# Twenty Five Years of Progress in Prestressed Concrete Bridges

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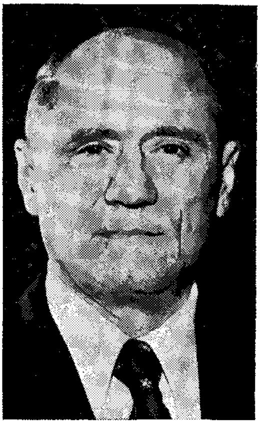

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A span of 25 years tells almost the entire story of the advancement in the use of prestressed concrete for bridges in the United States.

From the Walnut Lane Bridge in Pennsylvania in 1949 to the Pine Valley Bridge in California in 1974, prestressed concrete has been established as a functional, versatile, efficient, and economical bridge material.

At the 1957 World Conference on Prestressed Concrete, Professor T. Y. Lin said in his summary remarks with reference to the future of prestressed concrete "You ain't seen nothing yet!" How accurate and prophetic those words sound now.

## Synopsis

Since 1949, the use of prestressed concrete as a bridge construction material in the United States has experienced remarkable growth. This paper describes this growth and development as experienced by one of these states.

In California, the past 25 years have seen the annual use of prestressed concrete for bridges grow from nothing to 78 percent of the total. Reasons for this growth are presented.

Also discussed are the reasons for the increased use of cast-in-place prestressed concrete box girders and the corresponding reduction in use of precast bridge girders. Credit is given to the members of the prestressing industry for their cooperative and innovative attitude.

The concept of prestressing is quite old. Many years ago, some unknown genius discovered that if he built a container of fitted wooden staves, and wedged iron rings in place over these staves he had a barrel that was quite strong and would hold fluids without leaking. Iron bands were heat-shrunk over built-up wooden wheels to increase their resistance to damage by prestressing them.

In 1888 a man named **Jackson** from San Francisco, first applied controlled stresses to concrete by tensioning mild steel rods. Since engineers of those days were not aware of the plastic strain of both steel and concrete, Jackson's prestress soon disappeared, and his attempts were failures.

It was not until the late 1920's that **Eugene Freyssinet** first recognized that a high working stress steel would have to be used in order to retain a suitable level of prestress. Such high strength steel was available, and Freyssinet used it in the first application of permanent prestressing by means of internal tendons.

Later, **Gustave Magnel** of Belgium measured creep in various types of cold drawn wire and laid down many of the principles that we now take for granted.

The use of prestressed concrete grew for a while, but then was interrupted by World War II. When the war was finally over, all of the bridges over the Rhine River had been destroyed, as had most of the bridges over major rivers in all of Europe.

Along with this shortage of bridges, there was also a great shortage of steel production capacity. This combination of factors gave great impetus to the innovative use of prestressed concrete for long span bridges throughout Europe.

At this same time the United States, unscathed by the war, with none of its major bridges destroyed, had surplus steel production capacity. New bridges, as required, were built of reinforced concrete or steel.

In 1949, the City of Philadelphia built the Walnut Lane Bridge in Fairmont Park. This first major prestressed bridge to be built in the United States impressed American engineers with the potential of precast prestressed concrete. Several states, including Massachusetts, Oregon, Florida, Pennsylvania and California began designing rather modest precast girder highway structures.

In these early post-war years (say between 1950-1960) the construction of highways, especially freeways, was greatly accelerated. The need in this country was for short span overcrossings and undercrossings and the economic competition was fierce between structural steel and reinforced concrete, with prestressed concrete the new boy on the block.

In California, for example, in the year 1950, 34 percent of the bridges built were structural steel, 66 percent were reinforced concrete. In 1955, the figures were: steel 23 percent, reinforced concrete 74 percent, and prestressed concrete 3 percent; and in 1960; steel 9 percent, reinforced concrete 72 percent and prestressed concrete 19 percent.

With the growth of cast-in-place post-tensioned bridge construction, prestressed concrete by 1969 had become the dominant construction material. Since 1970, more than 50 percent of the total area of bridges going to contract each year has been prestressed concrete. In 1975, for example, reinforced concrete had 20 percent of the market, steel only 2 percent, while prestressed concrete had risen to 78 percent of the total.

The following is a discussion of the State of California's experience with prestressed concrete bridge design and construction. No doubt many other states have had similar experiences—ours were not unique.

## Early Applications

The year 1950 saw the design of the first prestressed concrete bridge in California—the Arroyo Seco Pedestrian Overcrossing (see Fig. 1). It was a small structure but a good one to begin on.

Professor T. Y. Lin instrumented it, ran tests, and confirmed that stress still equalled $P/A \pm Mc/I$ as expected, even in prestressed concrete. The bridge cost was high and construction more difficult than cast-in-place concrete, so it was 2 more years before we built our next prestressed bridge.

This was a narrow, short span precast girder bridge over Belmont Avenue in Fresno (see Fig. 2). This 67-ft span consisted of ten 3-ft deep T-beams placed side by side with a couple of inches of asphalt concrete on top as a riding surface.

In these early days prestressed concrete was generally considered in terms of precast elements that served as replacements for the rolled or welded steel beams. A significant advancement, at least for California, came in 1954 with the design of a two-span continuous cast-in-place prestressed concrete box girder bridge (see Fig. 3).

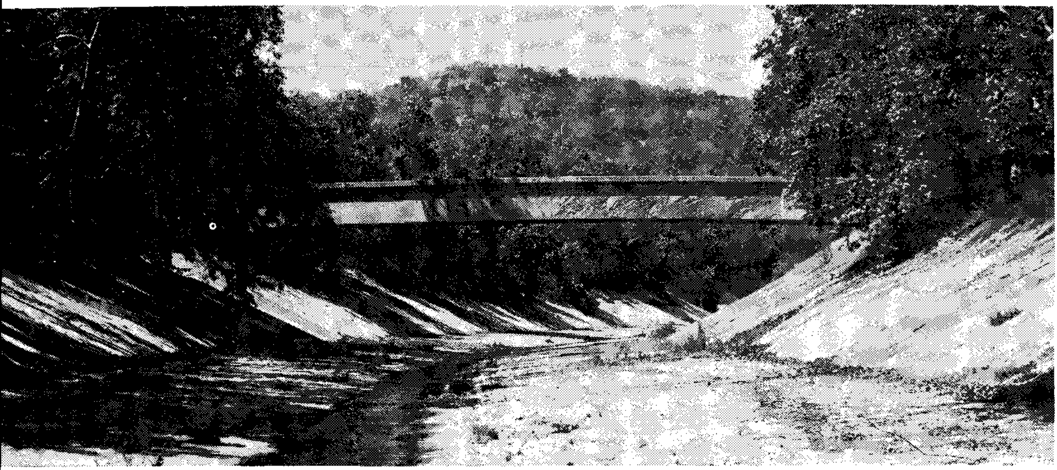


Fig. 1. Arroyo Seco Pedestrian Overcrossing.

This bridge employed a 4-ft structure depth for two 90-ft spans. This was about 1½ ft shallower than reinforced concrete would have been, and presented a very attractive aspect of cast-in-place prestressed concrete, i.e., a very low depth to span ratio.

## Special Situations

With another tool in his kit, the bridge design engineer found many special situations for which prestressed concrete was the best solu-

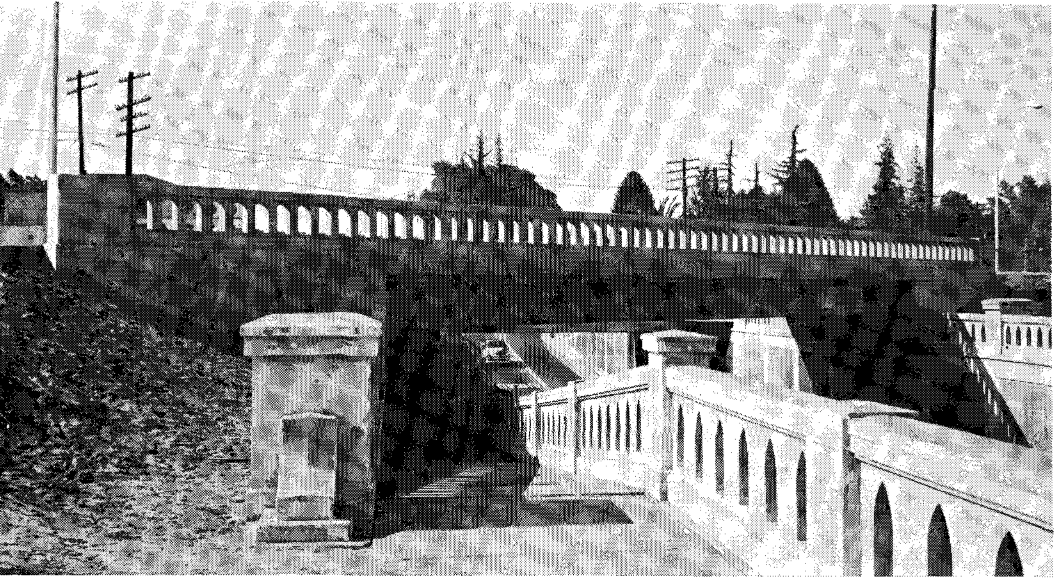


Fig. 2. Weber Avenue Overcrossing.

