Southern Loop Pipeline – Seismic Installation in Today's Urban Environment

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1 Introduction

The Southern Loop Pipeline is a key element of the 10-year Seismic Improvement Program (SIP) of the East Bay Municipal Utility District (EBMUD). The newly constructed 11-mile long Southern Loop Pipeline connects the Northern California cities of San Ramon and Castro Valley and is designed for flow in both directions so that it can provide an emergency water supply following major seismic events on either the Hayward or the Calaveras Faults or other kinds of emergency events that could disrupt the normal flow of water to these cities. The portion of the pipeline within San Ramon crosses the Calaveras Fault. This paper discusses how the EBMUD Southern Loop Pipeline (Figure 1) addressed the challenges in constructing a large diameter pipeline across a major fault with an anticipated magnitude 7± earthquake. The fault was crossed using a design that incorporates thick-walled pipe using non-standard pipeline steel (both minimum and maximum yield strengths had to be considered), specialty pipeline coating and custom backfill material into a system that accommodates the predicted ground movement.

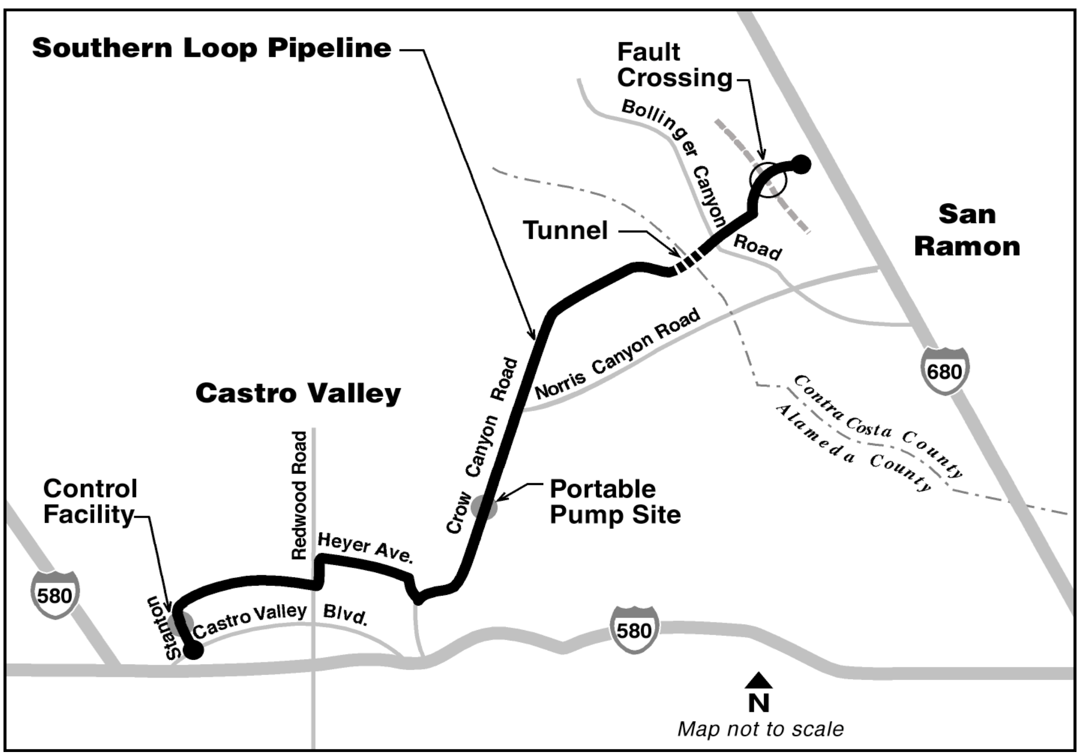

Figure 1. Southern Loop Pipeline, Showing Location of Calaveras Fault in San Ramon Area

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2 Fault Offset Design Criteria

The pipeline alignment crosses the active trace of the Calaveras fault. As the primary function of this pipeline is to deliver water in the event of a major earthquake (or other event) that might damage the other pipelines that bring water to the service areas, it was decided that the Southern Loop Pipeline should be designed to have a high reliability of remaining functional immediately after the earthquake (in other words, the pipe should not break).

