

## Design challenges of the San Bernardino Mountains tunnels along the Inland Feeder

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**ABSTRACT:** The design of two water supply tunnels through the San Bernardino Mountains in Southern California involved several unusual design considerations. Construction of these tunnels will involve tunneling through active faults, a portal excavation located in a geothermal field, pre-excavation grouting to minimize the effects of tunnel excavation on the groundwater regime, and pressure tunnel design for low *in situ* stress and high rock mass permeability conditions.

### 1.0 Introduction

The Metropolitan Water District of Southern California has embarked on a multibillion-dollar capital improvement program which will help ensure adequate water supplies are available to southern California well into the next century. A key component of this construction program is the Inland Feeder, a \$1 billion conduit system that will serve Metropolitan's six-county service area. The Inland Feeder's 45-mile alignment of large-diameter tunnels and pipelines will extend from its starting point in the foothills of the San Bernardino Mountains to the Colorado River Aqueduct in Riverside County (see Figure 1). When completed in 2000, the feeder will nearly double MWD's water delivery capability from the east branch of the State Water Project, providing southern Californians with as much as 650 million gallons of additional water each day. The new line will also help replenish local groundwater basins, improve the quality of southern California's drinking water, and be an important source of water for new and existing reservoirs. This paper focuses on the tunneling aspects of the first section of the Inland Feeder, the San Bernardino Mountains Segment.

### 2.0 Project Description

The Inland Feeder will convey raw water from Afterbay No. 2 of the California Aqueduct of the State Water Project in San Bernardino County to

the Colorado River Aqueduct in Riverside County. The San Bernardino Mountains Segment of the Inland Feeder consists of two 14-foot inside diameter tunnels through the foothills above San Bernardino with two intervening 12-foot inside diameter pipeline sections (see Figure 2). The two tunnels, the Arrowhead West Tunnel and Arrowhead East Tunnel, are 19,880 feet long and 27,349 feet long, respectively. Each tunnel will have two construction portals and two permanent tunnel access structures adjacent to each portal. The construction documents will give the Contractor the option to mine the tunnels with drill-and-blast methods or by both drill-and-blast and tunnel boring machine (TBM). Geology along the tunnel alignments consists of gneiss, granite, marble, and sandstone. The tunnels are situated close to the San Andreas fault, and several active splays of the San Andreas fault are crossed in tunnel.

### 3.0 Geologic Setting

The San Bernardino Mountains are part of a chain of ranges that trend east-west across Southern California in the Transverse Ranges geomorphic province. The San Bernardino Mountains are tectonically very young ranges, having been elevated by faulting and folding only in the latter part of the Tertiary Period, in response to regional stresses that caused development of the San Andreas and related fault systems.

