Seismic Retrofit of Southern Freeway Viaduct, Route 280 (Single-Level Segment), San Francisco, California

Roy A. Imbsen and Robert A. Schamber, *Imbsen & Associates, Inc.*
A. A. (Frank) Abugattas, *Brown & Root, Inc.*

The Loma Prieta earthquake of 1989 generated the need to strengthen the single-level Southern Freeway Viaduct. The double-deck portion just south of this project was damaged, and the whole viaduct was closed to traffic. The Southern Freeway Viaduct is a continuous reinforced concrete box girder bridge built in 1964 in accordance with the AASHO standard specifications. The viaduct is composed of three main lines, as follows: ES Line, SE/A Line, and R1 Line. The columns are rectangular with inadequate tied reinforcement. The columns at most multicolumn bents are pinned at the bottom. Several of the fixed-base columns have lap splices. The majority of footings are supported on steel HP piles; however, some are spread footings. The footings do not have top mat and shear reinforcing. Several of the A-Line bents north of 25th Street are outriggers. Soil conditions at the southern section (south of Bent 73 on the main lines) can be classified as soft bay mud sites, whereas more generally, the site has a combination of a thick soft bay mud layer and a large depth to bedrock. The northern segment is founded on bedrock or stiff soils. Most of the deficiencies found in the viaduct are related to the original design of the hinges, columns, footings, and outriggers. Solutions to retrofitting the viaduct were limited by the existing conditions and existing features (i.e., railroad lines, streets, leased airspace below the viaduct, utilities, etc.) within the project limits. The retrofit strengthening concepts used on the project included the following: hinge retrofits, separation of two level bents, steel column casings, column strengthenings (additional vertical steel encased within a steel casing), grade beam retrofit, new drop caps (bent replacements), elimination or retrofit of outriggers, and footing retrofits. This final retrofit strategy met the required seismic performance goals established by the California Department of Transportation for this project to prevent collapse and provide serviceability after a maximum credible earthquake.

The Loma Prieta earthquake of 1989 generated the need to strengthen the single-level Southern Freeway Viaduct. The double-deck portion just south of this project was damaged, and the whole viaduct was closed to traffic.

This paper describes the seismic retrofit of the single-level segment of the Southern Freeway Viaduct in San Francisco, California, which was under contract to Imbsen & Associates, Inc. (IAI), and Brown & Root, Inc. (B&R), from the California Department of Transportation (Caltrans) between 1990 and 1993. In addition, DRC Consultants, Inc., and Earth Mechanics, Inc. (EMI), provided retrofit design and geotechnical support, respectively. Anatech Research Corporation performed an analysis of joint shear. The design efforts culminated with a final set of plans, specifications, estimates, and construction contracts.

The objective was to seismically retrofit the single-level portion of the Southern Freeway Viaduct, Route 280, in San Francisco to prevent collapse or major damage in an earthquake with the maximum intensity expected to occur at this site. The structure's serviceability performance goals are that it will be repairable and that there will be access beneath the viaduct for emergency services and repair.

The single-level segment of Route 280 in San Francisco branches into the following viaduct lines (Figures 1 and 2):

- ES Line: beginning at the hinge adjacent to Bent ES-59 near Evans Street and extending to Bent ES-90 between 23rd and 25th Streets.
- R1 Line: beginning at the hinge adjacent to Bent R1-50 near Innes Street and extending to Abutment R1-72 near Main Street.
- SE/A Lines: beginning at the hinge adjacent to Bent SE-53 near Galvez Avenue and extending to Abutment A-111 north of 22nd Street.
- B and C Lines: all bents on both of these ramps between 23rd and 25th Streets.

For the purpose of facilitating construction contracts that expedite opening the bridge to traffic, the project was divided into three separate design projects.

- Project 1 included any retrofit work that would cause significant interference with traffic on Route 280. Completion of construction of this work was scheduled for the end of 1992 to allow opening the structure to traffic (SR-637).
- Project 2 included the retrofit of all bents south of Army Street that were not retrofitted in Project 1 (SR-605).
- Project 3 included the retrofit of the remaining Southern Freeway Viaduct north of Army Street. This project was eventually divided into two separate projects for construction (SR-604 and SR-641).

IAI was under prime consultant contract to complete Project 1, and B&R was under prime consultant contract to complete Projects 2 and 3. IAI, B&R, and EMI were teamed and involved in the retrofit design of all projects. DRC was involved in the retrofit design of Projects 1 and 2. Figures 1 and 2 show the locations of these lines and project limits.

Description of Existing Bridge

The Southern Freeway Viaduct is a continuous reinforced concrete box girder bridge built in 1964 in accordance with the AASHO Standard 1961 Specifications for Highway Bridges and subsequent interims. The columns are rectangular with vertical reinforcement and 12-mm bar ties typically at 305-mm spacing (no. 4 ties typically at 12-in. spacing). The columns at most multi-column bents are pinned at the bottom with four 35-mm bars (no. 11 dowels). Most of the fixed-base columns have lap splice connections. The majority of footings are supported on steel HP piles, whereas others

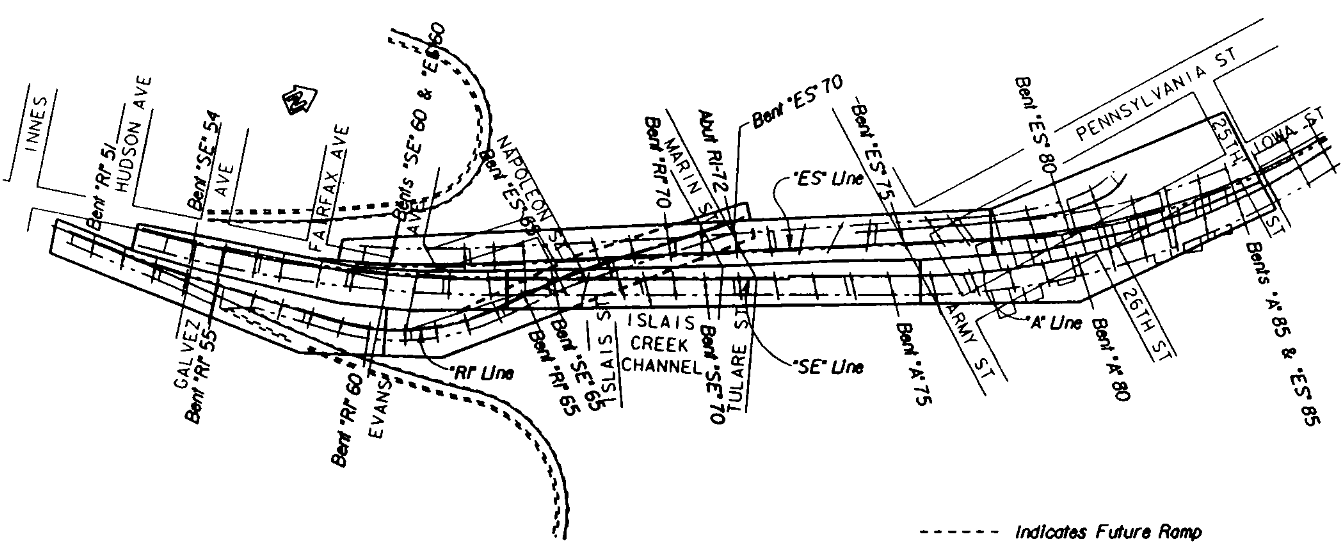


FIGURE 1 Projects 1 and 2, plan view.