As the first step in the design process, it was necessary to establish a suitable amount of fault offset. The amount of fault offset is an uncertain parameter, even if one can characterize the magnitude of the earthquake. Further, the magnitude of future large earthquakes is also uncertain. We combined these two sources of uncertainty to establish a probability of offset exceedence, given the occurrence of a characteristic earthquake. Figure 2 shows the result. Moment magnitude 6.9 to 7.1 earthquakes dominate the risk, although there is some chance (under 5%) that the magnitude could be has high as 7.4 to 7.6.

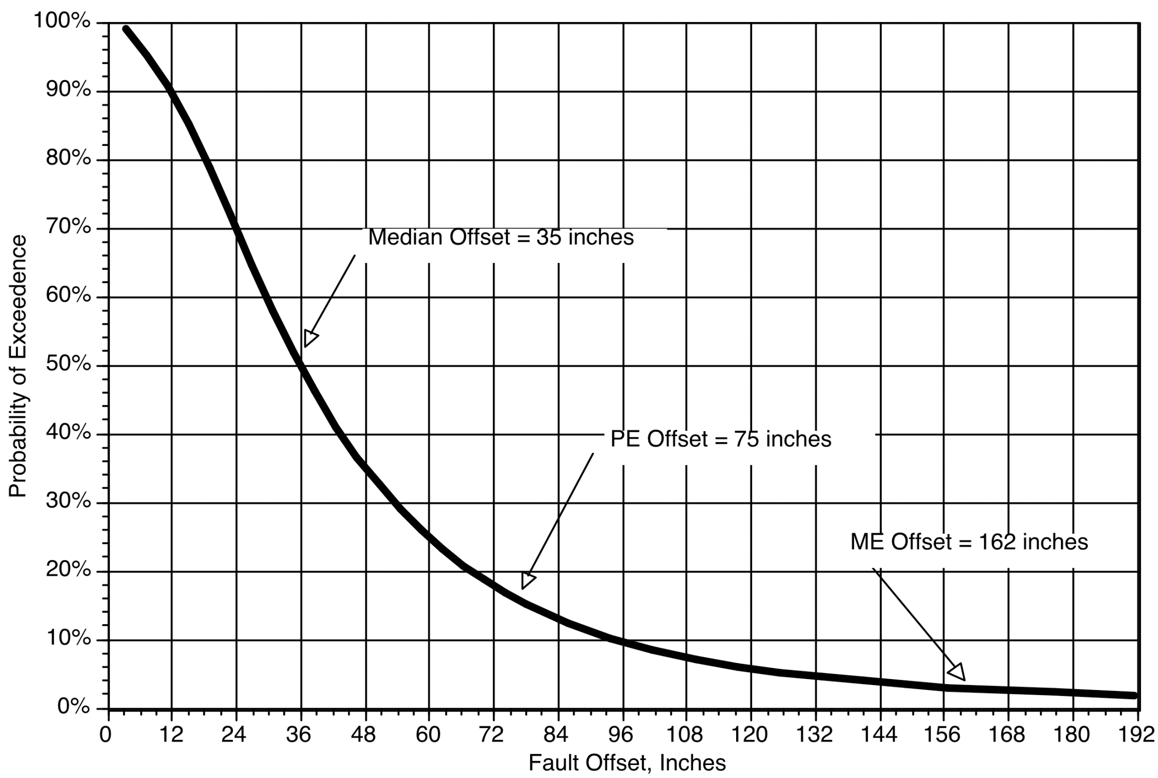

Figure 2. Range of Possible Offsets of the Calaveras Fault

Based on these findings, we decided to design the pipeline for reliable operation with a right lateral fault offset of 75 inches plus simultaneous vertical offset of 7.5 inches (16% chance of exceedence). We also recognized that fault offset could exceed this amount (about a 2% chance of offset of 162 inches or more), so the design concept included components to address these less likely but still possible occurrences.