The San Andreas fault at the southern edge of

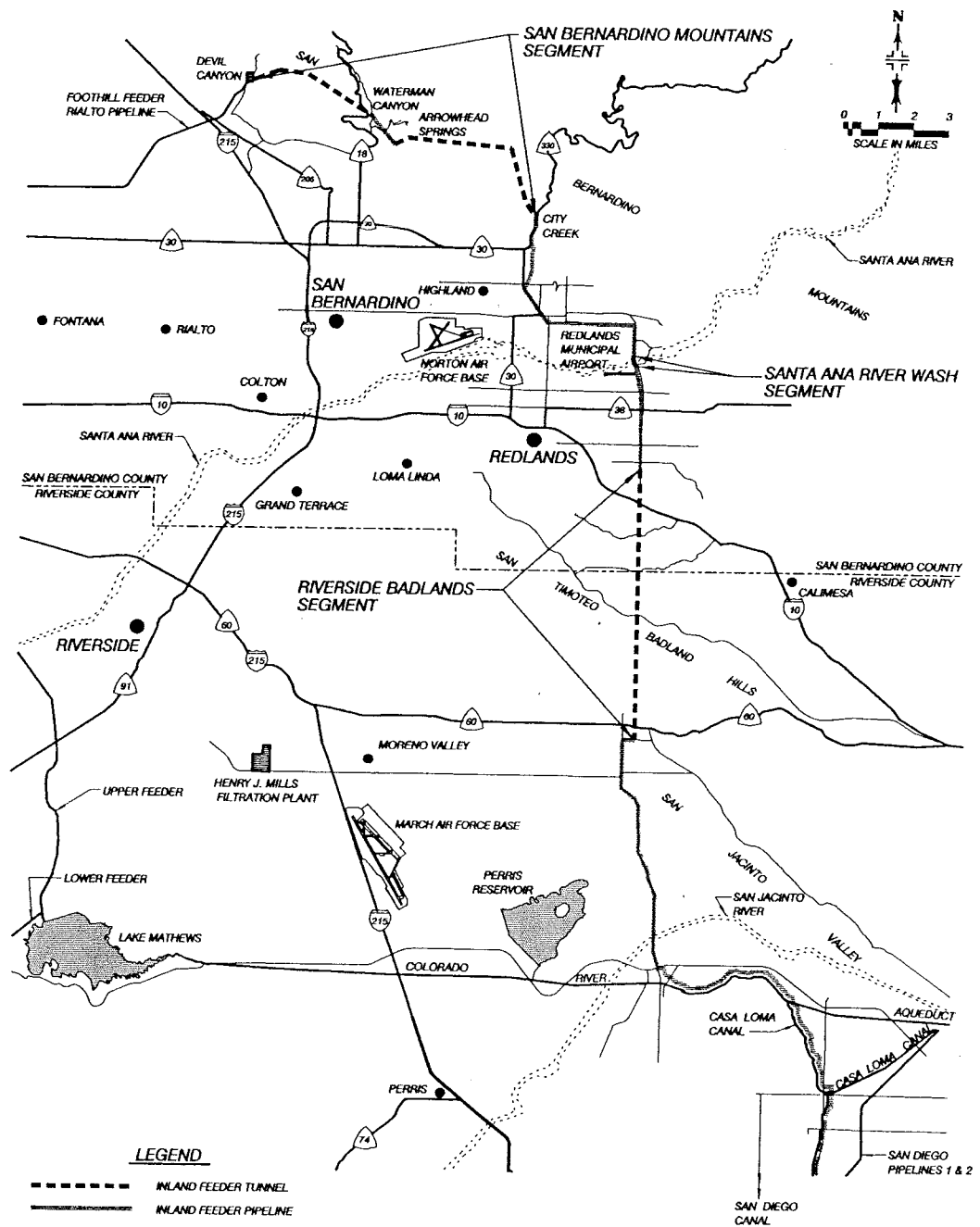


FIGURE 1: PROJECT LOCATION

the San Bernardino Mountains is the principal tectonic boundary between the North American and Pacific crustal plates. Right-lateral strike-slip offset occurs during major earthquakes along the fault resulting in an average slip rate of approximately one inch per year. Inhomogeneities in the composition and rigidity of the crust along the San Andreas have created local structural blocks and widely varying local stress fields.

The structural block of the San Bernardino Mountains comprises basement rocks that are largely composed of granitic intrusive plutons and metamorphic country rocks. Granitic rocks in and near the project area are Mesozoic in age and range in composition from quartz monzonite to quartz diorite. The metamorphic country rock is largely quartzo-feldspathic gneiss with lesser inter-foliated biotite and hornblende schists. Calcareous and dolomitic marble is common locally, containing interlayered quartzo-feldspathic and calc-silicate gneiss. The age of this assemblage of metamorphic country rock is generally thought to be Paleozoic based on the occurrence of the marble bodies.

The Miocene Potato Sandstone crops out as a band of conglomeratic sandstone between the San Andreas fault and the North Branch of the San Andreas (NBSA) fault. Along the tunnel alignment, it has been observed only in the area of the City Creek portal, where it has been mapped as a steeply dipping and partially overturned sequence of interbedded conglomerate, conglomeratic sandstone, sandstone, and siltstone.