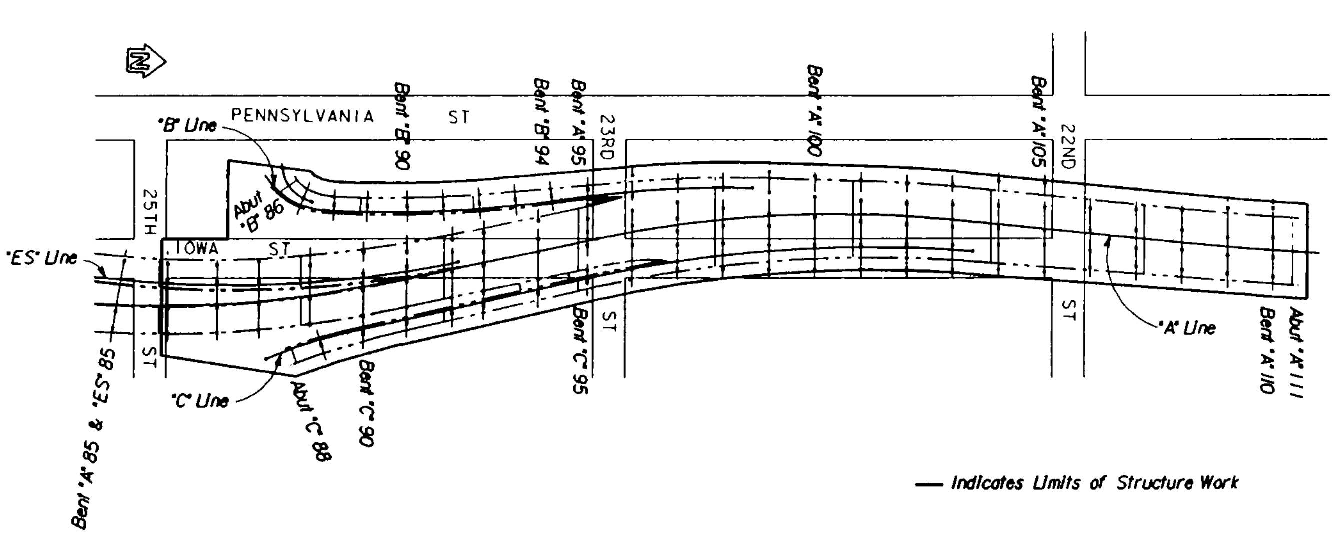


FIGURE 2 Project 3, plan view.

are spread footings. The footings do not have top mat and shear reinforcing. The HP piles are connected to the footings with one 20-mm bar (no. 6 rebar). Many of the A-Line bents north of 25th Street are outriggers. The outriggers were constructed to allow the viaduct to span over Iowa Street and existing and future railroad tracks beneath the structure.

The behavior of the single-level viaduct is complicated by the fact that the ES, SE, and R1 Lines intersect at three locations. The R1 and SE Lines intersect at Bent R1-66/SE-65, and the ES and R1 Lines intersect at Bents R1-69/ES-67 and R1-70/ES-68. At two of these intersections (i.e., R1-66/SE-65 and R1-70/ES-68) the supporting bent is a two-level frame. At these two locations the preferred retrofit was to separate the lower level from the upper level.

Following the San Fernando earthquake in 1971, Caltrans initiated the Phase One earthquake retrofit program. Seismic restrainers were installed at the intermediate expansion hinges on the Southern Freeway Viaduct in 1973. The cable units consisted of 14 cable restrainer units that are similar to the current Caltrans C1-Type restrainers [i.e., cable drum units, bolsters, 19-mm-diameter (3/4-in. diameter) cables]. The hinge seats are approximately 152 mm (6 in.) in length. Access holes for the cable restrainer units were placed in the top deck of the Southern Freeway Viaduct and were sealed with concrete. There are no access holes in the soffits.

The consultants divided the viaduct into five segments for analysis and design. A general description of each stage is provided in Table 1.

TABLE 1 General Description of Existing Bridge

Line	No. Spans	Span Length Ranges (ft)	No. Cells	Minimum Curb-to-Curb Width (ft)	No. Hinges	Single Column Bents	2 Column Bents	3 Column Bents	4 Column Bents	>4 Column Bents	Outrigger Bents	Shared Bents with Adjacent Superstructure
SE/A Line (Stage 2)	33	80-121	6-7	49	12	3	29	0	0	0	3	1
R1 Line (Stage 1)	22	80-104	4-8	28	8	17	4	0	0	0	2	3
ES Line (Stage 3);	26	70-132	6-12	49	10	7	16	3	0	0	0	2
Ramp R4	2	85-97	5	36	0	1	0	0	0	0	0	0
A Line (Stage 4);	13	66-113	13-25	52	4	0	0	0	9	4	12	0
Ramp B;	9	51-80	4-5	32	3	8	0	0	0	0	0	0
Ramp C	9	60-113	3-4	24	2	7	0	0	0	0	0	0
A Line (stage 5)	12	40-93	16-22	120	4	0	0	0	5	7	15	0
Total	126	N/A	N/A	N/A	43	43	49	3	14	11	32	N/A

Soil Profile and Response Spectra

The soil profile along much of the Southern Freeway Viaduct includes three major soil layers:

- Layer 1: a surficial fill layer of gravel, sand, and silt of moderate stiffness and strength;
- Layer 2: a second layer of very soft bay mud; and
- Layer 3: a layer of very dense sand or stiff clay above bedrock consisting of sandstones, referred to as the San Franciscan formation.

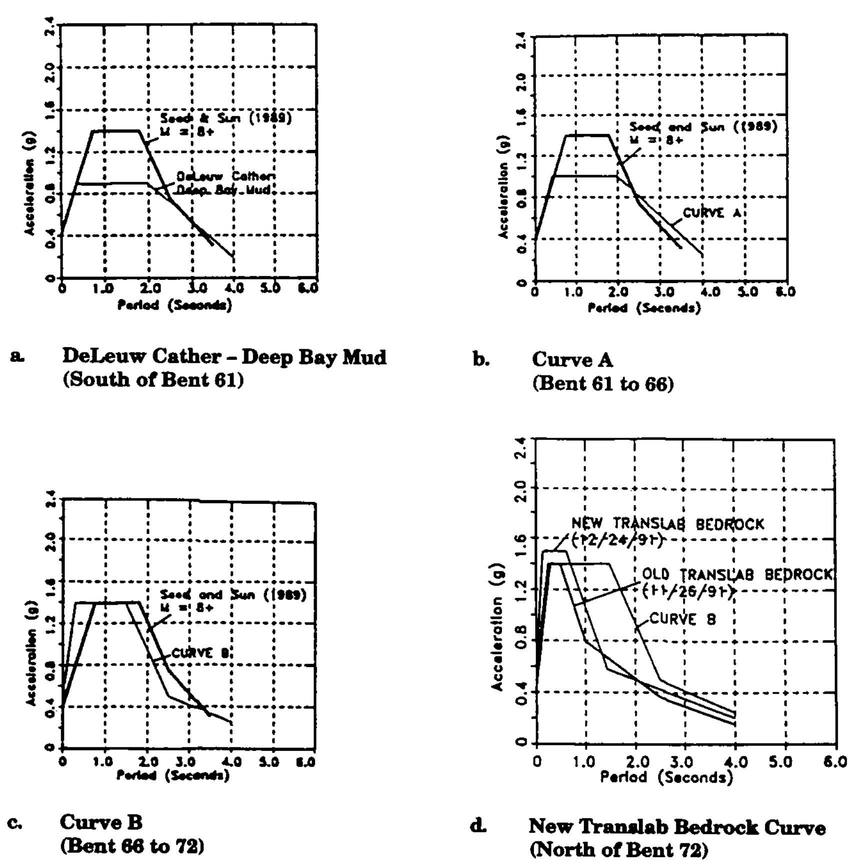
Soil conditions at the southern section (south of Bent 73 on the main lines) are classified as soft bay mud sites, whereas elsewhere there is a combination of a thick soft bay mud layer and a large depth to bedrock. The northern segment is founded on bedrock or stiff soils where the depth to bedrock is less than 15.25 m (50 ft), and the thickness of the soft clay layer is less than 1.53 m (5 ft). The soft bay mud layer is nonexistent in some areas.

On November 26, 1991, our project team and Caltrans adopted for Project 1 the Seed and Sun 8+ spectrum (1989) and a bedrock spectrum provided by Translab for the southern (soft soil site) and the northern (firm-ground site) portions of the Southern Freeway Viaduct, respectively.