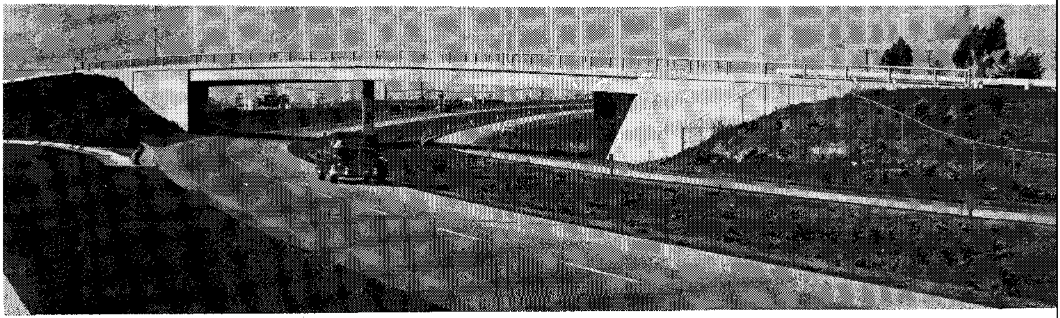


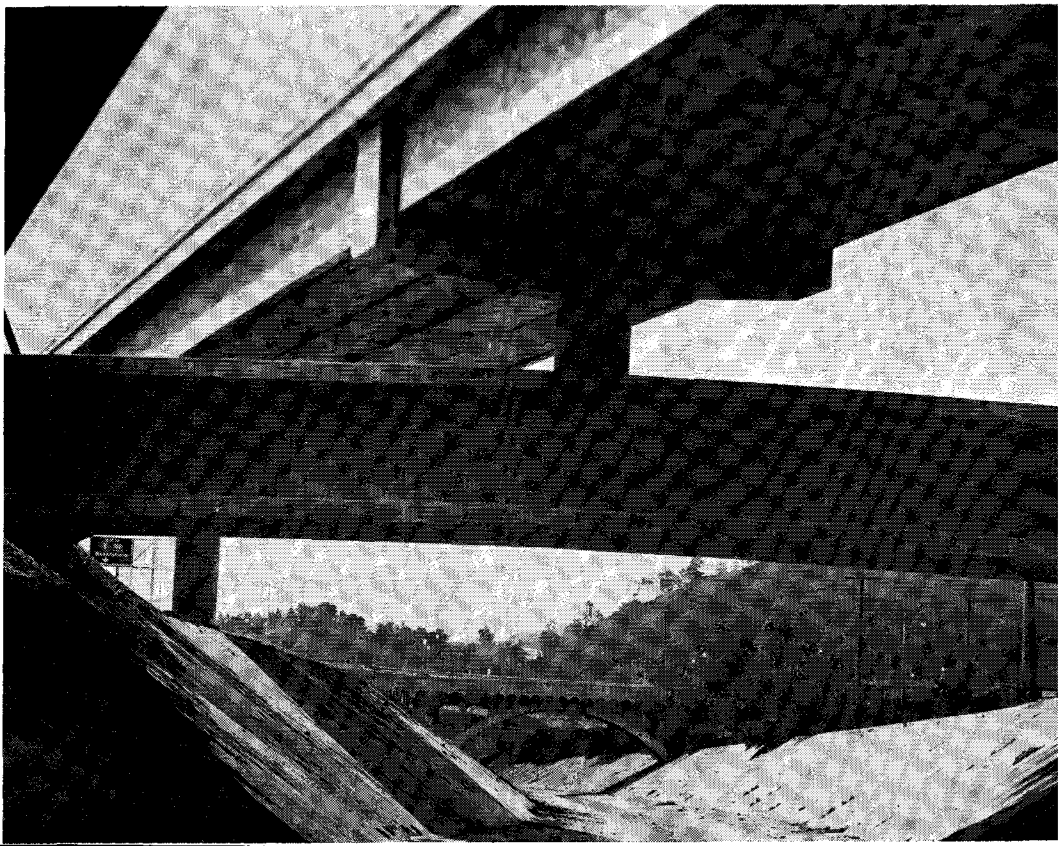
**Fig. 3. John Street Separation.**

tion. The carrying beam over the Arroyo Seco in Los Angeles is an example (see Fig. 4).

This structure supports the bent carrying two spans of the Elysian Viaduct over the concrete lined flood control channel of the Arroyo Seco. This carrying beam accommodated a shallow structure depth for the viaduct above without interfering with the hydraulic characteristics of the channel.

Another economical solution to a difficult problem is represented by the precast prestressed pedestrian span over the railroad tracks at Camarillo on the Ventura Freeway. Minimum structure depth was required,

**Fig. 4. Prestressed concrete carrying beam supporting spans of the Elysian Viaduct over the Arroyo Seco. Superstructure consists of precast inverted T girders with cast-in-place fascia beams.**



and falsework could not be used over the tracks.

This unusually shaped span caused much comment from designers and builders unfamiliar with the details of prestressed concrete design. The prestressing tendons look like they will pull the structure down when they are stressed—or perhaps cause it to curl up and fail that way.

Needless to say, since the tendons were below the neutral axis at midspan, the structure behaved in a completely conventional way in spite of its unusual appearance (see Fig. 5).

MacArthur Boulevard in Oakland is an example of a highly skewed, short span frame that contains two difficult corners to design (see Fig. 6 and 7). By means of in-place prestressing, the corner areas and portal beams could be built with no increase in structure depth.

## Early Problems

In these early days, roughly before 1965, the problems were many

**Fig. 5. Camarillo Pedestrian Overhead.**

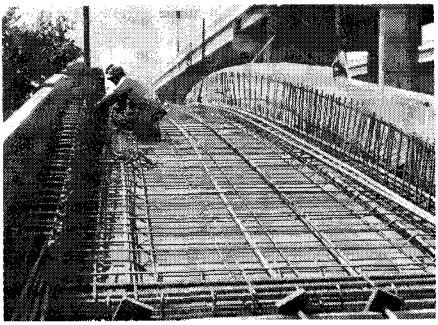


**Fig. 5a. Tendons being placed in slab and girders.**

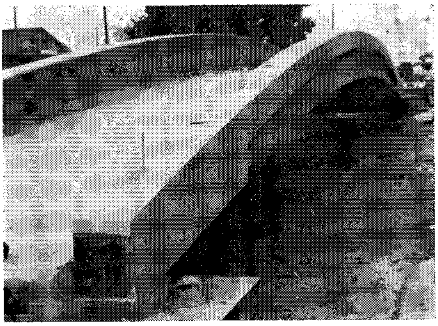


**Fig. 5b. Completed span after stressing.**

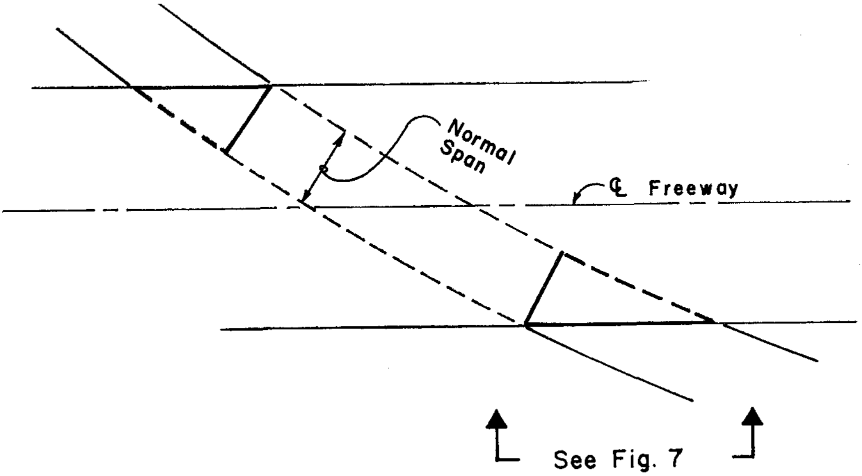


**Fig. 6. Plan of Mac Arthur Boulevard Undercrossing.**

and varied. We worried about rust. The contractor and the inspectors could not agree on how much rust was allowable. We seemed to have reached an impasse, until finally we said "No rust—period!"