According to criteria developed by the California Division of Mines and Geology, surface rupture of the San Andreas fault during historic time has not been documented along the San Bernardino Mountains segment of the fault, but this segment is considered to be active and likely to rupture in the next 100 years. Other faults that are classified as active for this project include the NBSA fault, the Arrowhead Springs fault, and the San Manuel fault (see Figure 2). These faults result in prominent aerial photograph lineaments. Other lineaments have been identified roughly parallel to the east-west trend of the Arrowhead Springs fault, suggesting that some of these lineaments may correspond to small faults, shear zones, or zones of closely-spaced discontinuities.

#### 4.0 Exploration Program

Geologic and geotechnical investigations were conducted for the project in two phases, a planning phase and a design phase. Field investigations for the design phase included field geologic mapping, test pit and trench excavations, geophysical surveys, borehole exploration using HQ and NQ wireline rock coring, Becker hammer drilling, and percussion drilling. Thirty-three boreholes were completed for a total of 13,841 feet of drilling. *In situ* testing of boreholes included packer testing (permeability and hydraulic jacking tests), acoustic televiwer surveys, downhole seismic velocity logs, and borehole deviation surveys for inclined and horizontal boreholes. The testing equipment used for the *in situ* hydraulic jacking tests is shown in Figure 3. After completion of the *in situ* testing, most boreholes were converted to open pipe piezometer, vibrating wire piezometer, or screened monitoring wells for water level measurements and for future monitoring. Water samples were collected from the piezometers and wells and analyzed for water quality.

Geomechanical laboratory testing was conducted on samples obtained during the field drilling program. The rock testing included bulk density measurements, uniaxial compressive strength, point load index, triaxial testing, discontinuity shear strength, slake durability, corrosion potential, TBM boreability testing, and fault gouge/breccia properties (moisture content, Atterberg limits, grain size distribution, and swell tests).

#### 5.0 Design Issues

The design of the San Bernardino Mountains tunnels presented several unique design challenges such as protection of groundwater resources (wells and springs) during construction, tunneling through active faults, a portal and short section of tunnel near a geothermal field, and low *in situ* stress conditions. A summary of the more critical design issues is given below.

##### 5.1 Groundwater Resources

During the project Planning Phase, a survey was made to identify groundwater resources such as springs, wells, and streams along the project corridor. Further investigation during the Design Phase identified additional groundwater resources