On December 24, 1991, Translab provided four response spectra: (a) DeLeuw Cather's deep bay mud spectrum, (b) Curve A, (c) Curve B, and (d) a new bedrock spectrum (*1*). The three soft soil spectra, including Curves A and B and the DeLeuw Cather deep bay mud curves, were considered appropriate for the southern portion of the project sites. The new bedrock spectrum was considered appropriate for the northern portion (north of Bent 72). See Figure 3 for the response spectra used.

To meet the schedule for the plans, specifications, and estimate (PS&E) submittal for Project 1, the project team and Caltrans decided to continue Project 1 work with the Seed and Sun 8+ spectrum and the unrevised Translab bedrock spectrum of November 26, 1991. However, it was agreed that the new bedrock spectrum and Translab's three soft soil spectra be adopted for Projects 2 and 3.

Discrepancies between the response spectrum criteria used in Project 1 and the revised response spectrum criteria are relatively small considering the level of uncer-



a. **DeLeuw Cather - Deep Bay Mud (South of Bent 61)**

b. **Curve A (Bent 61 to 66)**

c. **Curve B (Bent 66 to 72)**

d. **New Translab Bedrock Curve (North of Bent 72)**

FIGURE 3 Response spectra for Southern Freeway.

tainty on earthquake ground motion; therefore, no changes were made to the Project 1 design.

Retrofit Design Criteria

The design criteria were in conformance with Caltrans's procedures for retrofitting (2). Seismic retrofit analysis techniques and retrofit schemes were continuously developed during the project. The project team maintained close coordination with the Caltrans contract administrator to ensure that the very latest criteria were used. Demand/capacity ratios were obtained for all bridge components.

The retrofit was based on the following criteria:

- Material strengths. The columns are composed of reinforced concrete that are typically rectangular in shape. The reinforced concrete strengths specified on the plans for the bridge were f_s of 137 800 kPa (20,000 lb/in.^{2}) for rebar and f'_c of 20 670 kPa (3,000 lb/in.^{2}) for Class A concrete and f_s of 137 800 kPa (20,000 lb/in.^{2}) and f'_c of 31 005 kPa (4,500 lb/in.^{2}) for high-strength concrete. Based on recent tests conducted by Caltrans and recognizing that higher strengths are appropriate for retrofitting measures, f'_c was increased to 37 895 kPa (5,500 lb/in.^{2}) for the single-level portion of the Southern Freeway Viaduct. The steel strength was chosen as f_y of 275 600 kPa (40,000 lb/in.^{2}) for the reinforcement.
- Hinges. Caltrans's simplified procedures for designing restrainer hinges were used. Pipe seat extenders and long cable restrainers were proposed. The pipe seat extenders are designed with 203-mm-diameter (8-in.-diameter) double-extra-strong pipes and a maximum vertical load of 445 kN (100 kips), based on tests at Cypress Street Viaduct.
- Columns. Procedures outlined by Caltrans's Memo-to-Designers 20-4 (2) were used to obtain ductility demands for single and multicolumn bents. The moment ductility demand on existing columns was limited to 1.0 in single-column bents (tied) and 2.0 in multicolumn bents (tied). The moment ductility demand for retrofitted columns with steel casing was limited to 6-in. single-column bents and 8-in. multicolumn bents. For ductilities that exceeded those values, a pin was forced at the tops of the columns to approximate a plastic hinge.

The thicknesses of the column steel casings were designed by using the procedures from lecture materials obtained at the retrofit seminar at the University of California, San Diego (3). Casings were full height, and thicknesses varied, being thicker within the plastic hinge zones.

- Footings. Pile loads were determined by conventional analysis methods (i.e., linear elastic). The majority of existing columns in multicolumn bents are pinned at the base; therefore, only axial loads for uplift and compression were checked in the as-built condition. For the retrofitted condition several columns were made fixed to the footing by using a column-strengthening retrofit measure. A steel pipe pile was chosen as the pile for retrofitting. Capacity curves, based on the as-built log-of-test borings, were provided by EMI to determine the additional number of piles required. In some instances the footing size needed to be reduced to avoid utilities or adjacent footings, so nonlinear analysis was provided by EMI to design the footing. The footing was assumed to be infinitely rigid. A moment-rotation analysis was used by assuming a neutral axis, and pile deflections were calculated. These deflections were used to determine pile reactions from nonlinear force deflection curves. The analysis was iterated on the neutral axis location until the sum of vertical forces was zero. The applied moment was determined by summing the pile reactions.
- Outriggers. Outrigger bents were evaluated with the latest criteria from Caltrans, including the Terminal Separation Design Criteria dated December 4, 1991.
- Superstructure. The superstructure capacity was checked on the as-built structure by distributing the plastic column moment in the longitudinal direction of the nominal moment [1.3 times (M_n)] to each face in the superstructure and adding the dead load moment effects. Both top and bottom fibers in the superstructure were checked in the deck and soffit, respectively.

Seismic Analysis

Four computer programs were used to analyze the Southern Freeway Viaduct: SEISAB (*4*), GTSTRUDL (*5*), MSTRUDL (*6*), and IAI-NEABS (*7*). SEISAB was used to generate the model coordinates along the alignment. Various widths in the superstructure were accounted for in the model.

With the coordinates generated from SEISAB, various GTSTRUDL, MSTRUDL, or IAI-NEABS models were developed. Consideration was given to modeling a limited number of frames for analysis, but with the line intersections being located in the middle of the segment, it was determined that the level of production time would be of the same order as that for a full-scale model or a limited number of frame models. In addition, IAI provided a postprocessor for the GTSTRUDL and IAI-NEABS programs, and DRC provided a postprocessor for the MSTRUDL program to calculate ductility demands in the columns at the tops and bottoms for both moment and shear.

The computer program PILECAP was provided by EMI and was used to determine the foundation soil spring stiffness matrices. The program performs the analysis for a pile group foundation considering the interaction between soil, individual piles, and the pile cap. Individual pile head stiffness matrices and pile head-to-pile cap connectivities were included in the analyses. The resulting foundation stiffness matrices were input into the structural models at every column.

Both tension and compression models were used to evaluate the proposed retrofit strategies. The following are the main features of the structural model:

- Space frame members (linear elastic analysis), a minimum of three interior nodes per superstructure span, and a minimum of two interior nodes per column were incorporated into the model.
- Linear springs to model the soil-foundation stiffness, both piles and pile cap, were used.
- Additional frames plus one bent were modeled at each end. Lumped masses and springs were placed at the end of the model.
- Ninety percent or more of the mass participated in each of the horizontal directions.
- Gross member sections were used for all sections except for outriggers (20 percent gross for torsion in the as-built model).
- Spring constants to model soil-foundation interaction were modified to reflect any eccentricity between the columns and the footings.
- Finite size joints between the superstructure's center of gravity and the top of the column were used.

As-Built Structural Deficiencies

Review of the as-built plans and results of the as-built dynamic analysis provided information on the structural deficiencies of the existing structures. In reviewing this information the following conclusions were reached.