With excellent cooperation between the State and the contractor's forces corrosion inhibitors and packaging forms were developed that have, essentially, eliminated all rust on the steel when it goes into the structure.

Prestressed concrete requires relatively high strength concrete. In California, strength requirements are generally in the vicinity of 4500 psi. On early prestressed jobs, the State's representative and the contractor had to get used to the idea of less water, more cement, and smaller and better aggregate. Again, through mutual cooperation, major concrete strength and quality problems have been solved.

Designers have also helped to minimize this problem by finding ways to avoid requiring especially high strength concrete whenever possible. For example, a moderate length two-span continuous box girder bridge would have the highest strength requirement in the bottom slab close to the interior support. By increasing the slab thickness near this support, the strength requirement can be substantially reduced.

The most disturbing problem, in some ways, was the difficulty we frequently had with grouting the tendons after they were stressed. Tendons are grouted for two reasons: the first is to develop the required ultimate moment capacity, and the second is to protect the steel from rust.

Remember, in these early days we were starting with rusty (sometimes very rusty) steel, so a less than perfect grout job did not leave us with high hopes for the longevity of that

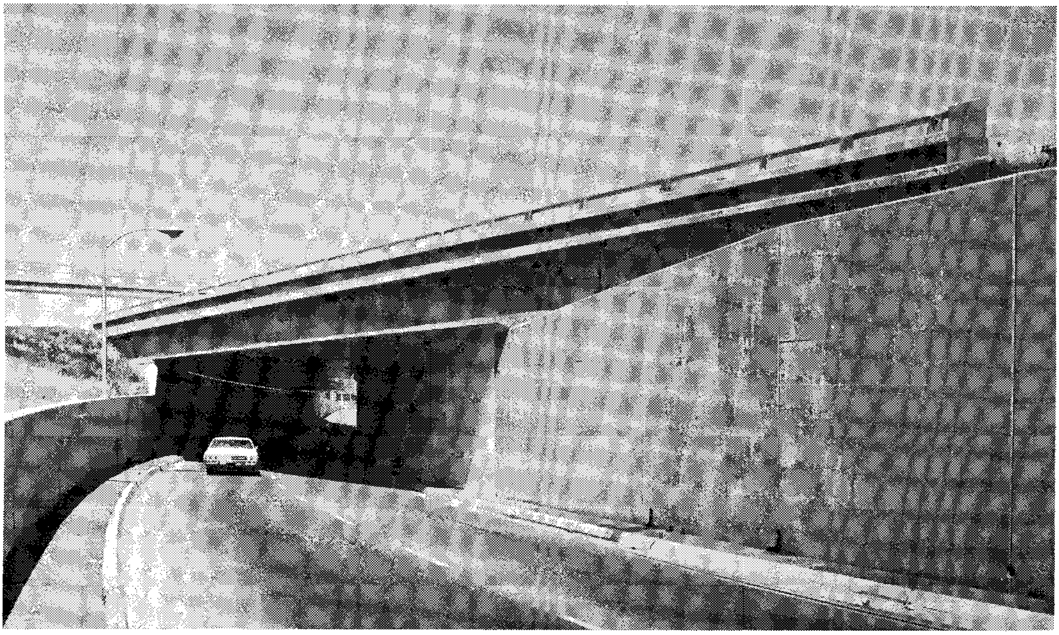


**Fig. 7. Mac Arthur Boulevard Undercrossing. Elevation of prestressed portal beam.**

prestressed bridge.

The causes of the early grouting problems were many, so the following is only a partial listing:

1. Lack of knowledge of what constituted good grout.
2. Improper mixing and pumping equipment.
3. Inadequate injection ports and vents on the tendons.
4. Blockages caused by the very nature of the old style flexible conduit.
5. Lack of knowledge and skill by the grouting personnel.
6. Lack of knowledge and expertise on the part of the State's inspectors.

Again, through the cooperative efforts of State and contractor's personnel, grouting problems have almost disappeared. All of the prestressing companies in California have excellent mixing and pumping equipment and skilled operators. We now think our grouting results are excellent.

## Alternative Designs

In the early days we were frequently uncertain as to the most economical section or structural type. Several times we presented complete details of structures designed in reinforced concrete or structural steel, and one in prestressed concrete. Usually the contractor selected the prestressed concrete alternative, although the apparent differences in cost were not very great.

In some cases, such as the Yolo Causeway on I-80 and the Sacramento River Bridge at Butte City, we showed five different superstructure types and let the low bidder select the one he wished to use (see Fig. 8).

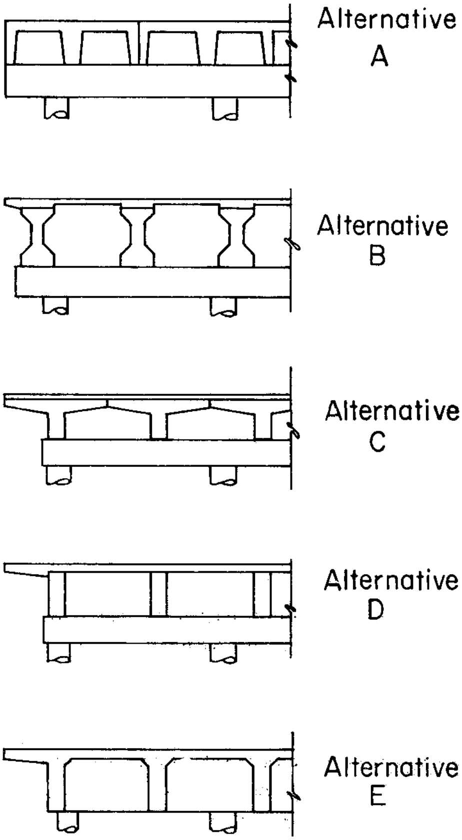


**Fig. 8. Alternative designs.**

Again, the prestressed concrete alternative was usually selected. These experiences gave us confidence in our ability to select the best and most economical structure type, and alternative designs went out of style until recently.

In the last few years, the State of California has again put out complete designs in both steel and prestressed concrete. As you know, the Antioch Bridge was recently bid, and will be built of steel.

We had hoped to see another cantilever type like Pine Valley, but at least we got an unexpectedly low price.

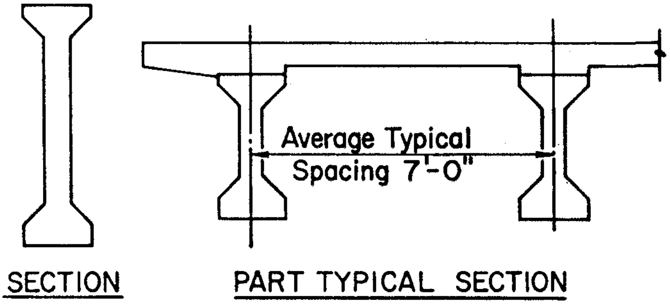


**Fig. 9a. California Standard I girder.**

## Increased Use of Precast Units

While we were experimenting with various structure types in the late 1950's, our individualistic designers were each trying to develop his idea of the "best" I or T girder section. The result was that each contract used a slightly different girder shape, and there was no real possibility of reusing girder forms on subsequent contracts.

We soon realized that we should standardize our I and T sections in the interest of best economy. The California Standard I and T sections (see Figs. 9a and 9b) were developed as a cooperative effort between the State and the California pretensioning plants.

Our standard I's have been used regularly since 1958 or so, but the T's are no longer used. Because they are prestressed and have no cast-in-place slab over them, the T's continue to creep upward because of stress distribution, resulting in a bumpy ride. The cast-in-place concrete slab used with the I girders allows much better grade control and composite I's seldom change camber significantly after the structure is completed.