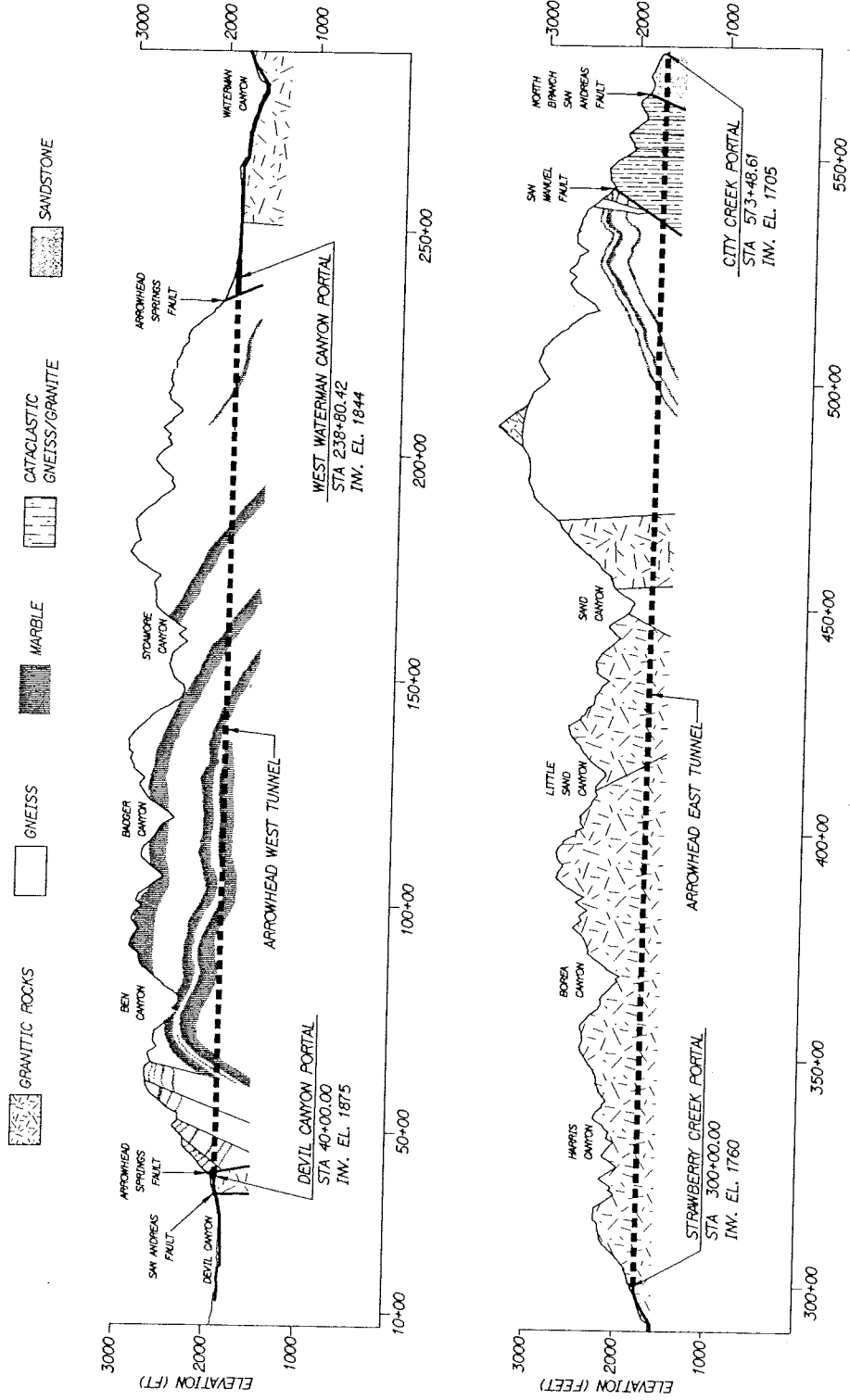


FIGURE 2: SAN BERNARDINO MOUNTAINS SEGMENT TUNNELS

which have been added to the catalogue of identified groundwater resources. Both tunnels will pass under or near several of these groundwater resources located in the San Bernardino National Forest and adjacent private properties. Groundwater resources within the San Bernardino National Forest are mostly intermittent springs with low flows. However, they are important resources for the forest environment.

Metropolitan has developed an on-going groundwater monitoring plan to provide monitoring and management of selected resources. The monitoring program includes flow measurement, temperature measurement, geochemical testing, and water quality testing at the selected springs, wells, and stream flow gaging stations. A total of approximately 160 monitoring locations are included in the monitoring program.

Agreements with the U.S. Forest Service have resulted in the requirement for grouting ahead of the tunnel excavation (pre-excavation grouting). This type of tunnel grouting is required to achieve the following objectives:

- Minimize and control the effects of tunnel excavation on the identified groundwater resources, and;
- Reduce groundwater inflows during tunnel construction to permit a reasonable rate of advance of the tunnel excavation and to facilitate construction of a high quality final lining.

Pre-excavation grouting has been used successfully in numerous concrete lined and unlined tunnels (including tunnels excavated by TBM) where long term reduction of the rock mass permeability has been an important part of the overall design. The pre-excavation grouting procedure for the San Bernardino Mountains tunnels involves drilling probe holes ahead of the excavation and observing groundwater inflows. If certain threshold limits of groundwater inflows are observed, drilling of additional holes and grouting will be performed. In areas adjacent to groundwater resources, stricter threshold criteria will be required in an effort to minimize the effects of tunneling on groundwater resources. In other areas of the tunnel a more liberal threshold criteria will be required (i.e., for constructability purposes).