3 Design Concept

As the Calaveras Fault trace within San Ramon is well established it was projected that the bulk of the 75" of design fault offset would occur within a relatively short fault zone, approximately 10 feet wide. The location of this 10 foot wide fault zone was somewhat uncertain, and this was reflected in the design. Rather than trying to accommodate this offset within the fault zone, the design concept adopted was to allow the strain to be distributed over an extended length of the pipeline. This would be achieved by providing a slick polyurethane coating for the pipeline within and near to the fault zone combined with a sand backfill. The combination would allow the pipeline to slip within its bed during the predicted fault offset, distributing the strain over a greater distance. Outside of the fault zone the pipeline would be anchored using a controlled-density fill to prevent the strain from extending too far into the remainder of the pipeline. Within this anchor region, the pipe has exterior steel rings welded on to provide 'teeth' to grab onto the controlled density fill. The length of the 'slip zone' is around 600 feet and each of the anchor zones are approximately 300 feet long. Thus the 75" of design fault offset will be absorbed within a total design length of around 1,200 feet.

As noted above, fault offset prediction is not an exact science and there is a probability that the actual fault offset will exceed the design offset. The design concept addressed this in two ways. First, the pipe in the anchorage zones was designed to yield if the offset exceeds the design assumptions, allowing the strain to be distributed over a greater length. An additional element of design redundancy was included in the form of manual shut-off valves and bypass manifolds as part of the design. These components (see Figure 3) allow for bridging of the flow across the fault in the event the actual strains exceed the design assumptions and the pipeline leaks or breaks.

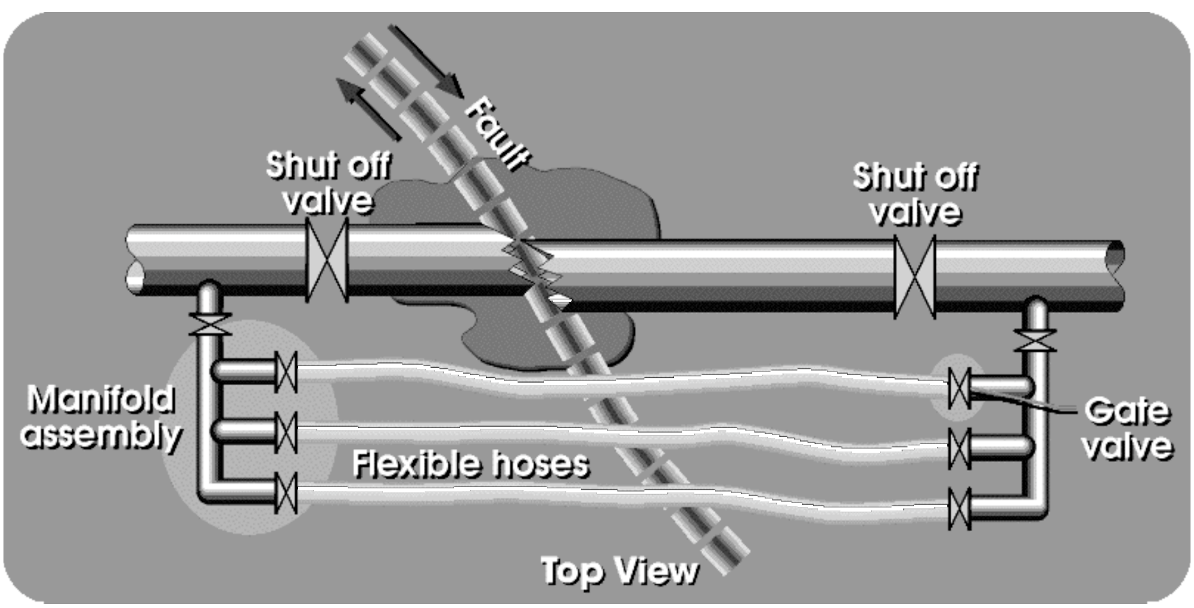

Figure 3.Bypass Design Concept

4 Alignment Selection Across the Fault Zone

During the preliminary design phase of this pipeline, several possible alignments were considered for the pipeline. From an earthquake / fault crossing point of view, the optimal alignment was to install the pipe in a straight alignment for several hundred feet either side of the fault, oriented such that right lateral offset would produce net tension everywhere in the pipeline. In order to use this type of alignment, it would have been necessary to purchase a right-of-way from private property owners through undeveloped land. From a construction and ownership point of view, EBMUD desired to keep the pipeline within the right-of-way of an existing street.