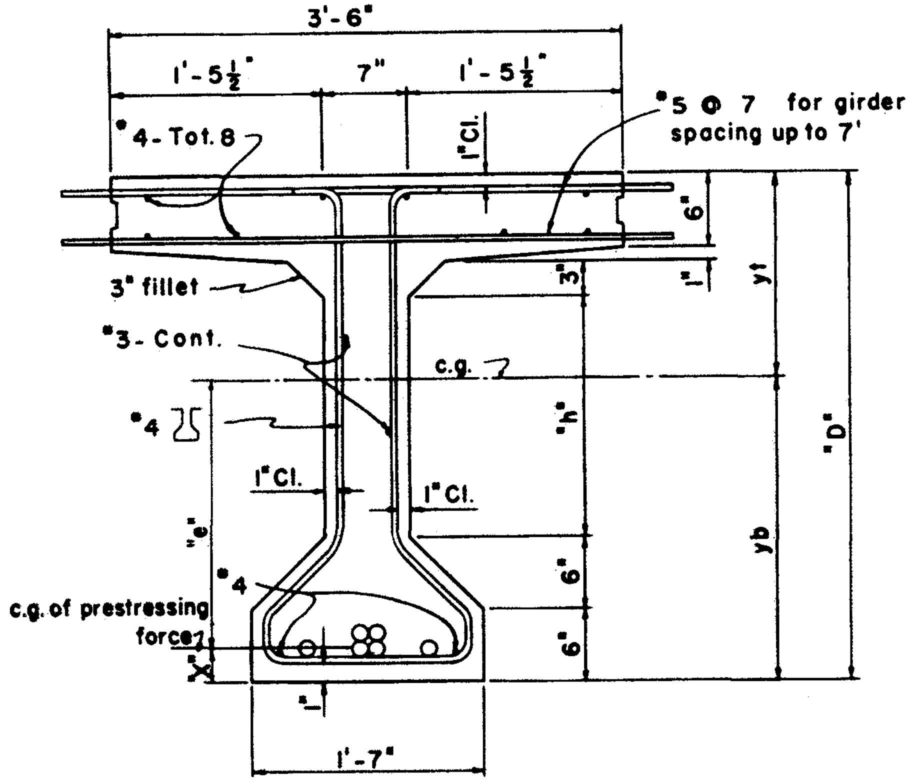
## Growth in Use of Cast-in-Place Designs

Precast I's and T's were very useful for relatively short spans, say from 80 to 90 ft, but were not really suitable for spans of over 100 ft. A four-span overcrossing might have two main spans of 90 ft and end spans of 50 ft.

Aesthetics, economics, and concern for public safety influenced designers to find ways to eliminate the bent at the right side of the roadway. Removing the columns on the driver's right side improves safety, the resulting two-span bridge allows for future widening, and a two-span continuous bridge looks better than four spans of approximately the same length (see Fig. 10a and 10b).

We discovered that a two-span continuous cast-in-place prestressed box girder bridge could be substituted for the above four-span I girder at the same structure depth.

The Federal Highway Administration for years has encouraged the various states to increase horizontal



STANDARD "T" GIRDER

SECTION PROPERTIES

| D ft.in. | h inches | Reinf. lbs/ft. | A sq.in. | $y_t$ | $y_b$ | $I_{c.g.}$ | $\frac{I_{c.g.}}{y_t}$ | $\frac{I_{c.g.}}{y_b}$ | $r^2$ | $\frac{ey_t}{r^2}$ | $\frac{ey_b}{r^2}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3-0 | 14 | 32 | 599 | 14.60 | 21.40 | 91,900 | 6,300 | 4,300 | 153 | .0952e | .1396e |
| 3-6 | 20 | 33 | 641 | 17.21 | 24.79 | 138,300 | 8,040 | 5,580 | 216 | .0798e | .1150e |
| 4-0 | 26 | 34 | 683 | 19.86 | 28.14 | 195,900 | 9,865 | 6,960 | 287 | .0693e | .0982e |
| 4-6 | 32 | 35 | 725 | 22.56 | 31.44 | 265,900 | 11,790 | 8,460 | 366 | .0616e | .0858e |
| 5-0 | 38 | 36 | 767 | 25.29 | 34.71 | 348,700 | 13,790 | 10,050 | 454 | .0557e | .0764e |

Weight of girder (lbs/ft) = 1.042 x A
"X" = Distance from bottom of girder to c.g. prestressing force
A = Gross area

Fig. 9b. California Standard T.

and vertical clearances, eliminate fixed objects, such as columns, from the vicinity of the traveled way, and to increase median and shoulder widths. All of these influences have increased the need for longer spans, and we discovered that cast-in-place prestressed concrete enabled us to do so economically.

Another factor influencing the emphasis on cast-in-place rather than precast construction is the great complexity of many of our structures. The right angle, straight, constant width bridge is not common in California. Most of the structures are skewed or curved horizontally and vertically, and often of varying width. Fig. 11 is an example of a curved bridge for which cast-in-place construction produces best results.

These variables complicate precast construction much more than cast-in-place. Normally, where average height falsework can be used and the bridge is in an accessible area, cast-in-place construction is cheaper than precast. Conversely, when falsework would be too high or too complicated, i.e., China Basin Viaduct in San Francisco, the precast girders are economical.

With the start of the trend toward cast-in-place prestressed concrete in

Fig. 10. Harbor Boulevard Overcrossing.

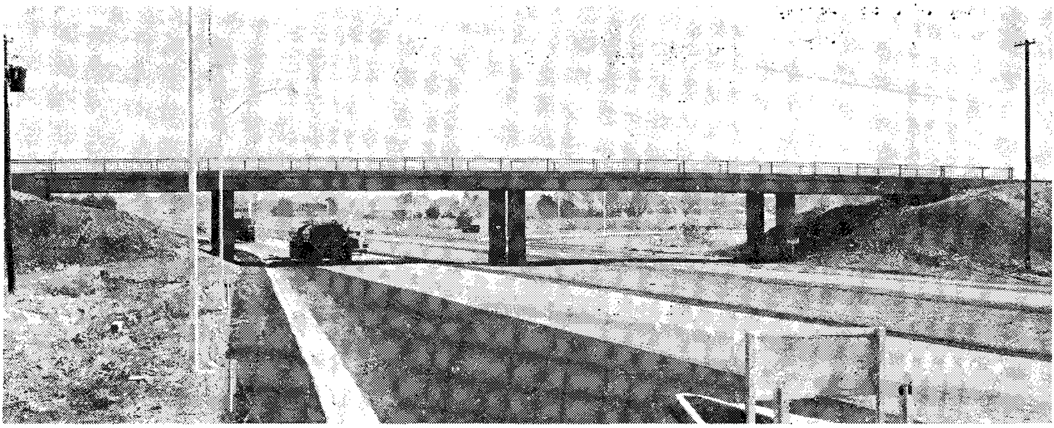


Fig. 10a. Original four-span structure.

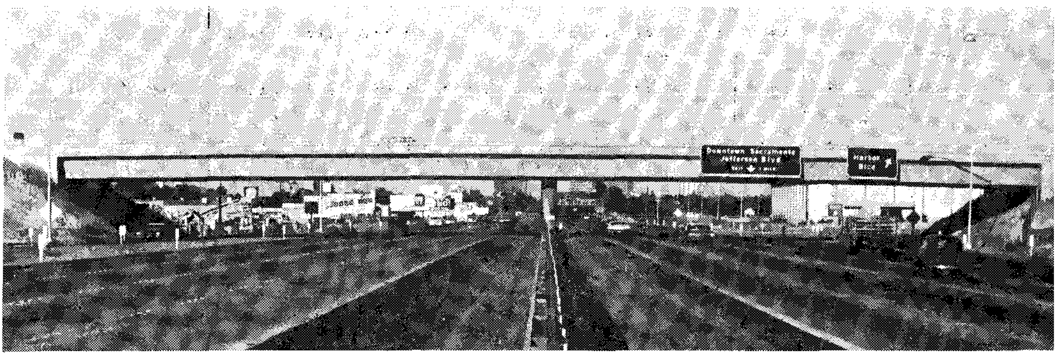


Fig. 10b. Two-span replacement with same length from abutment to abutment.