Pre-excavation grouting can be readily combined with a drill-and-blast excavation operation as the face is fully accessible and the probe hole drilling involves the same equipment used for drilling of blast holes. Pre-excavation grouting is relatively more difficult to incorporate in the excavation of a TBM driven tunnel as access to the face is limited and by the fact that TBM excavation is inherently less cyclical. Recognizing this difficulty, special requirements were written into the TBM specification to facilitate pre-excavation grouting, such as probe/grout hole drilling capability and provisions for stand-by time during probing and grouting.

## 5.2 Active Fault Crossings

Metropolitan has set a schedule criterion of 6 months for repair of the tunnels after a major earthquake. The design earthquake for the tunnels is a magnitude 8.0 event along the San Andreas fault. It is anticipated that the aqueduct will most likely experience the design earthquake during the design life of the tunnels (100 years).

Permanent re-entry points for the pipeline and tunnel sections will be provided in each of the four portal areas. Permanent re-entry provisions are required for routine inspection and maintenance as well as for inspection and repair following major earthquakes. Areas which may be damaged by movement at known active faults will be accessible to workers from both sides of the fault and accessible to equipment from at least one side of the fault.

Earthquakes impart additional incremental loads on tunnel support, subject tunnel linings to transient strains due to ground shaking, and can cause localized permanent strains in zones of fault rupture. Therefore, the three fundamental seismic design considerations for tunnels involve:

- The additional seismic load imposed on the tunnel support;
- The ground strains induced by seismic wave propagation, and;
- The localized displacements induced by fault rupture.

The observational database indicates that damage to tunnels as a result of earthquakes is more severe in zones of poor rock quality and in areas of

low cover and suggests that thick linings are more susceptible to damage than thinner linings in comparable geologic conditions. Theoretical principles and observations also indicate that flexible tunnel support and linings are likely to suffer less damage than more rigid support elements.

The seismic design philosophy was based on the above principles and incorporates the following general provisions:

- Zones of poor rock quality, areas of low cover, and fault zones will be the focus of the seismic design effort;
- The design of the initial ground support will emphasize ductile detailing, and;
- Tunnel linings will be designed to be as flexible (i.e., as thin) as possible.

In areas of identified active fault crossings, it is considered that damage in the event of fault rupture is inevitable. However, the design has been developed to minimize damage and facilitate the repair of damaged areas.

A specific combination of initial ground support and final lining will be utilized in the sections of tunnel intersecting active faults. These measures are collectively known as "Seismic Sections." The maximum estimated magnitude of fault slip for the active faults crossing the tunnel is approximately 4 feet. The Seismic Sections will be over-excavated by approximately 4 feet on each side of the finished inside diameter to allow for this future fault movement. The initial ground support within the Seismic Sections will consist of closely spaced steel ribs, with rib spacing closer than dictated by static load considerations to allow for seismic loading and to improve the overall seismic performance of the tunnel. Shotcrete and steel mesh lagging will be utilized to assure long term, continuous contact between the initial support and rock. Steel linings will be utilized in the Seismic Sections and the annulus around the steel lining will be backfilled with a low-strength concrete.

The primary design objectives for the initial ground support in the Seismic Sections are:

- (1) To prevent collapse of the tunnel during construction in the event of a major earthquake, and;
- (2) To support the ground during post-earthquake repair of the final lining, if necessary.

Based on the expected fault slip for the active faults that cross the tunnel, it is unlikely that the entire tunnel cross section could be offset during an earthquake (i.e., tunnel closure). Further, the closely spaced ribs in the Seismic Sections will provide ductile support resistant to complete closure of the tunnel due to ground deformation and associated ground loads. Therefore, the use of temporary emergency egress adits or shafts during construction did not appear to be warranted. However, the potential risk of construction workers being trapped in the tunnel by rockfalls and the need for alternative escape measures was considered in the design. Emergency construction egress will utilize thick walled steel pipes extending through the identified fault zones. This pipe will be 30 inches in diameter to allow construction workers to use it as a means of escape.

### 5.3 Geothermal Groundwater

The tunnel and pipeline alignments traverse through a known geothermal area located in the Arrowhead Springs area near the West Waterman Canyon portal. The source of the geothermal water appears to be closely associated with the Arrowhead Springs fault. Recognizing that hot groundwater can cause significant problems during tunnel construction, an alignment was selected to avoid the hot geothermal waters to the greatest extent possible.