After much discussion it was decided to keep the pipeline within the public right-of-way. This necessitated a pipeline design that would include a few minor to medium bends near the primary fault crossing zone, in order to accommodate the right-of-way and the presence of other utilities already in the street (Figures 4a and 4b). As will be further discussed, this caused somewhat higher strains in the final design than would otherwise have been possible, and contributed to the decision to include a set of manual shutoff valves and bypass outlets on either side of the fault.

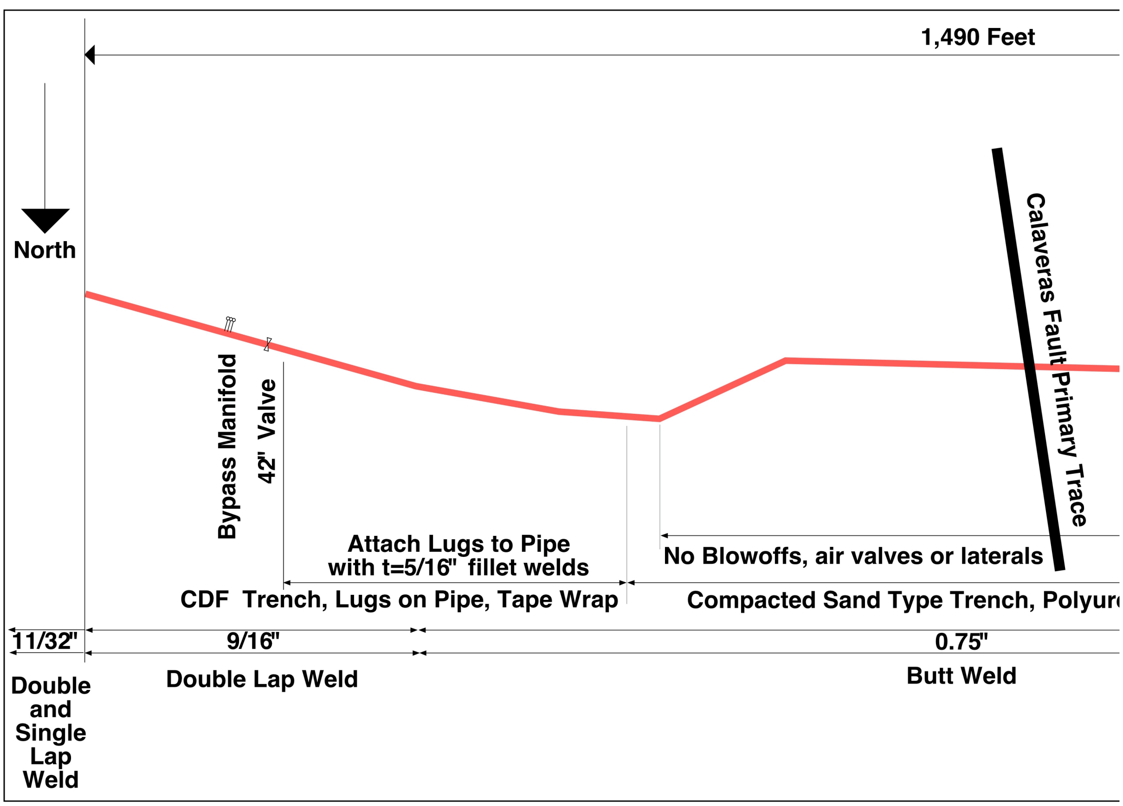

Figure 4a. Pipe Alignment With Main Design Features (East of Fault)

