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# Designing a Large-Diameter HDD Crossing in San Diego's Balboa Park

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## 1. ABSTRACT

The Upas Street Pipeline Replacement Project will replace approximately 28,500 feet of deteriorated 30-inch and 24-inch cast iron water mains within the City of San Diego. The most significant trenchless construction on the project is the crossing of CA State Highway 163, located within the northern limits of historic Balboa Park. The proposed crossing consists of replacing approximately 1,700 feet of 30-inch cast iron water main with a new 24-inch inside diameter HDPE water line.

Design of the large-diameter HDD bore was complicated by several site challenges including: an entry point located within the popular and historic Balboa Park; the Highway being located at the bottom of a canyon 90 feet below the bore end points; Caltrans' requirement for a large-diameter casing of the portion of the bore beneath Highway 163; minimizing disruption to both Girl Scouts and Boy Scouts facilities located near the exit point; and planning for a two-stage pipe fabrication and testing plan to minimize disruption to neighborhood traffic and an adjacent middle school.

## 2. INTRODUCTION

The City of San Diego's Upas Street Pipeline Replacement Project will replace approximately 28,500 feet of deteriorated 30-inch and 24-inch cast iron water mains which have begun to break and leak. The project runs primarily beneath Upas Street, between Ray Street and Pacific Highway, within the city limits of San Diego, CA.

Infrastructure Engineering Corporation (IEC) was contracted by the City of San Diego's Public Works Department to design the overall project and provide California Environmental Quality Act (CEQA) compliance documents, community outreach services, and bid and construction phase services. IEC sub-contracted and managed several consultants for the project, including Helix Environmental Planning (biological and historical resources reports), RCE Traffic Transportation Engineering (traffic impact study and traffic control plans), and Allied Geotechnical Engineers (geotechnical investigation and recommendations).

Bennett Trenchless Engineers was also sub-contracted by IEC to evaluate the feasibility of, and subsequently design, the proposed trenchless crossing of CA State Highway 163. The crossing is located between the intersection of Upas Street and 7th Avenue, on the west side of Highway 163, and the intersection of Upas Street and Vermont Street, on the east side. The trenchless portion of the project consists of replacing approximately 1,700 feet of 30-inch cast iron water main with a new 24-inch inside diameter water line.

The design was a collaborative effort by the IEC team (including BTE) and the City. The City and IEC identified the environmental and community constraints, and BTE provided design solutions and options to work within the constraints, as described below.

## 3. SITE CONDITIONS

Figure 1 shows the proposed trenchless crossing of CA Highway 163, located approximately two miles north of downtown San Diego, along the northwest edge of Balboa Park. The majority of the proposed replacement pipeline will be constructed by open-cut within the Upas Street right-of-way (ROW). However, at the location where Upas Street would cross Highway 163, the Highway is running north and south along the bottom of a canyon approximately 100 feet below either end of Upas Street. The new water main must be installed beneath the canyon and the Highway ROW using a trenchless crossing that extends between the ends of Upas Street, on either side of the canyon.

Figure 1. Project Site Map

The west side of the crossing is located at the intersection of Upas Street and 7th Avenue, as shown in Figure 2. This site is located in a developed urban neighborhood, with two high-rise apartment/condominium complexes along the north side of Upas Street between 6th Avenue and 7th Avenue, and the northwestern extent of Balboa Park along the south side of the street. The apartments/condos along the north side have their driveway access from Upas. Additionally, the historic Marston House, and a few additional residences located along 7th Avenue north of Upas Street, rely on Upas for access. Therefore, the construction must allow for at least one-way traffic along the street. An alley located north of the condominiums can provide access for traffic in the opposite direction. The portion of Balboa Park to the south consists of an open, grassy area with occasional mature trees and paved trails. An existing path begins at the intersection of Upas Street and 7th Avenue that winds down the west side of the canyon to a pedestrian bridge crossing of Highway 163. The pedestrian bridge is heavily used and access must be maintained during construction. A low cobblestone retaining wall located along the south side of Upas Street between 6th and 7th Avenue is of historic importance and must be protected during construction. The design effort placed a significant focus on minimizing disruption to the public’s use of this portion of Balboa Park.