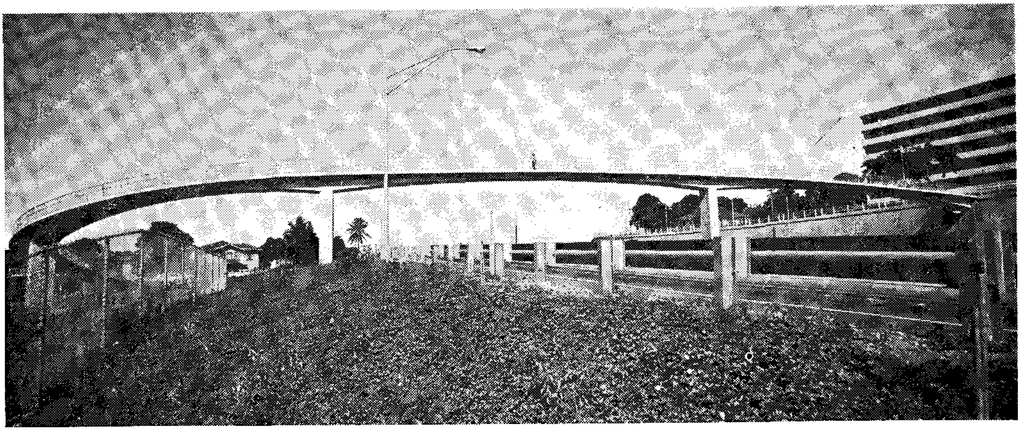


Fig. 11. Alapai Street Pedestrian Overcrossing—one of Hawaii's attractive, prestressed concrete bridges.

the early 1960's several post-tensioning companies either were formed or began to branch out from their previous area of emphasis. These companies brought experience and expertise to our prestressed bridge construction which had been previously lacking.

Fig. 12 shows how cast-in-place prestressed concrete has replaced precast prestressed concrete, in California, as the dominant type.

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## Introduction of Rigid Conduit

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Perhaps the major cause of the emergence of cast-in-place prestressed concrete as the dominant bridge construction material in California was the introduction of "rigid" conduit in 1967. In 1966, VSL, one of the new post-tensioning companies of that era, experimented with rigid conduit and a new "pull-through" technique.

At this time, our Bridge Department had become very strict in en-

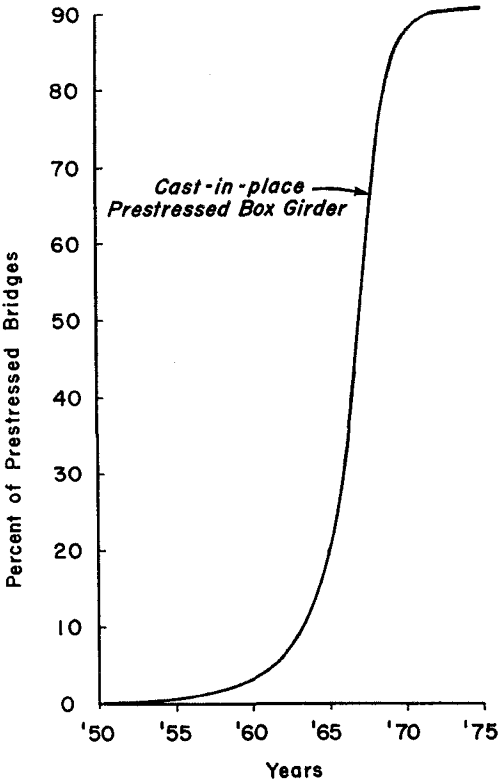


Fig. 12. Cast-in-place prestressed concrete bridges in California expressed as percent of all prestressed concrete bridges.

forcing a rigid corrosion specification. In an attempt to limit the amount of time the prestressing steel was exposed to the elements, VSL tried placing conduits of semi-rigid tubing in the forms, casting the concrete, and then pulling in the made-up strand tendons after the concrete had reached stressing strength.

A large bridge contract in Monterey in 1967 was the first job on which rigid conduit was used in all the bridges, and to everyone's surprise, VSL discovered that the cost of placing the tendons was only a fraction of what it was the old way. The old way consisted of fabricating the tendons in the company's plant, installing the strands or wires in flexible conduit, coiling up the tendons, shipping them to the job site and then installing them in the forms.

When you consider that a 12-strand tendon weighs about 6½ lb per ft, and that a 300-ft long tendon weighs nearly a ton, you can see that handling it requires a crane and much effort. On the other hand, a 40-ft length of rigid conduit weighs only a few pounds, and one man can place all the conduit for a bridge all by himself. When stressing time comes, the strands are pulled from the packs and into the ducts by means of simple air tuggers and three or four-man crews.

Although rigid conduit results in lower friction losses and reduced quantity of steel in a bridge, the major savings come from the great reduction in labor costs.

## Evolution of Prestressing Systems

The prestressing system used on the Arroyo Seco POC was the original button headed wire system developed by the Prestressed Concrete Corporation, later to become today's Prescon. Other early systems that were used in California included the early Freyssinet tendons with the concrete cones and 0.194-in. wire, Stress Steel rods, and a number of other systems that have since disappeared. Pretensioning plants started with wires, but quickly changed to seven-wire strands.

The development of the "harping" technique took place in California in the middle 1950's. A field trip sponsored by the World Conference on Prestressed Concrete in 1957 included a demonstration of the technique at the Gerwick-Pomeroy Plant in Petaluma.

Freyssinet introduced a strand and steel cone version of the original concrete cone system in about 1958 but it was not perfected until a few years later.

Rods and button headed wires were the common types of prestressing tendons used in California for many years. Rods predominated in short simple spans, while the Prescon, Ryerson, and Western Concrete Structures wire systems were used in the longer continuous bridges.

In those days it was commonplace for the prime contractor to buy the fabricated tendons from the supplier, and then do the placing, stressing, and grouting himself with his regular reinforcing steel ironworkers. These people frequently had had no previous experience in this type of work, so it is not surprising that the results were not always satisfactory.

In 1965 a new system was introduced, namely, VSL. This system used twelve ½-in. strands anchored in individual conical holes in a bearing block with two-piece machined wedges. The wedge type anchorage had a great advantage over button headed wires because exact length was not critical.

In addition, the ½-in. 270-ksi

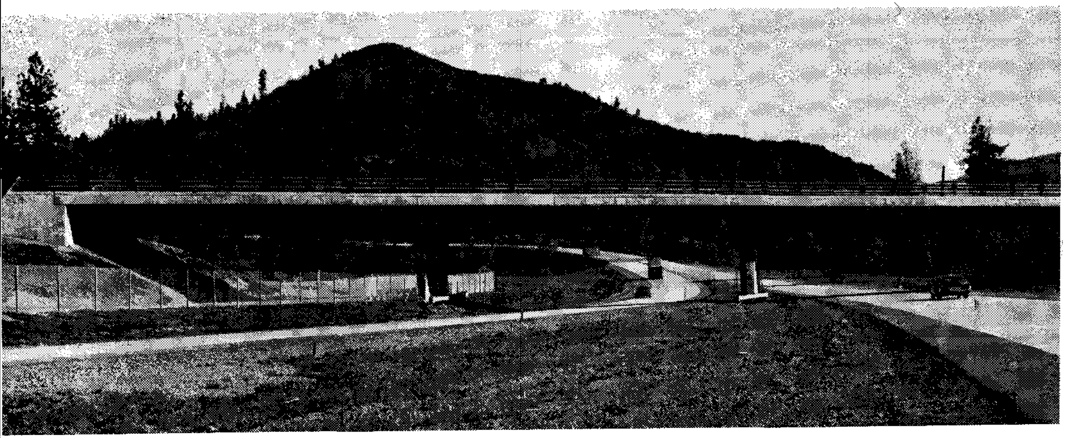


Fig. 13. Antler Underpass. Three-span continuous through-girder railroad bridge.