Hinges

The as-built structure contained a minimum number of cable restrainers per hinge. These cables are similar to Caltrans C-1-Type restrainers. The typical seat width was only 152 mm (6 in.) and required pipe seat ex-

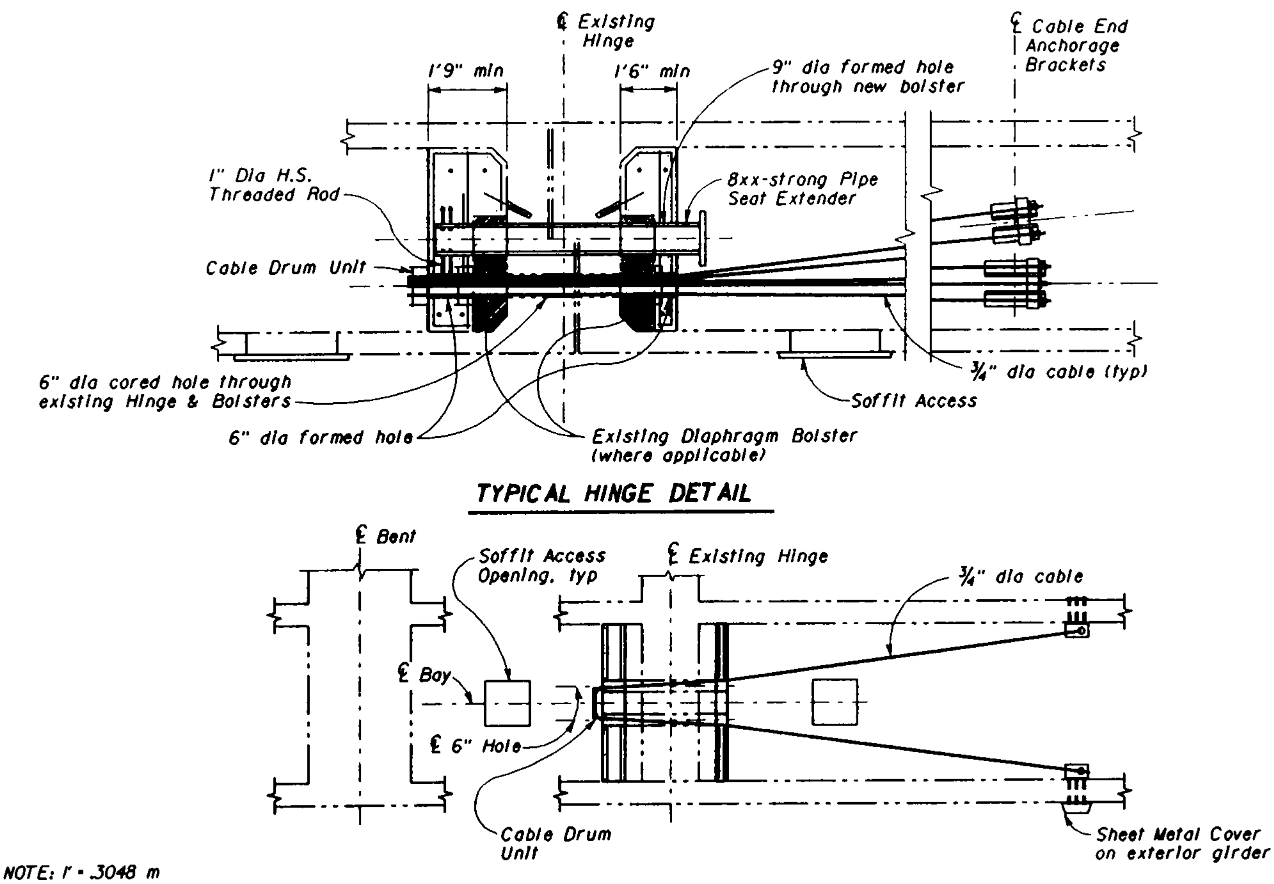


FIGURE 4 Typical hinge retrofit.

tenders to prevent the seat from dislodging. Caltrans's simplified procedure was used to determine the number of cables required incorporating 203-mm-diameter (8-in. diameter) double-extra-strong pipe seat extenders and longer cables (*8*).

Columns

- The percentage of main reinforcement was inadequate in some cases.
- All columns have ties of 12-mm bar at 305 mm (no. 4 bars at 12 in.), which was inadequate.
- A weak connection was the pinned connection between the column and footings four 35-mm bar dowels (four no. 11 dowels). The development length of reinforcement dowels at this joint was inadequate.
- Column tension capacity was exceeded in many columns.
- The connection between the column and the bent cap was deficient for the development length of longitudinal reinforcement, with 45-mm bar (no. 14 bars), and 60-mm bar (no. 18 bars) being most critical.
- The lap splice for fixed columns at the base was inadequately confined and insufficient in length.
- Moment ductility demand/capacity ratios were high in many cases.
- The demand/capacity ratios for shear exceeded 1.0 in most of the columns.

Footings

- There was no top mat of steel and shear steel.
- There were inadequate pile connections to the footing: one 20-mm bar (no. 6 bar) per pile.
- The footings were inadequate to resist column plastic moments.

Superstructure

- There was limited moment capacity in the superstructure for positive moments at support locations.

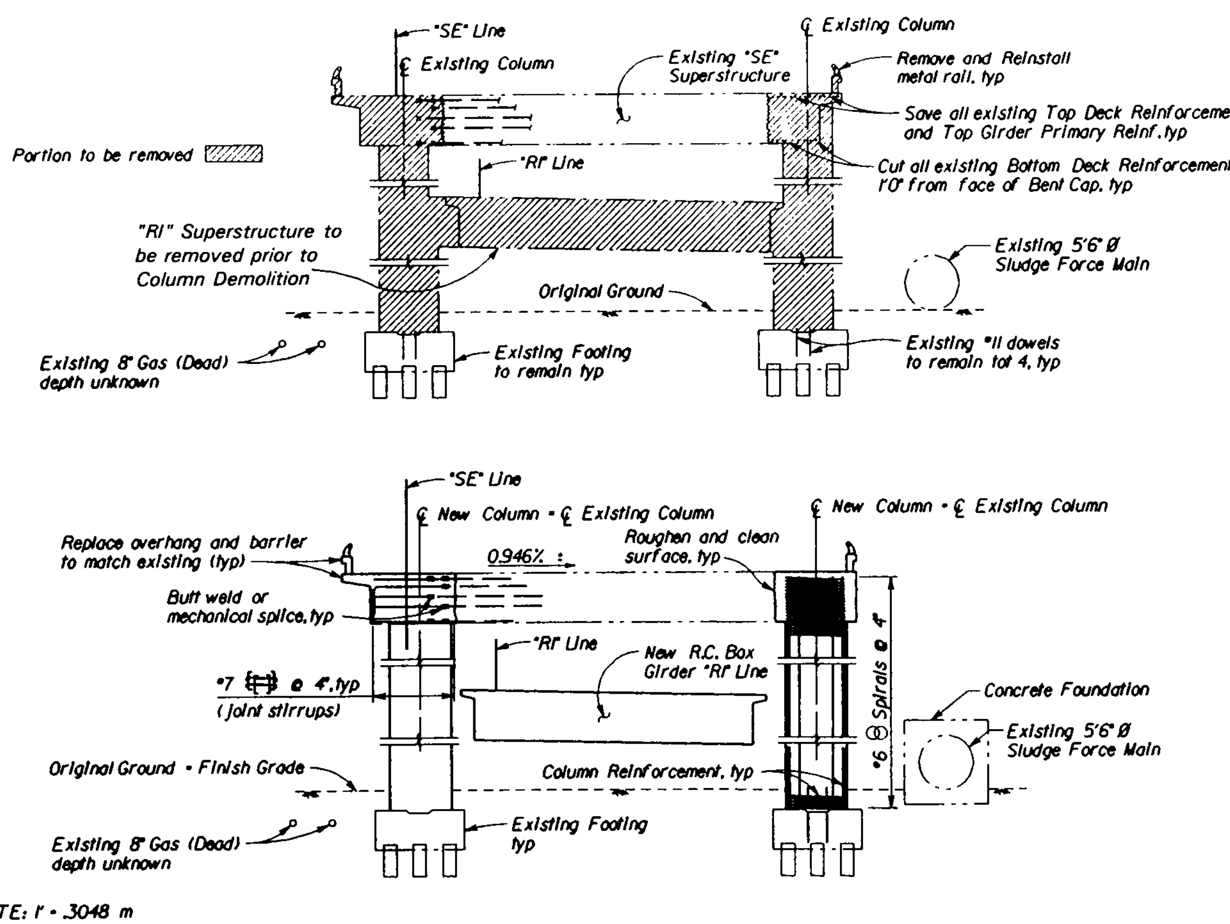


FIGURE 5 Separation of two-level bent (SE-65).