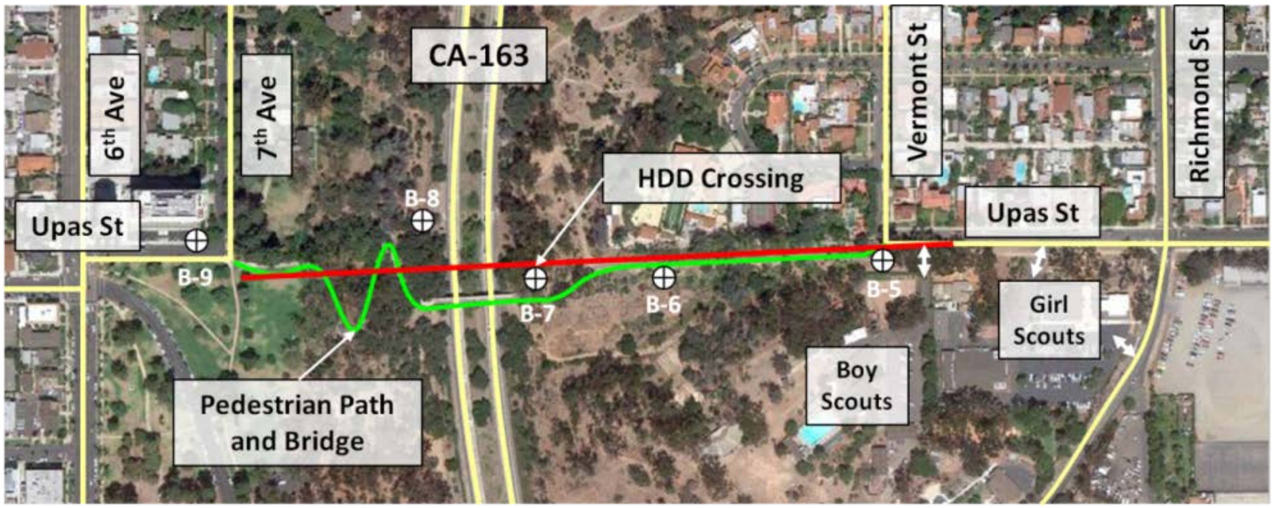

Figure 2. Trenchless Crossing Location Map

After crossing Highway 163, the pedestrian path continues east, climbing up the opposite side of the canyon to the intersection of Upas and Vermont Street. The section of Upas between Vermont Street and Park Street contains single-family homes along the north side and both Boy Scout and Girl Scout facilities, as well as a middle school, along the south side. Avoiding disruption to these existing facilities was an important factor during the design of the crossing.