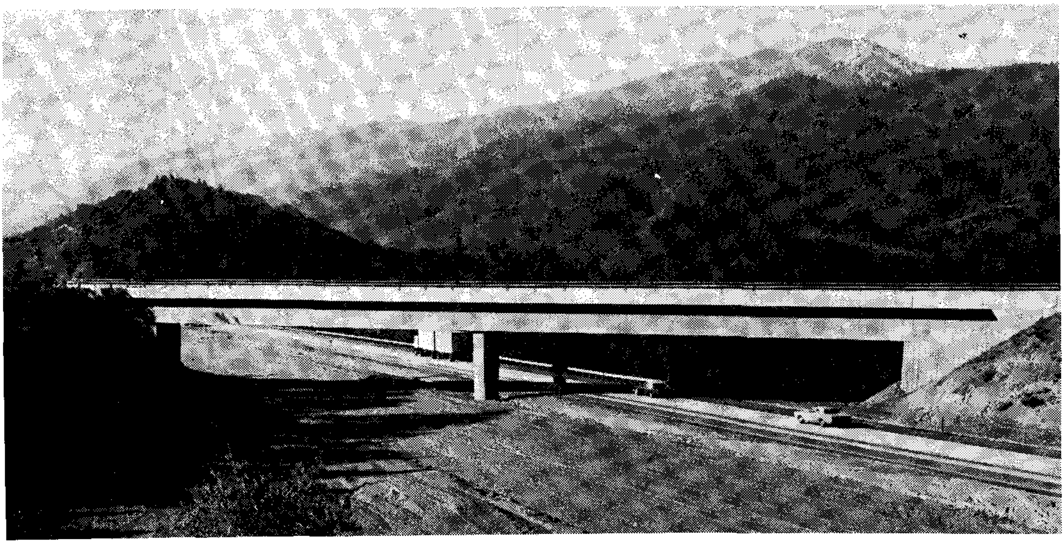
strands were cheaper than rods or wires per kip of anchored force. The VSL system proved so attractive that Western Concrete promptly developed its own strand system, later followed by Prescon and Stresstek.

These new companies acted as subcontractors on bridge jobs and not only supplied material, but also placed, stressed, and grouted the tendons with their own forces and equipment. This meant that we now had experts doing this specialized work and the quality of our prestressed bridges improved markedly.

## Prestressed Railroad Structures

In the middle 1960's California began designing prestressed concrete through girder railroad structures (see Fig. 13). These were very attractive to us because of their low cost compared to steel, and were attrac-

Fig. 14. Bailey Hill Underpass. Two-span continuous deck type railroad bridge.



tive to the railroads because of their minimal maintenance requirements.

Since railroad bridges are roughly twice as deep as a highway bridge of similar span, they take full advantage of the low friction characteristics of rigid conduit. We have had some troubles with them in the form of unexpected cracks. Research has shown that these cracks are primarily due to temperature gradients in the concrete produced by the heat of hydration.

These sections are much thicker and deeper than highway bridge girders and require more special precautions during construction. Closure castings are required, and a small concentric prestressing force is introduced when the last placed concrete has reached a strength of 1500 psi. This early compressive stress has eliminated the cracking problem.

We have also used simple and continuous span deck type prestressed box girder structures for railroad bridges where there is sufficient clearance available (see Fig. 14). Sloping exterior girders and wide deck overhangs have been used on these prestressed railroad bridges to improve their appearance.

## Evolution of Design Specifications

In the early 1950's we were designing and building prestressed concrete bridges although there were no formal specifications for us to follow.

The Joint ACI-ASCE Committee report on "Prestressed Concrete," which was published in the *ACI Journal* in October 1952, was one of the earliest design aids available to us.

The paper, "Designing for Continuity in Prestressed Concrete Structures," published in the Proceedings of the First United States Conference on Prestressed Concrete in 1951 was our first guide to continuous design.

Other early specification aids were found in "Criteria for Prestressed Concrete Bridges" published by the Federal Bureau of Public Roads in 1954.

The first edition of Professor T. Y. Lin's book, *Design of Prestressed Concrete Structures* published in 1955 was widely used by designers of prestressed concrete bridges in California.

Early design specifications allowed no tension in the precompressed concrete under any service loading. This requirement applied to both pre- and post-tensioned construction.

In the early 1960's AASHO conducted a series of tests of a prototype bridge and highway system. Various types of bridges were subjected to many cycles of intentional overload. When the testing program was completed, the bridges were taken apart and inspected in detail.

Based on the results of these inspections, AASHO in 1962 recommended designing pretensioned girders for a moderate tensile stress under live load, but post-tensioned girders were still required to have no tension under full design loading.

This distinction favored pretensioning over post-tensioning, as did the fact that we designed pretensioned girders by the net-and-transformed area method while the post-tensioned girders were still designed by gross area.

Our precast girder contract plans frequently showed two different concrete strength and working force requirements—one if the girders were pretensioned and another for the post-tensioned option.

For some years now we have designed both pre- and post-tensioned girders for a limited tensile stress under full load.

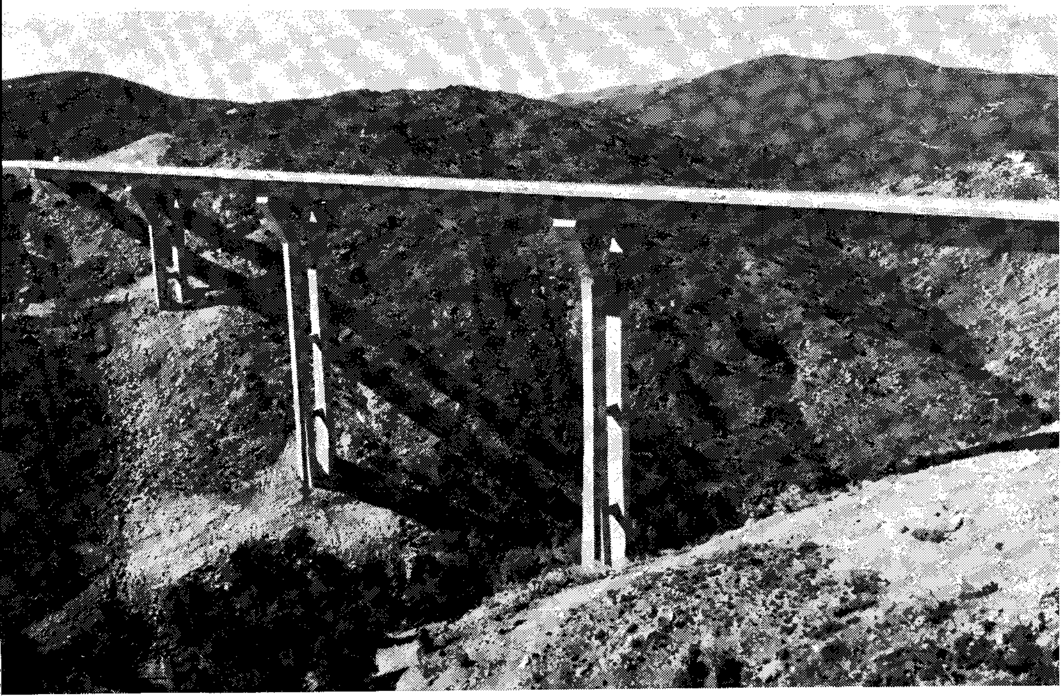


Fig. 15. Pine Valley Creek Bridge.

## Present Practice And Future Trends

Now prestressed concrete has become an established construction material. It is as controlled by specifications and computerized design techniques as any other material. All bridges, of whatever material, are now designed by the load factor method.

Computer programs are available that handle the most complicated framing systems and tendon layouts, including variable moment of inertia, internal hinges, and partial length tendons. Free standing, segmental cantilever design has also been computerized.

Conventional box girder bridges have their prestressing tendons placed in girders spaced at 8 to 10-ft centers, and have reinforced concrete top and bottom slabs. In cantilever construction it is economical to reduce the number of girders to two or three, with a spacing of 20 to 30 ft. Because of this wide girder spacing the deck slab is prestressed transversely, and the longitudinal tendons are placed in the top and bottom slabs.

On two contracts, a cantilever type typical section has been used by the contractor, but the structure has been built on partial length falsework supported from the ground, rather than being supported from travelers, as at Pine Valley.

This segmental-on-falsework technique requires a minimum amount of falsework and does not require expensive travelers. In addition, the contractor's forces are performing tasks that are familiar to them and do not need on-the-job training to learn new construction techniques.

In normal design, the tendons must be placed in the girder stems so that their trajectories may roughly follow the variation in positive and negative moments. In cantilever construction the bridge is built as a series of cantilevers balanced over the supports.

When the approaching cantilever ends meet, so-called "continuity" tendons are stressed in the bottom slab to give positive moment capacity. Since the stems do not contain tendons, they may be sized for shear and thus two fairly thin stems generally suffice.

The Pine Valley Creek Bridge near San Diego is California's first bridge built by the free cantilever method (see Fig. 15).

