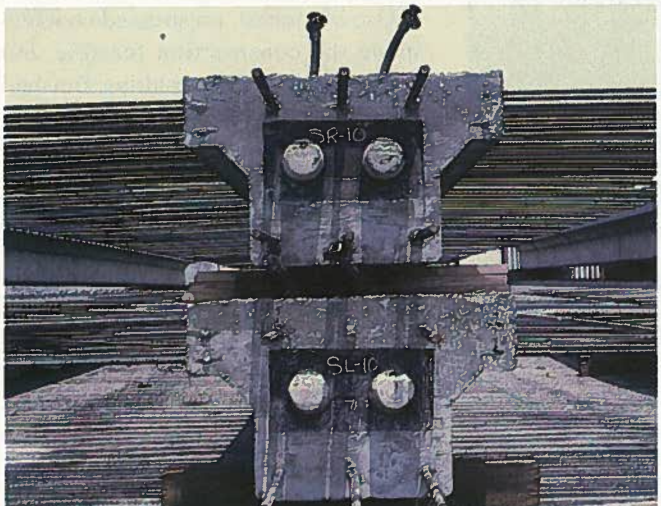


Fig. 25. Two stem beams in the storage yard are ready for transport to the site. Precast concrete beams were post-tensioned in the yard to carry their own weight and construction loads.

Fig. 26. Web beam forms were made from plywood secured to a series of 90-degree timber frames. Side forms were flat planks sheathed with plywood, thus creating a flexible yet not too rigid form.

Fig. 27. Panoramic view of Getty Center tram guideway project nearing completion.

CREDITS

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