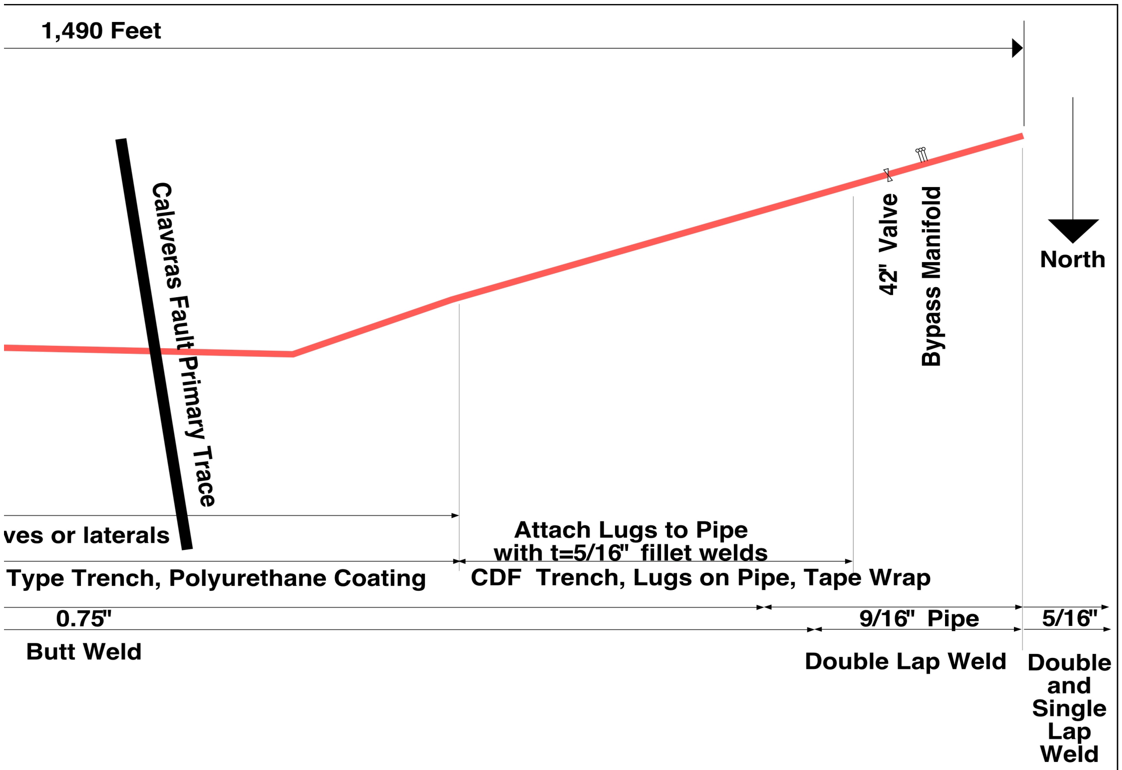

Figure 4b. Pipe Alignment With Main Design Features (West of Fault)

5 Pipeline Design

A series of nonlinear structural analyses of the pipeline in its final alignment were undertaken. Of most importance was the prediction of high tensile and compressive strains. After iteration on the design wall thickness, it was decided to use a 42" diameter butt welded steel pipeline, with wall thickness of 0.75" in the immediate fault crossing zone, tapering off to 3/16" wall thickness at some distance from the primary trace of the fault. The wall thickness was adjusted along the length of the alignment to minimize the cost of installation, while maintaining pipe strains at all locations within tolerable levels. Figure 5 shows typical results from the nonlinear analyses. Highlighted in Figure 5 are the strains at points A, B, C, D and E.