Outriggers

- Torsional capacity in the outriggers was limited because of inadequate cross-section sizes, lack of closed torsion stirrups, inadequate longitudinal reinforcement for torsion, and insufficient stirrups.
- Shear capacity in the outriggers was inadequate. Additional shear stirrups were required.
- Bending capacity in the outriggers for positive and negative moments at both ends of the outrigger cap was inadequate.
- Joint confinement within the outrigger-to-column connection was insufficient.

Retrofit Solutions

The existing structure was deficient in several areas. The final retrofit solutions addressed these deficiencies as well as other concerns related to utilities, roadway traffic, leased airspace, and railroads.

Several retrofit schemes that addressed these items and that improved the structure's response to earthquake forces were studied. The following is a discussion of some of the retrofit schemes evaluated and the final retrofit strategy selected for the various bridge components.

Hinges

New hinge restrainers will be placed at all hinges. Caltrans's Simplified procedure was used to determine the numbers and lengths of new restrainers. Pipe seat extenders were also used to transmit lateral force and to support the structure if seismic movements exceeded the small existing hinge seat width (Figure 4).

Columns and Bents

One of the major problems of the structure was its flexibility, primarily in the longitudinal direction. Several retrofit schemes were analyzed. The use of superbents was studied. Superbents are retrofits to selected bents to make them very stiff and strong, and therefore they resist most of the seismic force, thus reducing the ret-

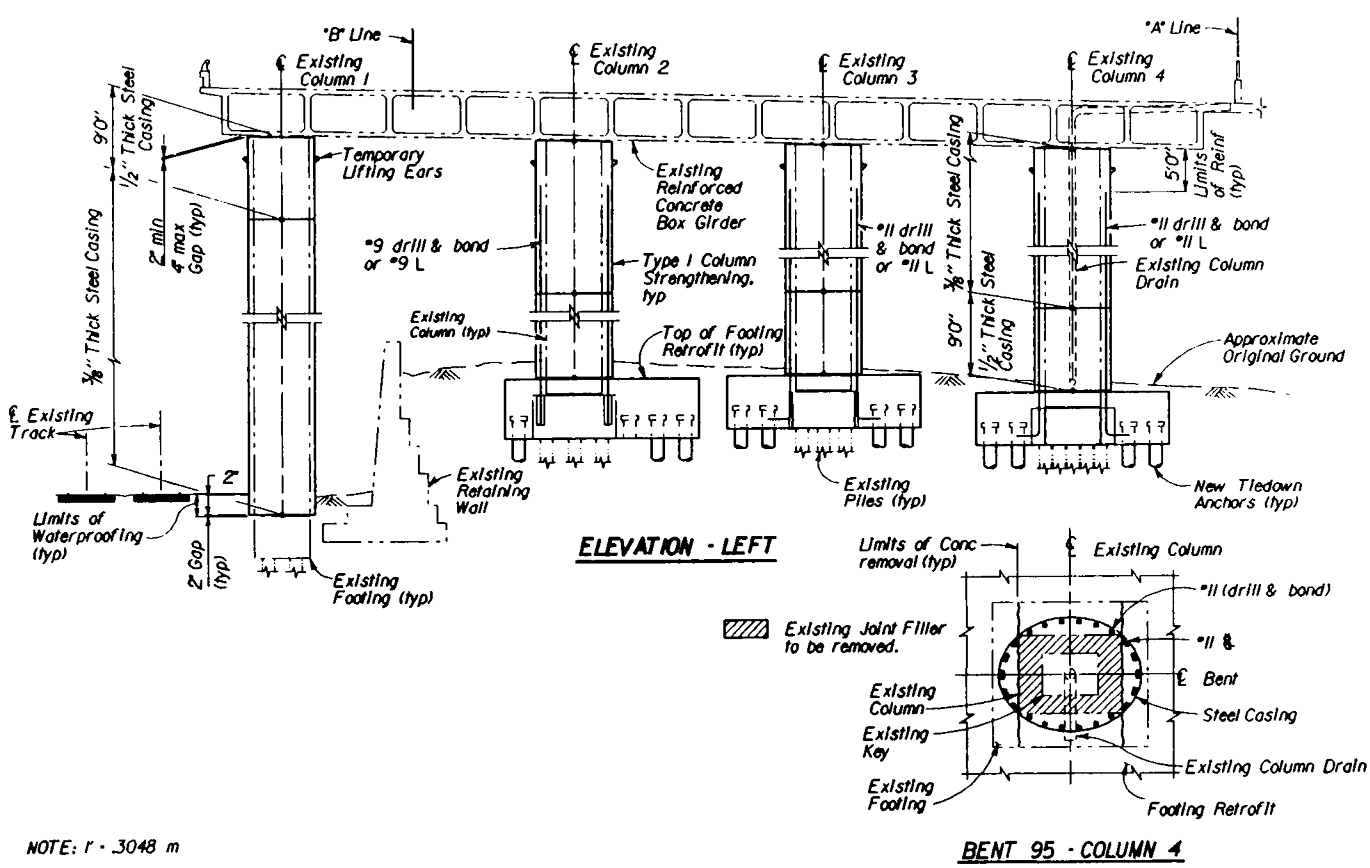


FIGURE 6 Column casing and column strengthening (A-95).

rofit work on other adjacent bents. It was determined that the use of a few superbents was not feasible. The bents could not be made strong enough to eliminate the retrofit work on the adjacent bents.

At intersecting Bents R1-66/SE-65 and R1-70/ES-68 the preferred retrofit was to separate the upper-level and lower-level superstructures. Columns were placed under each superstructure (Figure 5).

The use of column strengthenings was also studied in an attempt to increase the stiffness of the structure. This concept was eventually used extensively on the project. A column strengthening involves placing a steel casing around an existing column and placing vertical reinforcing steel in the void between the casing and the column. The voided area is then filled with concrete. The new rebar is anchored in the footing. This concept allowed the transformation of an existing pinned column base into a fixed column base and thus increased the stiffness of the structure in response to seismic forces. The live load carrying capacity of columns needed to be evaluated when column fixities were changed. Footing retrofit was required when a column strengthening was used. The top of column connection to the superstructure remained unchanged from the as-built condition by using this concept (Figure 6).

Grade beam retrofits were also used on this project. A grade beam retrofit involves constructing a concrete member connecting the columns of a two-column bent at the column base, just above the top of the existing footing. This concept provides frame action to resist transverse earthquakes forces without the need to retrofit the footing for column moments (a pinned connection still exists between the column frame and the footings). This concept was used in an area where the limits of footing work were restricted and the transverse bent stiffness was weak (Figure 7).

Another method of improving transverse stiffness was the use of bent replacements. The use of bent replacements involves building a new drop cap beneath the superstructure and supporting the drop cap on new columns and footings. This concept provided higher capacity at the top of column and bent cap connection and was used at bents weak in transverse stiffness that had minimal conflicts with the existing features below (Figure 8).