For aesthetic reasons we use box girders over city streets. When a precast element is needed for that type of location we use an inverted T section which simulates a closed soffit (see Fig. 4). Precast box sections have been used for this purpose, but they are relatively expensive.

The bottom flange of the inverted T has been designed with a width of over 6 ft, and can easily be built to a variable width. The inverted T is designed as an I girder with a wide bottom flange and has a cast-in-place deck just like the I girders. A fascia girder is cast in place with the forms supported by the adjacent inverted T's.

An innovation of the late 1960's was California's first use of partial length tendons in the Eel River Bridge at Benbow (see Fig. 16). This haunched, three-span continuous box girder structure had continuous tendons in each girder and a number of partial length tendons that extended through the areas of high negative moment over the bents. This enabled the designer to fit the area of prestressing steel to the moment requirements.

In a deeply haunched, continuous box girder, the increased moment of inertia attracts applied moment at a greater rate than the build up of resisting moment. If all continuous tendons are used, there is too much prestressing force in the positive moment regions. Partial length tendons added in the high negative moment areas can be a practical and economical solution.

In 1962 a freeway interchange in West Los Angeles was being designed. The highway alignment required long connecting ramps with spans of up to 193 ft over the San Diego and Santa Monica Freeways (see Fig. 17).

At this time we had no experience with long span, curved post-tensioned bridges. If the long spans had been designed in reinforced concrete, the 193-ft span would have required a structure depth of about 10½ ft. The same span in prestressed concrete could be reduced to a structure depth of 7 ft.

Two of the ramps were designed to include a pair of three-span continuous prestressed units crossing the two freeways. A fifth continuous unit crossing a city street was designed to include extra tendons which were to be instrumented and tested to verify the validity of the friction factors in use at that time.

Since this bridge was to be the first one of the five to be built, if the friction factors were found to be too small, the other four could be redesigned accordingly. When the first structure was built and tested, the measured friction agreed substantially with the calculated values.

Prior to the construction of these five curved bridges, many designers were unsure of what would happen when a horizontally curved structure was prestressed. Some designers thought the bridge would tend to curl up, while others expected it to

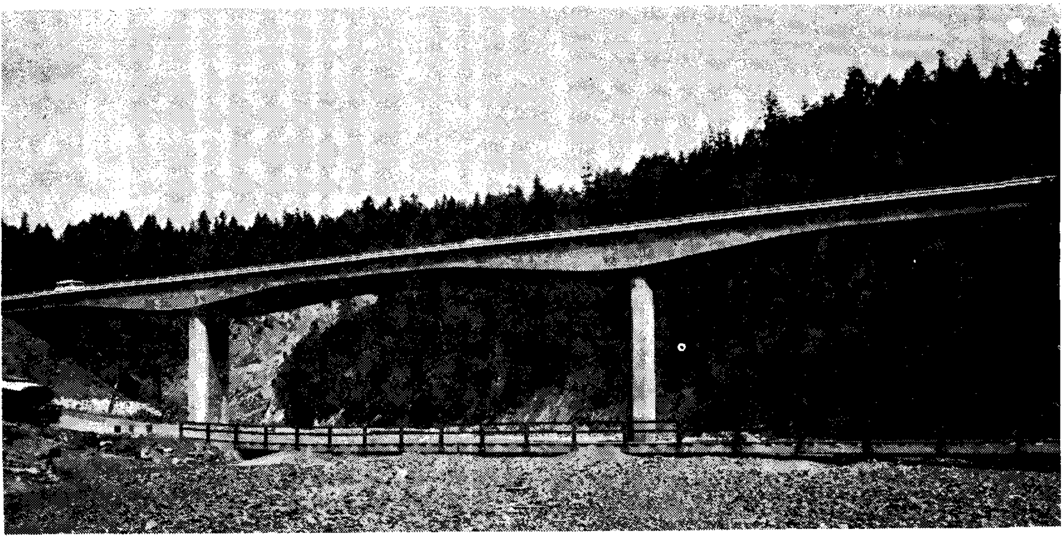


Fig. 16. Eel River Bridge at Benbow.

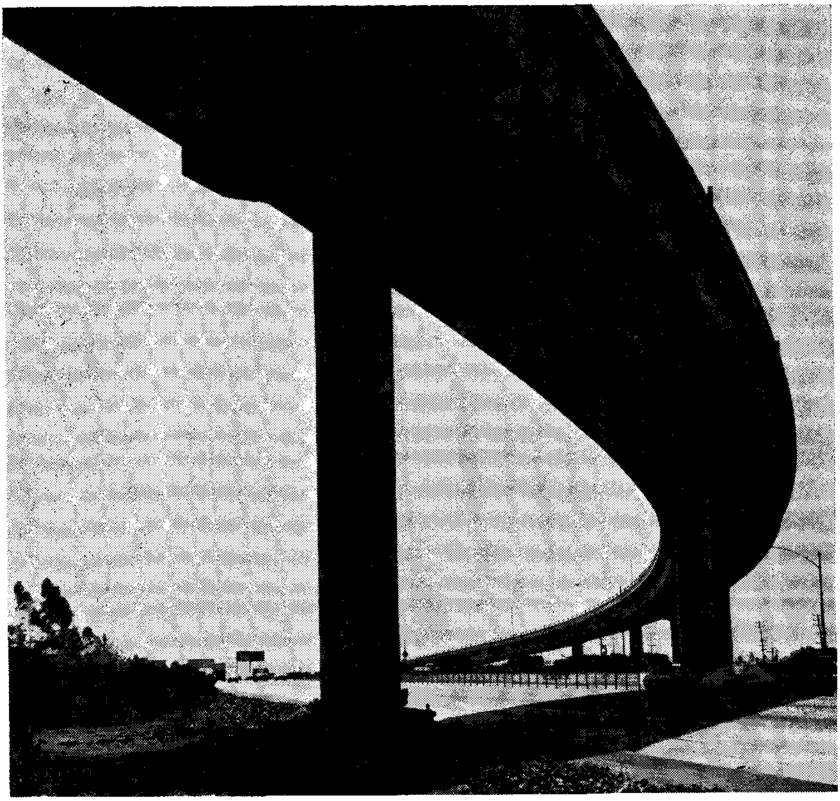


Fig. 17. Southeast Connector Overcrossing. Prestressed unit with spans of 136, 193, 136 ft.