Geologic mapping was used in an attempt to locate the boundaries of the hot thermal plume. Groundwater conditions (i.e., depth and temperature) were then confirmed by boreholes along the optimized alignment. Near the West Waterman Canyon portal, temperatures recorded in wells near tunnel invert level are less than 100 degrees Fahrenheit. In a borehole located along the tunnel alignment 200 feet north of the portal, a maximum groundwater temperature of 80 degrees Fahrenheit occurs near the bottom of the hole at a depth of 120 feet (near the tunnel invert). Other borehole data also indicate that temperatures in the Arrowhead

West Tunnel would not be expected to exceed 100 degrees Fahrenheit near the West Waterman Canyon portal. Furthermore, measurements in a borehole located along the alignment approximately 0.5 miles from the West Waterman Canyon portal indicate typical ambient groundwater temperatures of approximately 65 degrees Fahrenheit.

#### 5.4 *In Situ* Stress Conditions

*In situ* rock stress was investigated indirectly by *in situ* hydraulic jacking tests which were performed in field boreholes. Hydraulic jacking tests measure the point at which a hydraulic pressure will open a discontinuity or set of discontinuities in the rock. This pressure is equivalent to the minimum normal *in situ* stress acting across discontinuities penetrated by the test borehole. Hydraulic jacking pressures are compared with the internal conduit pressure to assess the ability of the rock mass to provide adequate confinement.

The purpose of the hydraulic jacking tests performed for this project was to investigate the need for steel tunnel lining as a means to confine transported water under operating pressure conditions. Analysis of the hydraulic jacking data indicated a potential for hydraulic jacking exists in the area under Harris Canyon near the Strawberry Creek portal and in the area adjacent to the City Creek portal. In both areas, steel tunnel lining is required due to hydraulic jacking and/or permeability considerations. *In situ* permeability and hydraulic jacking tests will be performed during construction to confirm the appropriate length of steel lining.

The hydraulic jacking tests also suggest that typically the minimum *in situ* stress is significantly less than the vertical overburden stress. The test results indicate that the ratios of minimum stress acting across discontinuities to the vertical overburden stress,  $K_{min}$ , have a lower bound value in the range of 0.2 to 0.3 along both tunnel alignments. In addition, it was found that below a depth of 400 feet, jacking pressures generally increase with depth, implying that  $K_{min}$  ratios increase with depth (see Figure 4). However, above 400 feet of depth there is significant scatter in the data. This variation of stress ratios above 400 feet may be attributed to several factors, including stress relief due to tectonic uplift and the different types of faulting observed locally in the San Bernardino Mountains

Goodman (1989) points out that the ratio of horizontal stress to vertical stress,  $K$ , may vary depending on whether tectonic forces in the rock are extensional (normal faulting) or compressional (reverse faulting). Furthermore,  $K$  theoretically approaches zero, particularly at shallow depths (i.e., less than 400 meters), and in association with normal faulting. Values of measured *in situ* stress published by Hoek and Brown (1980) indicate that above a depth of 500 meters, lower bound  $K$  values are in the 0.4 to 0.5 range. However, these published *in situ* stress measurements may not be indicative of stress conditions adjacent to active faulting, as *in situ* stresses near faults are rarely investigated. The hydraulic jacking tests conducted for the San Bernardino Mountains Tunnels were adjacent to and in some cases across active faults. Both reverse and normal faulting was observed in the project area. While it is possible that the low  $K$  ratios indirectly measured along the tunnel alignments are in part the result of extensional movement associated with normal faulting, the relative effect of stress relief due to tectonic uplift and weathering cannot be quantified.