Every effort was made to eliminate outriggers by removing existing columns and reconstructing them un-

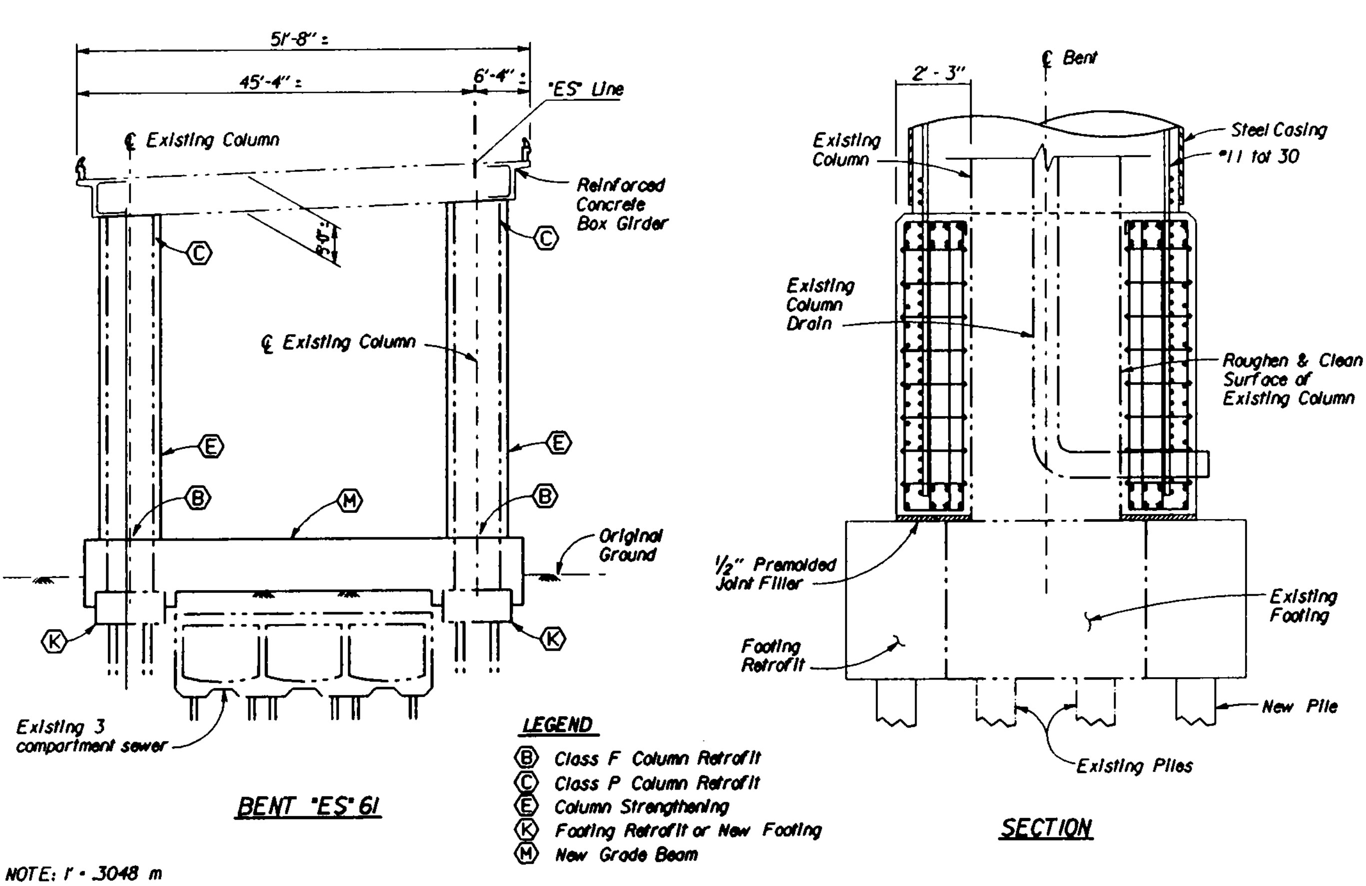


FIGURE 7 Grade beam retrofit (ES-61).

der the edge of the superstructure. Outriggers that could not be eliminated were reconfigured into pinned connections on top if the resulting forces could be handled in the remaining bent frame. At those locations where the pinning at the top of the outrigger resulted in excessive forces in the remaining bent frame, the outrigger column and portions of the cap were removed and replaced to provide higher capacity (Figures 9 and 10).

Steel casings were placed around all existing columns not being replaced or strengthened with longitudinal steel and a steel casing. The casings provide confinement and shear capacity.

Superstructure

The superstructure capacity was checked on the as-built structure by distributing one-half of the plastic column moment in the longitudinal direction (1.3 times the M_n) to each face in the superstructure and adding the dead load moment effects. Both top and bottom fibers in the superstructure were checked in the deck slab and soffit slab, respectively. Initially, an effective width of *D* (depth of the superstructure) on each side of the column was added to the column width to check the longitudinal capacity of the superstructure. The results indi-