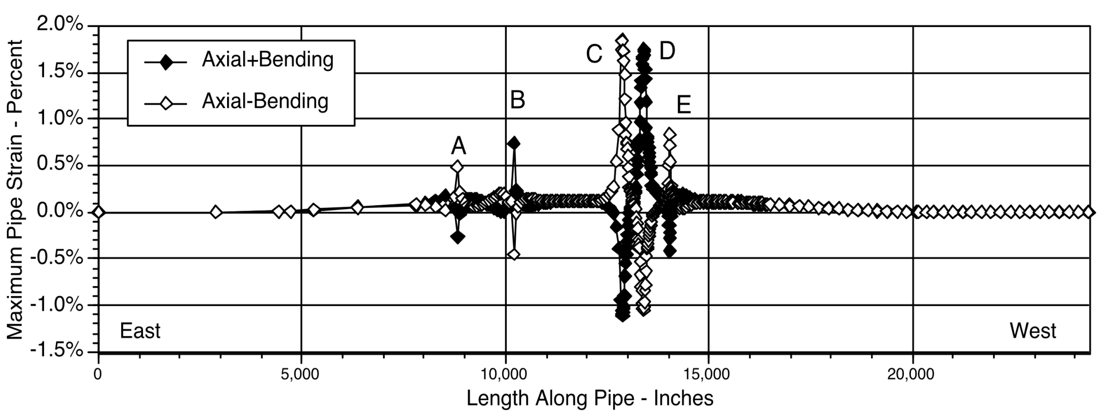

Figure 5. Pipe Strains Due to Fault Offset

Points A, B and E correspond to bends in the pipeline that could not be avoided due to interferences from existing utilities within the right of way. Points C and D represent the highest strain points in the pipeline immediately either side of the fault. As can be seen in Figure 5, the slight acute orientation of the pipeline from a 90 degree crossing results in a slight net tensile strain over about 15,000 inches of alignment (1,250 feet). The strains are greatly magnified at the three bend points, reaching about +0.8% / -0.5%. The strains at the fault crossing itself are highest, at about +1.9% / -1.1%.

When considering the level of strain, it is important to reflect that the tensile strain is usually easiest to resist, with a well installed butt welded pipe with ductile steel able to accommodate about 5% tensile strain with a small chance of failure. In compression, a 42" diameter x 0.75" thick pipe wall will begin to wrinkle somewhere about 0.6% to 0.8% compression, and reach a full wrinkled state somewhere about 1.5% to 2.0% compression. The analytical prediction of –1.1% strain suggests that there would be modest factor of safety against large wrinkling, given a 75 inch fault offset. Even with major wrinkling, the potential for a pipe tear is modest, and even with a pipe tear, the leak rate would likely be small enough to allow the pipe to be kept in service. Still, the urban requirement to keep the pipe within the right of way results in a much higher compressive strain than could have been achieved with a better alignment. (Note: all strains mentioned here exclude additional strains due to localized wrinkling).

6 Material Specification

During the course of the design, it became apparent that a ductile steel with yield stress of about 36 to 40 ksi and ultimate of about 60 to 78 ksi or so would result in the lowest cost installation. As yield stress goes up, the force generated in the pipeline due to fault offset goes up, and hence a longer anchorage length is needed of thicker wall pipe. Accordingly, the pipeline steel purchase specification listed both minimum *and* maximum yield and ultimate stresses. Several iterations were required with the pipeline vendor in order to assure that the actual steel delivered was not stronger (higher yield stress) than what the design would allow for (see also Section 7). It was found that steel vendors often produce steels with actual yield strengths on the order of 54 ksi to 62 ksi, even if the minimum specified is just 36 ksi to 40 ksi; this would not have been the usual case 30 years ago, but apparently the modern decision to re-use scrap steel as part of the make-up of new steel has resulted in limiting steel manufacturers' economic capability of producing steel within a relatively tight range for its actual yield strength.

In addition, the controlled density fill placed around the pipe within the anchor zone required a minimum compressive strength in order to function effectively as an anchor for the pipe elongation and a maximum compressive stress in order to ensure that the anchor failed before the pipe was overstressed . Thus the controlled density fill was specified with a minimum compressive strength of 70 psi and a maximum compressive strength of 150 psi.

7 Steel Procurement

The above described design process produced a design that addressed the inherent uncertainty of fault offset in an innovative and cost-effective manner. However, construction of the fault crossing identified several real world constraints that need to be addressed when implementing a design solution of this type. Procurement of the steel to be used in pipe fabrication was the first of the challenges encountered. Working with the selected pipeline vendor, it became apparent that the vendor had little experience with specification of both minimum *and* maximum yield and ultimate stresses for pipeline steel. Their internal quality control processes were based upon assuring that the minimum strength was achieved but they had no data on what the maximum yield and ultimate strengths were (perhaps the engineer should have watched over the unusual steel specification and procurement process a little closer). A representative set of steel samples were sent to a testing laboratory and it was determined the supplied steel material did not comply with the maximum stress allowed by the specifications. After several iterations a specific heat of steel was identified that met both the minimum and maximum strength criteria. Unfortunately, when several cylinders had to be rejected due to weld defects, it was determined that the specified heat was from a mill that had just gone out of business (thanks in part to globalization) and no additional steel was available from that vendor. After several weeks of querying steel vendors throughout the United States a supplier was located in Alabama that could produce a steel that was within 5% of the maximum specified. After several reiterations of the design calculations it was determined that this new steel could be used in the areas outside of the primary fault zone. Ultimately, in order to save on construction installation cost and schedule, individual spool pieces had to be carefully marked and installed, to assure that the spool pieces of pipeline nearest the fault did not have excessively high yield stress. While careful factory and on-site inspection ensured that the material installed matched the design criteria, the experience re-emphasizes that designers need to be address the potential procurement issues, when non-industry standard materials are specified.