#### 6.0 Summary

The San Bernardino Mountains Tunnels will traverse a range of ground conditions through igneous, metamorphic, and sedimentary rocks. The contract documents provide the construction contractor with the option to excavate the tunnels with either drill-and-blast methods or by both drill-and-blast and TBM methods. Pre-excavation grouting will be used as a means to minimize the effects of tunnel excavation on groundwater resources and for constructability purposes. Portions of the tunnel crossing active faults will utilize special types of initial ground support and final lining to minimize damage and facilitate post-earthquake repair. Low *in situ* stress and high permeability conditions have resulted in the requirement for steel lining in portions of the tunnels.

It is anticipated that the various Inland Feeder tunnels will go to bid between the spring and summer of 1995. Construction of the Inland Feeder is expected to take over 4 years.

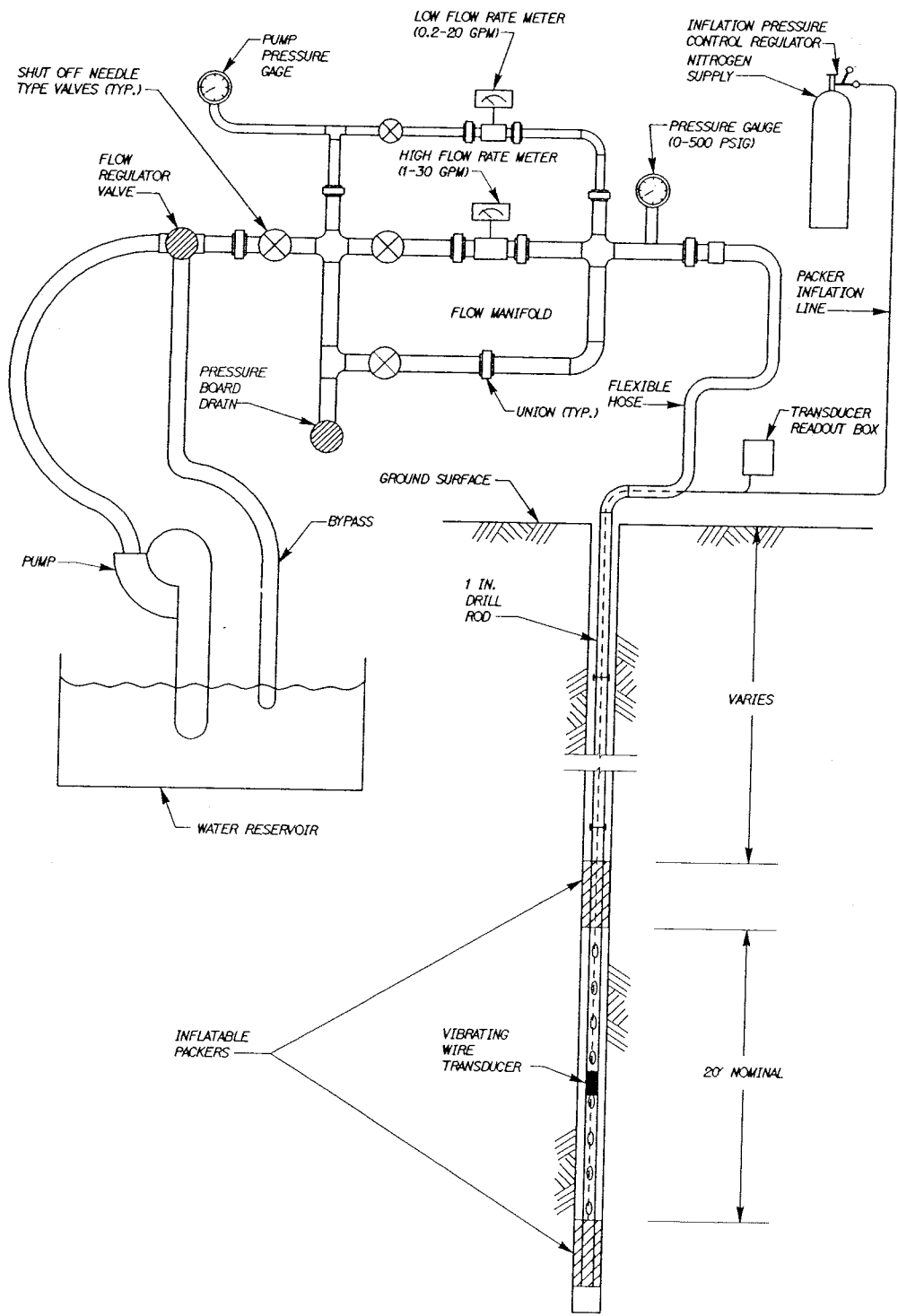


FIGURE 3: HYDRAULIC JACKING TEST EQUIPMENT

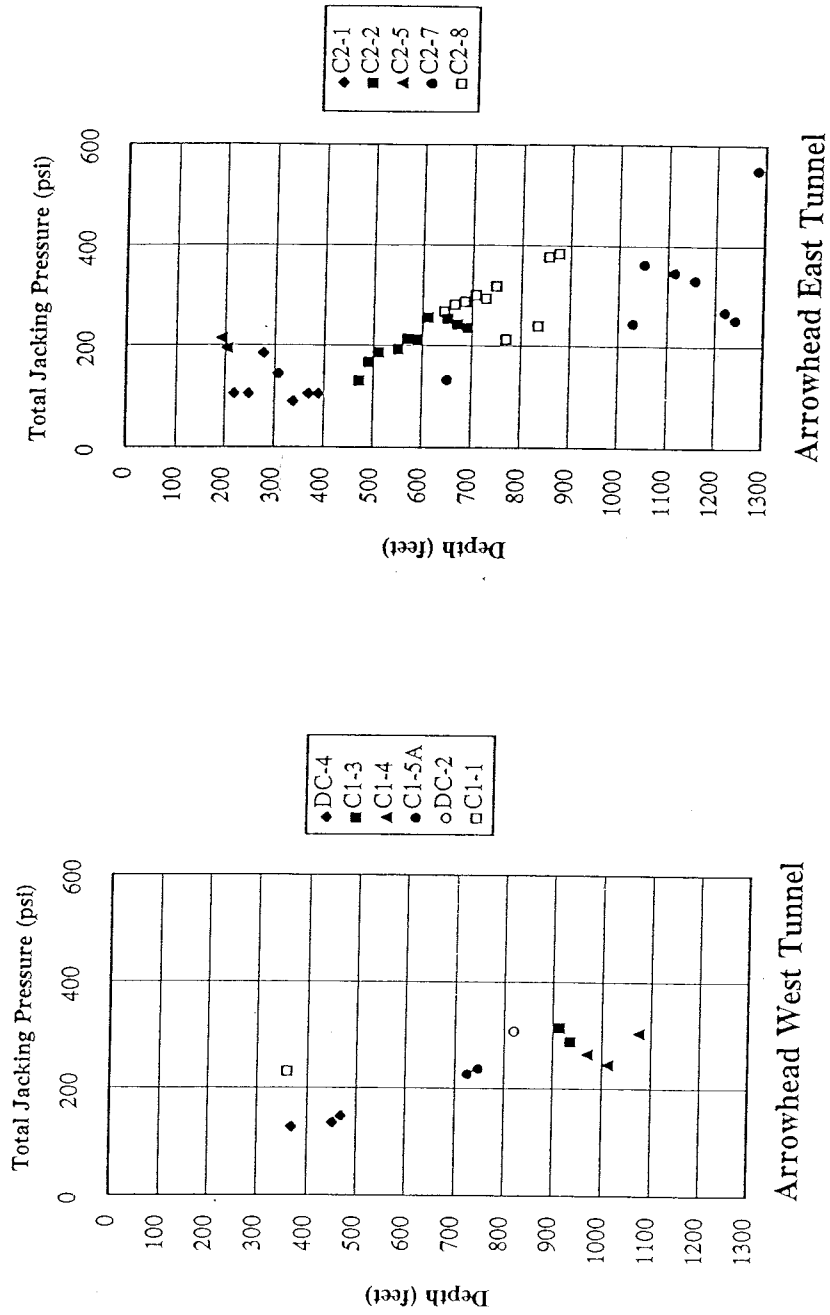


FIGURE 4: HYDRAULIC JACKING TEST RESULTS

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