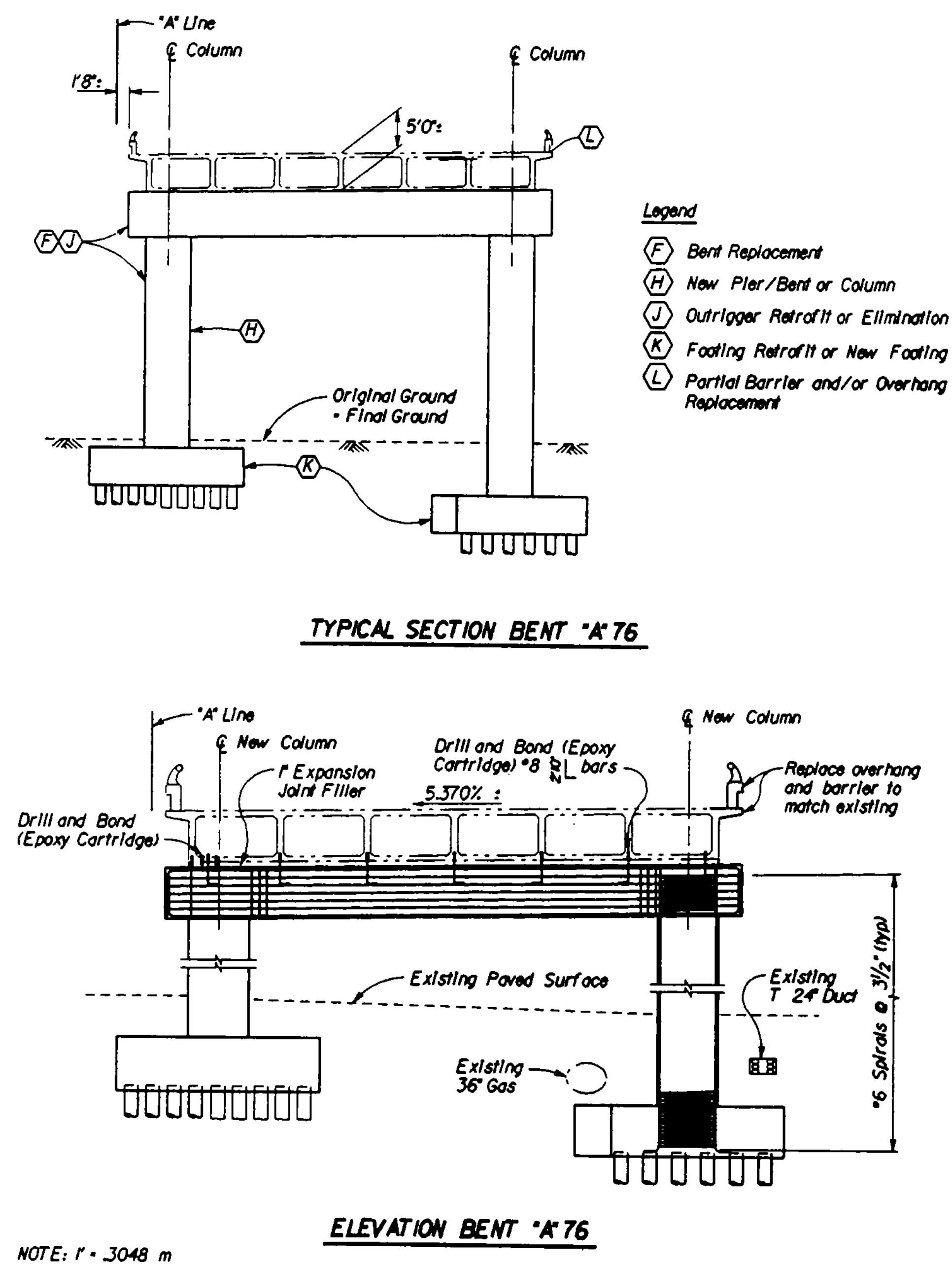
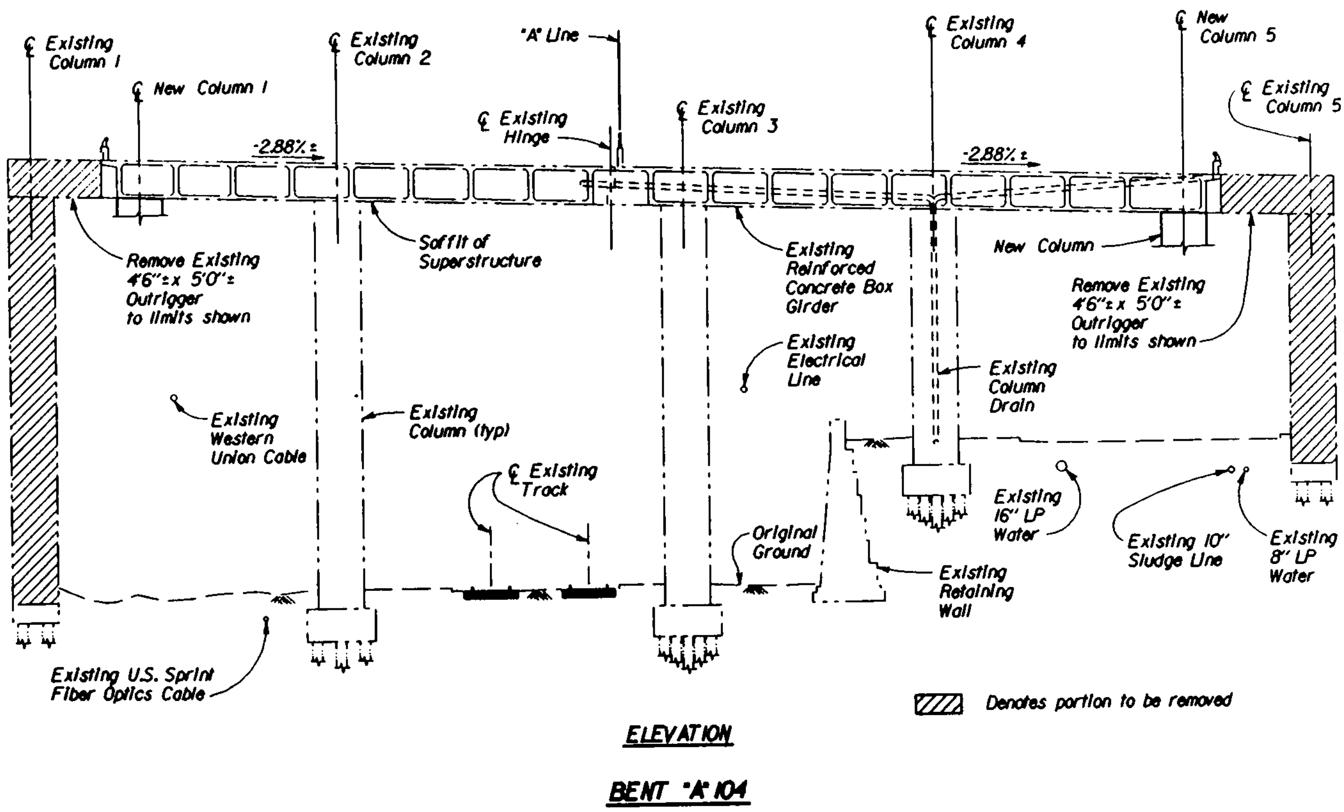
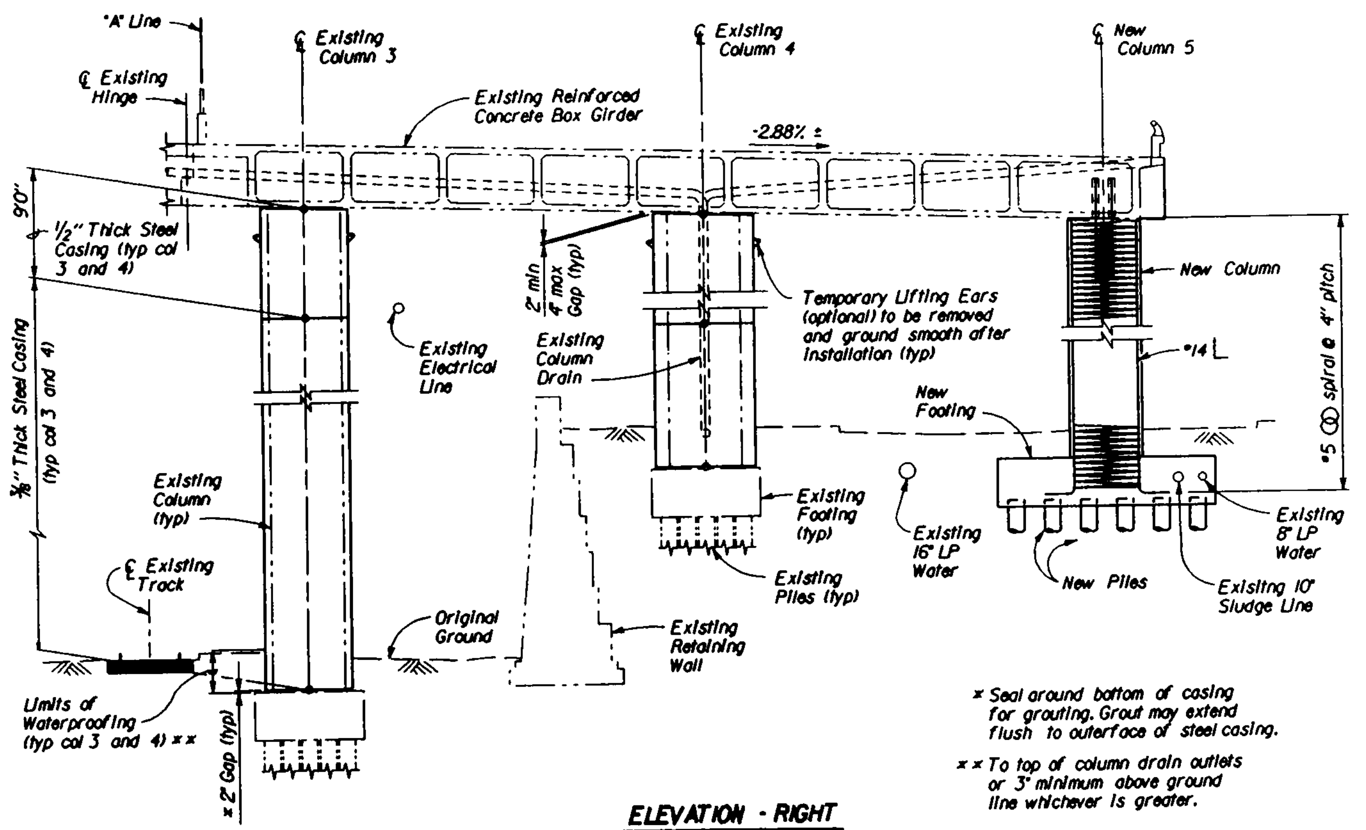


FIGURE 8 New drop cap (A-76).



NOTE: 1' = .3048 m

FIGURE 9 Outrigger elimination (A-104).



NOTE: 1' = .3048 m

FIGURE 10 Reconstruction of outrigger bent (A-104).

cated that at a few single bents (i.e., R1-63 and ES-64), the capacity of the superstructure was exceeded. It was believed that the full width of the superstructure would be mobilized during an earthquake, and on the basis of that rationale the capacity was rechecked. Capacities were checked at bents in Projects 1 and 2 at R1-51, R1-63, R1-55, SE-54, SE-56, SE-59, SE-70, A-73, A-75, A-78, A-80, A-84, SE-60, ES-64, ES-71, and ES-78. The results gave capacity/demand ratios of greater than 1. Studies were also conducted by using a full-width effective section at selected bents in Project 3, and the results indicate that adequate superstructure capacity was achieved.

Joint Shear

Many of the bents of the Southern Freeway Viaduct are not of the outrigger configuration, and so their bent cap to column joints are relatively inaccessible for retrofitting. In a major seismic event, joint shear and the overall performance of these joints are still concerns.