8 Controlled Density Fill Quality Control

The specification of the Controlled Density Fill with both a maximum and minimum strength also presented several challenges. While Controlled Density Fill, or CDF, has seen widespread acceptance over the last decade as a backfill material, it is not typically utilized as a structural element and therefore does not have the extensive quality control standards that have been established for Portland cement concrete. When asked for quality control history of CDF compressive strengths, the local cement vendors had no data but indicated strength variations between 50 psi and 500 psi are not uncommon. In addition, the standard cylinder breaks used to monitor concrete performance cannot be utilized for CDF. Due to its low strength, there is a high potential for cylinder fractures during transport and bands of aggregate can produce anomalous breaks. Also, the strength vs. cure time relationship established for concrete are not applicable to low-strength CDF and predicting final strengths from early cylinder breaks was not possible. Eventually, a specialized testing protocol was established, a series of test batches was run and strict quality control instituted at the batch plant to ensure that this atypical strength criteria was met. If future designs anticipate utilizing CDF as a structural fill then a similar testing and quality control program should be included in the specifications. Photo 1 shows the installation of the CDF around the pipeline. Several of the exterior steel rings that provide the “teeth” for the CDF to grab onto can also be seen in the foreground.

Photo 1. Placement of CDF Around the Pipeline

9 Utility Realignment

The other challenge that arose during the construction of the pipeline was the conflict with an unanticipated utility. Every effort was made to locate known utilities during the design phase. However, the designers were really not thinking much about *new* utilities still being built in the area. During the actual construction sequence, as the pipeline construction got closer and closer to the fault crossing zone, it was determined that only four weeks earlier a new sewer had been installed that conflicted with the proposed pipeline alignment at the fault crossing zone (a few choice words were muttered by the field team upon discovery of this). The problem required quick resolution, as the pipeline installation crew would reach the fault zone within a matter of weeks. Since the installation crew and equipment were costing on the order of $16,000 per day, the cost of delays would mount quickly. The initial approach was to include changes in pipeline angles within the design length so as to go around the sewer. However, even minor additional bends would increase the stresses and strains in the pipeline to unacceptable levels. Similarly, lowering the pipeline by the 12" to 18" required to avoid the sewer would compromise the pipeline performance as the amount of overburden affected the pipeline’s ability to ‘slip’ within its sand bed.

Ultimately a fast track design was developed in cooperation with the sewer agency in order to realign the recently-installed sewer line.

Towards the end of the pipeline installation within the fault zone a buried concrete vault was discovered directly in the pipeline alignment, see Photo 2. As discussed in the previous paragraph, modifying the pipeline alignment to the degree necessary to avoid the vault would have a major impact on pipeline performance. Relocating the vault, if at all possible, would have had major cost and schedule impacts. Surprisingly, the owners of the vault quickly determined that its removal would have minimal impacts on their operation and the vault was demolished within one day. Future designs with similar tight dimensional constraints within an urbanized area should anticipate the potential for similar conflicts.

Photo 2. Large Concrete Vault Discovered in Pipeline Alignment

10 Acknowledgements
The authors would like to acknowledge the contributions and efforts of both Kennedy/Jenks Consultants, the Lead design firm on the project, as well as Ranger Pipelines Inc., the construction General Contractor. Construction of a major pipeline is never a solo effort, and the teamwork exhibited by the personnel involved greatly contributed to a successful installation of a state-of-the-art design for crossing a critical water lifeline across a major earthquake fault.