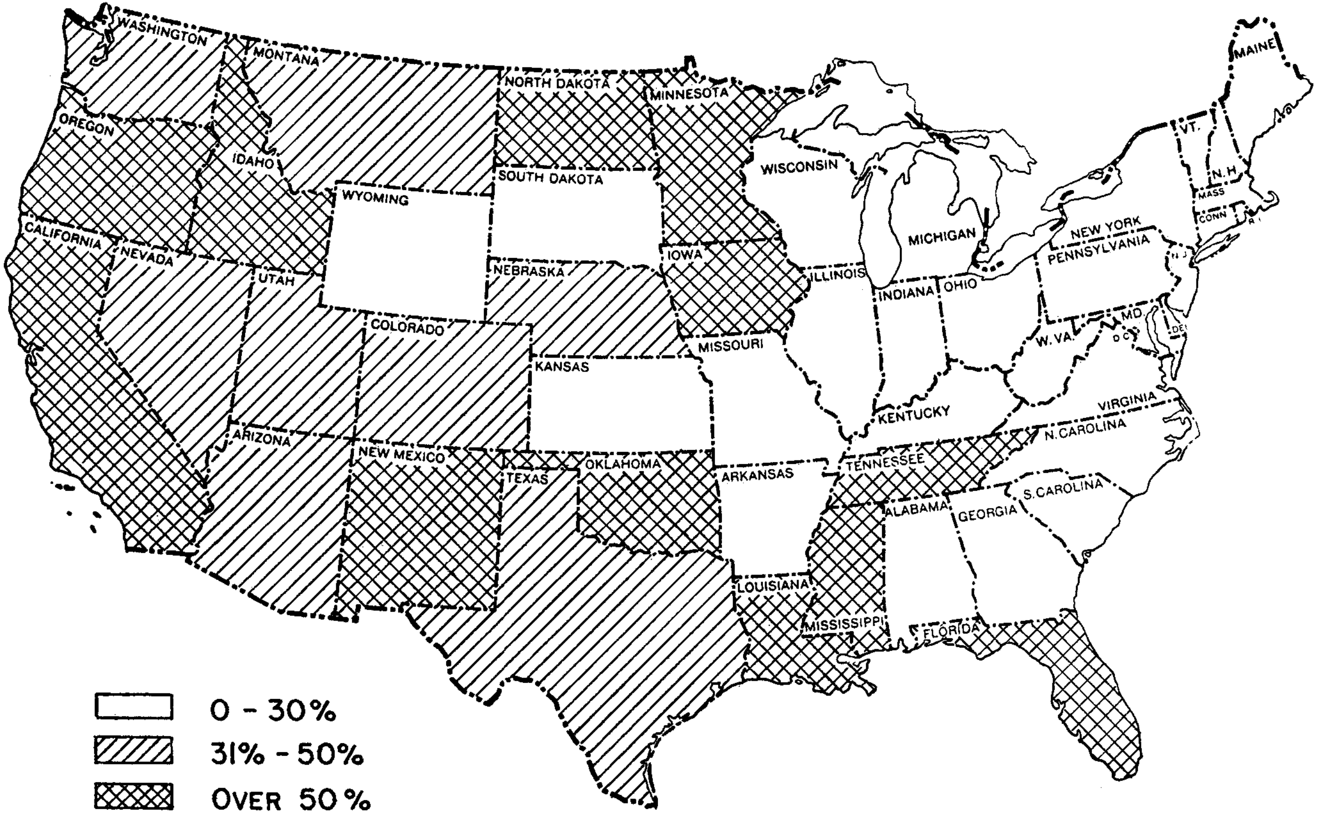


**Fig. 18.** Use of prestressed concrete for bridges throughout the United States. (Data from "New bridge construction and major reconstruction authorized during calendar year 1975" issued by the FHWA.)

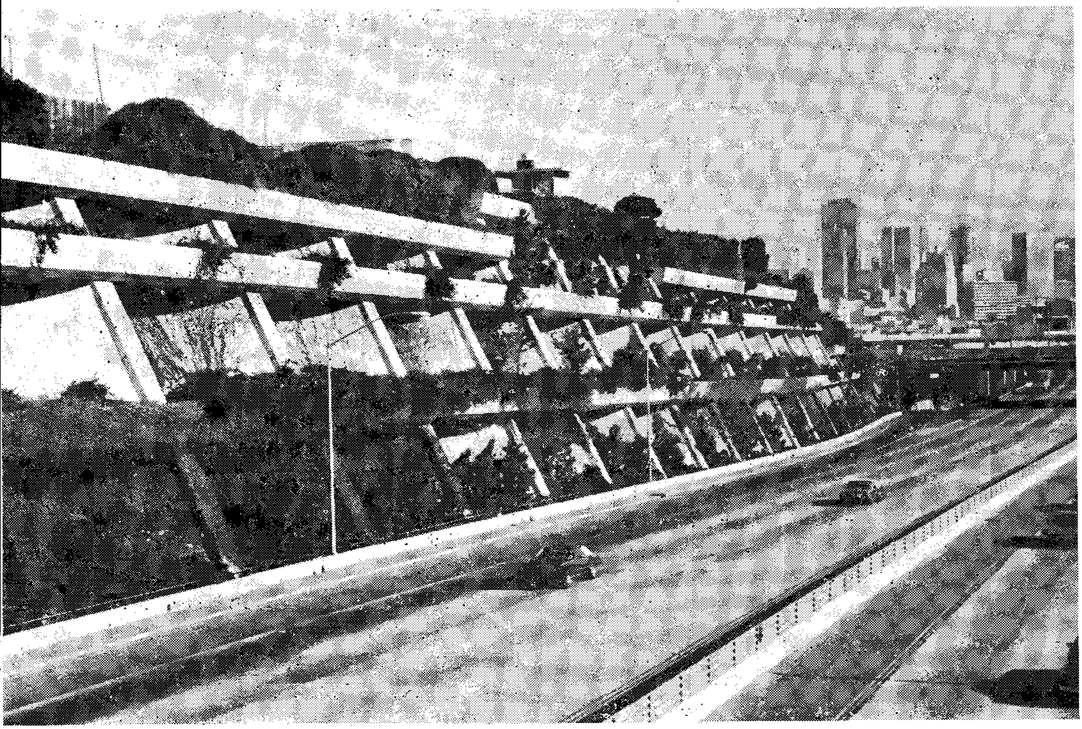


Fig. 19. Potrero Hill Retaining Wall.

straighten out.

Of course, everyone now realizes that a prestressing force concentric with the longitudinal axis of symmetry of the member has no effect on the member's shape, but this was not generally recognized 15 years ago.

It is interesting to note in Fig. 18 the differences in the use of prestressed concrete for bridges by the various states. In general, usage is low in the New England and eastern seaboard states with the exception of Florida which pioneered in the use of prestressed concrete and continues to favor it.

West of the Mississippi usage is much greater than in eastern states. This regional difference may in part be explained by the influence of climatic conditions and proximity to eastern steel producing sources.

## Prestressed Tie-Backs And Rock Anchors

An interesting application of post-tensioning was the construction of the Potrero Hill Retaining Wall in San Francisco (see Fig. 19). The design concept consisted of essentially vertical beams stressed back into the original ground. These beams acted as abutments for vertical arches spanning between them holding back the earth. The extrados of the arch consisted of mortar, air blown against the excavated surface.

The wall was built from the top down. The earth was excavated to a safe depth, holes were drilled into the hillside, and prestressing rods were anchored in the lower ends of the holes with grout. A portion of the vertical beam was cast, concave excavations were made into the hillside between the beams and the arch portions were constructed of air-blown mortar.

The beam and arch segments were then prestressed back into the hillside. This operation was repeated several times until the bottom of the cut was reached, leaving the wall with a maximum height of over 60 ft.

The footings of the Pine Valley Bridge were stressed into the foundation material by means of Dywidag rod rock anchors. Because of the height of this bridge and the design earthquake moment, the footing dimensions would have been excessively large if they had been designed otherwise.

## Research Projects

Through the years, the California Transportation Laboratory and the Bridge Department's research sections have conducted numerous research projects to solve problems that arose from the increasing use of prestressed concrete. Friction factors have been researched numerous times.

In the early 1960's friction was investigated on long tendons in curved bridges and on galvanized wires passing over steel saddles. Later, friction factors were determined for galvanized rigid conduit, and most recently, for ungalvanized conduit.

The California Transportation Laboratory has run extensive tests to determine the parameters affecting the quality of grout and the determination of the best ways to inject grout into the stressed tendons. Bridge Research later ran tests to observe and determine the quality of the grout in field-grouted tendons after it had hardened.

Tendon relaxation caused by creep, shrinkage, and plastic flow has been measured by Bridge Research and TransLab in three or four different projects.

Research is still going on to determine the creep-caused reduction of column moments created by prestress shortening.

As serious problems or questions arose, and were alleviated by research, our confidence grew and led us to more innovative applications of prestressed concrete.

It must be emphasized that for many years a climate of mutual respect and cooperation has existed between the Division of Structures and the prestressing contractors in California.

It was realized that job level problems—such as excessive friction or duct blockages during grouting—were mutual problems. The prestressing contractors cooperated willingly with the Transportation Laboratory and the Division of Structures in solving these problems.

## Lab-Testing Experience

TransLab, over the years, has developed suitable acceptance criteria for post-tensioning systems. In the early days, tendon hardware was used before it was thoroughly researched. Development was empirical rather than rational.

As tendons grew larger, the design of the anchorage hardware became more critical, and the difference between a 6-ft long laboratory test sample and a 100-ft long prototype tendon became too great to ignore. More representative performance tests were developed jointly by the Laboratory and industry.

In addition to extensive theoretical exposition, a number of full-sized, 25 ft (±) long tendons are tested to destruction by the company proposing them and the tests are witnessed by Laboratory personnel.

The past 25 years has been a period of significant progress in the development of prestressed concrete and its application to bridges.

Several important factors contributed to the progress and should be recognized.

First there had to be the challenge of a large construction program—the Interstate Highway Program provided this. Cooperative top management was needed to provide a favorable climate for skilled, motivated engineers to innovate and adapt a new material to design solutions.

A competitive, innovative industry played an important part in solving fabrication and construction problems. To achieve a quality end product there was a need for skilled construction engineers and testing procedures.

Finally, all through the process the teaching and writing of men like Professor T. Y. Lin and other pioneers provided the inspiration to engineers everywhere to overcome obstacles and meet the challenges that accompany change.