Anatech Research Corporation performed an analysis of the joint shear concern as part of B&R's retrofit contract with Caltrans. Anatech constructed a three-dimensional continuum, finite-element model to evaluate joint shear behavior and ultimate strength, ductility, and potential failure modes under seismic motion. They modeled a typical two-column bent (Bent A-78) in the single-level portion of the viaduct.

Anatech's report states that two incremental analyses were performed, one for primarily transverse motion and one for primarily longitudinal motion, but in each case smaller orthogonal motions were applied to create a realistic biaxial response (9).

Implementation of Anatech's report as a design guide has not been completed to date. Further review of the results of the present study is needed to determine a general design memorandum that would cover all bridges with joint designs similar to those of Southern Freeway Viaduct joints. We were informed by Caltrans that any retrofit recommendations required for joint shear would be part of a later contract.

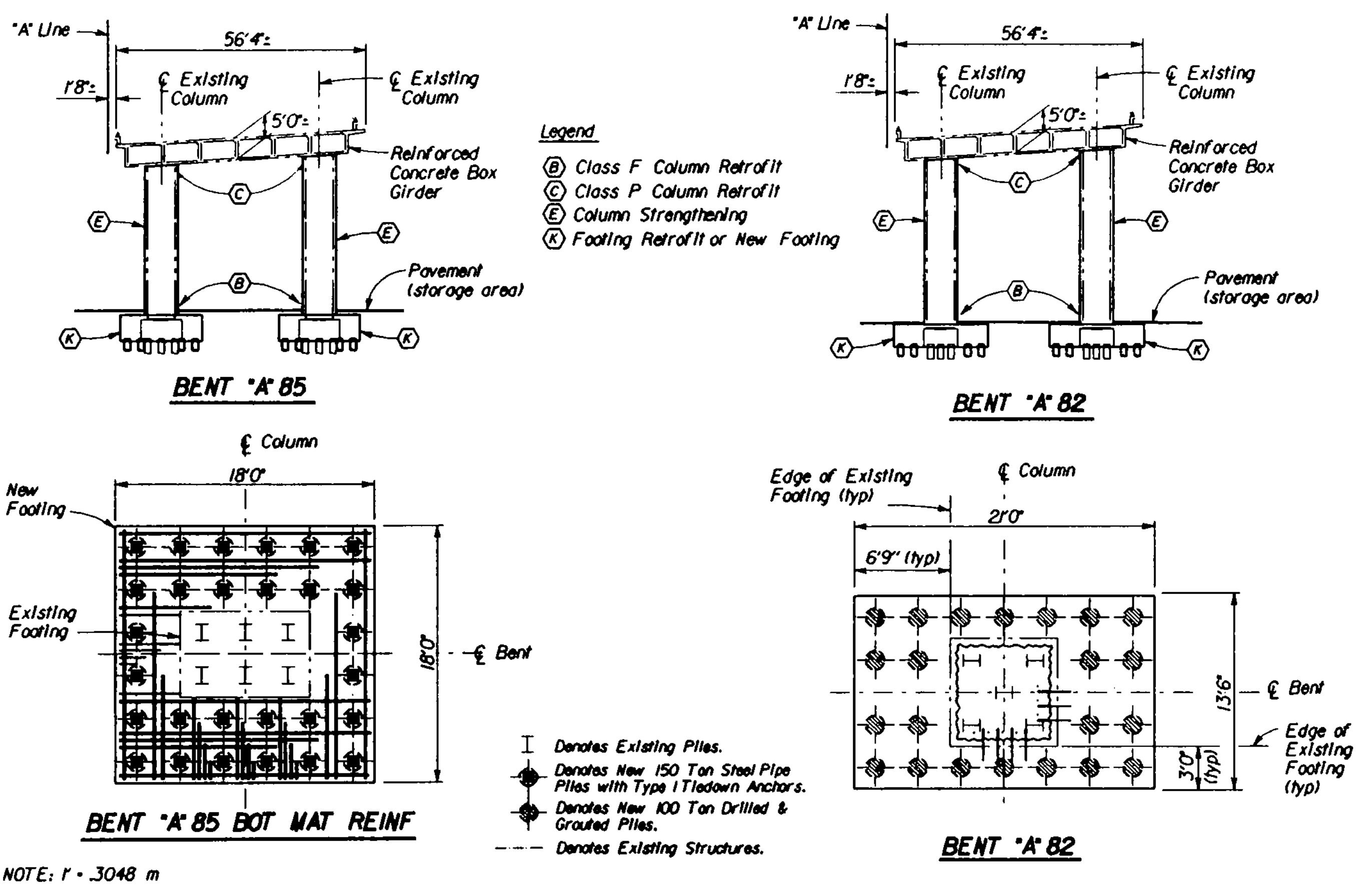


FIGURE 11 Footing retrofit.

Footings

Footing retrofits were required primarily at those locations where a pinned base column was retrofitted to be a fixed base column (column strengthenings). The moment capacity of the footing had to be increased at these locations (Figure 11).

The variable soil conditions along the length of the viaduct resulted in several footing retrofit solutions. The south end of the project consisted of deep bay mud with bedrock at a depth of approximately 42.7 m (140 ft). Long steel pipe piles were used to provide the tension and compression resistance at these bents. The northern end of the project consisted of thinner deposits of bay mud with depths to bedrock in some cases of only 6.10 m (20 ft). Steel pipe piles were used again, but tiedowns were installed inside the piles. The tiedowns were drilled into the bedrock to provide the required uplift resistance.

Some existing footings at the north end of the project are spread footings placed near or on bedrock. As part of the retrofit program, the footings are to be enlarged and tiedowns are to be placed to provide the required uplift resistance.

Noise and vibration concerns in the leased airspace occupied by mini-warehouses led to the development of a drilled and grouted pile for footing retrofits in that area. A hole is to be drilled through the soil and into the bedrock layer. A steel pipe pile is to be placed in the hole, and the void between the pile and the soil-bedrock is filled with grout. The pile interior is then filled with concrete. The embedment of the pile into the bedrock provides the required uplift resistance. By this method, the noise and vibration of pile-driving operations are eliminated.

ACKNOWLEDGMENTS

Robert M. Jones, who was the contract administrator from Caltrans, provided oversight throughout the project. James Gates from Caltrans provided guidance during the retrofit strategy phase of the project. Other personnel contributing substantially were Tim McGrady of B&R, Richard J. LeBeau of IAI, and Erich Aigner of DRC, who were project managers. Also, Eli M. Aramouni of IAI and M. A. Ravanpour and Dan Copps of B&R were lead project engineers on the job. Thomas G. Tracy of IAI provided the specifications for the project. Po Lam and Lino Cheng of EMI provided geotechnical support throughout the project.

REFERENCES

1. *Southern Freeway Viaduct.* Final Retrofit Strategy Report. Imbsen & Associates, Inc., Sacramento, Calif., Jan. 23, 1992.
2. Memo-to-Designers 20-4. California Department of Transportation, Sacramento, April 6, 1992.
3. *Seismic Assessment and Retrofit of Bridges.* University of California, San Diego, La Jolla, July 1991.
4. *Seismic Analysis of Bridges.: User Manual.* Imbsen & Associates, Inc., Sacramento, Calif., 1993.
5. *GTSTRUDL, User's Manual.* GTICES Systems Laboratory, Georgia Institute of Technology, Atlanta, 1990.
6. *MSTRUDL—Users Manual,* Version 2.7.2. CAST Corporation, Fremont, Calif.
7. *Linear and Nonlinear Earthquake Analysis of Bridge Systems.* Imbsen & Associates, Inc., Sacramento, Calif., Dec. 1993.
8. *Caltrans Bridge Design Aids 14.* California Department of Transportation, Sacramento, Dec. 31, 1992.
9. Dameron, R. A. *Detailed 3D Analysis of Shear in Unretrofitted Joints of Bent A-78 on the Southern Viaduct.* Anatech Research Corporation, June 5, 1992.