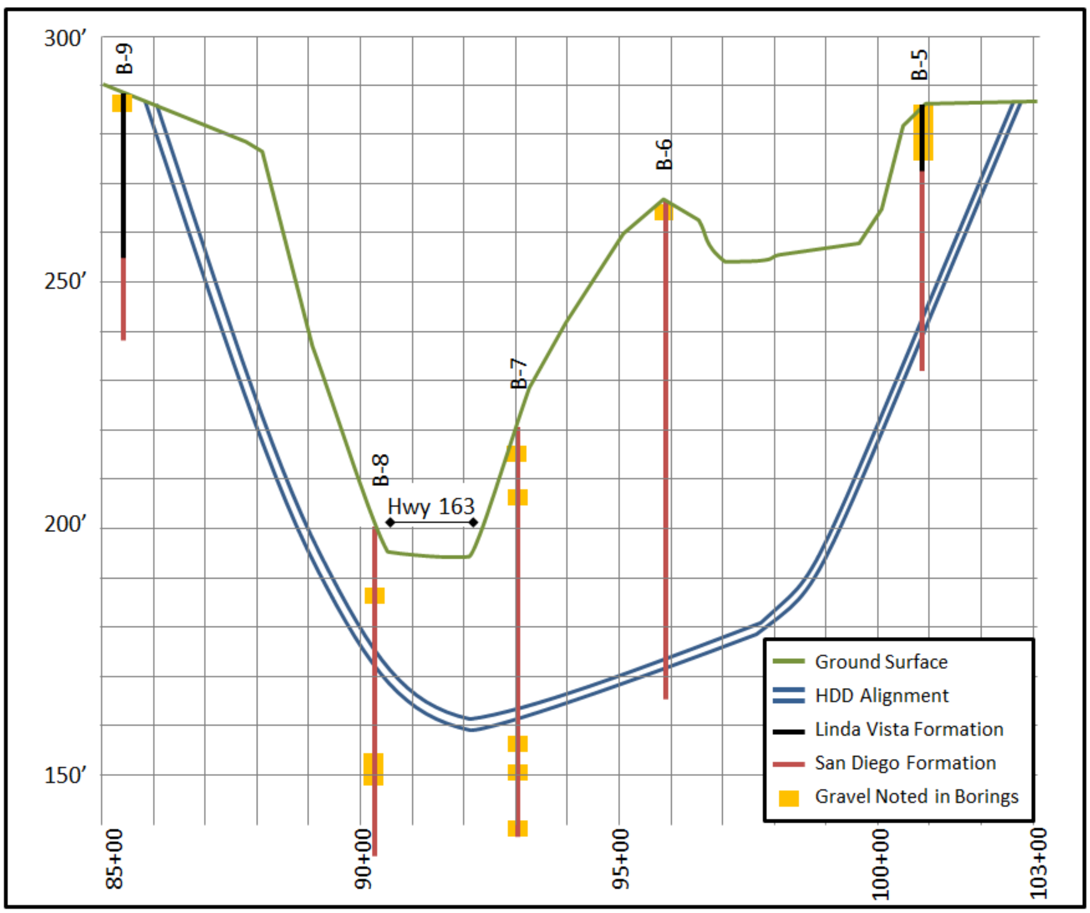

Figure 3. Geotechnical Conditions

The geotechnical investigation for the Highway 163 crossing was performed by Allied Geotechnical Engineers of Santee, CA. Five geotechnical borings were completed along the proposed crossing alignment. The locations of the borings are shown in Figure 2, as B-5 through B-9, from east to west. The five borings all encountered similar ground conditions at the depth of the trenchless crossing. The soil units encountered in the upper two to twelve feet of each boring consisted primarily of medium dense to dense silty and clayey sand with varying amounts of gravel and cobbles. Below this surficial layer, the San Diego Formation soils found at each boring location, and the Linda Vista Formation soil found in Borings B-5 and B-9, consisted primarily of dense to very dense fine silty sand, with occasional gravel layers. The soils were described as being weakly cemented and friable. As illustrated in Figure 3, gravel zones were encountered in the upper portions of Borings B-7 and B-8, between elevations 220 feet and 184 feet. Gravel and cobbles were also encountered in Borings B-7 and B-8 below elevation 158 feet. Generally, these soil conditions do not pose a significant risk for the proposed trenchless construction, however focus was placed on avoiding the gravel layers, where possible. Groundwater was only encountered in Boring B-8, at an elevation of 147 feet.

## 4. TRENCHLESS METHOD SELECTION AND CROSSING DESIGN

Several trenchless construction methods could be suitable for installing a pipeline beneath a canyon or roadway, including auger boring, microtunneling, open-shield pipe jacking, pipe ramming, and horizontal directional drilling (HDD). However, due to the significant length of the required crossing (~1,700 feet) on this project, auger boring and pipe ramming were not considered feasible. Microtunneling was considered technically feasible, but would be challenging for this project due to high jacking forces and guidance difficulties that can occur on jacked bores exceeding approximately 1,000 feet. Additionally, the very deep vertical shafts and steel casing required for a microtunneled bore would prevent microtunneling from being cost competitive. These factors left HDD as the sole feasible, practical, and cost efficient method for completing the Highway 163 trenchless crossing for the Upas Street Pipeline Replacement.

Figures 4 and 5 illustrate the bore alignment and profile chosen for the crossing. The bore design was developed based on the capabilities and limitations of the HDD method, the required carrier and casing pipe configuration, and the significant site constraints. The proposed bore alignment is 1,700 feet long, measured horizontally between the entry and exit points and is 1,730 feet long measured along the curved vertical profile. The entry point is located approximately 60 feet southeast of the intersection of Upas Street and 7th Avenue, at Station 85+75. The bore will generally follow the alignment of the existing water main down the west wall of the canyon, beneath the Caltrans ROW, then up the east canyon wall to the intersection of Upas Street and Vermont Street. The bore will exit approximately 200 feet east of the Upas St/Vermont St intersection near Station 102+75. The proposed exit point is east of the Boy Scouts of America driveway, approximately 20 feet south of the Upas Street curb line. The entry angle for the proposed bore is 16 degrees and the exit angle is 14 degrees. Both vertical curves have a radius of 1,000 feet. The lowest elevation of the proposed bore alignment is 158 feet.

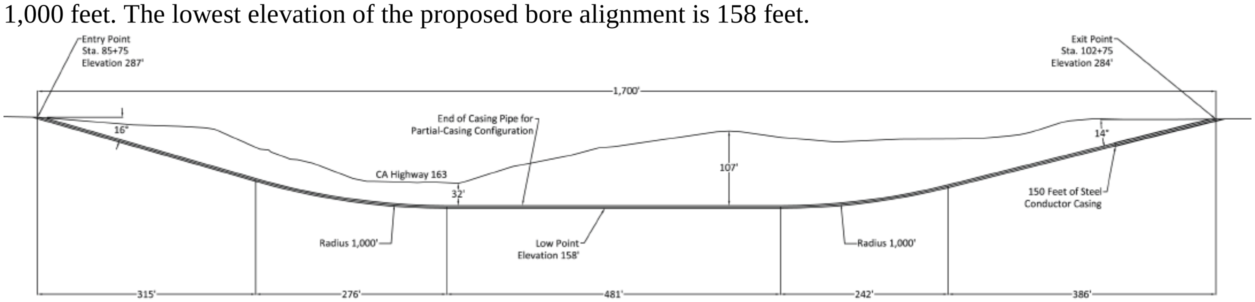


Figure 4. Highway 163 Crossing HDD Bore Profile

The entry point was chosen to maintain at least one-way traffic flow on Upas Street between 6th and 7th Avenue; to protect a retaining wall located along the south side of Upas Street that is thought to be of historical significance; to minimize disruption (specifically tree removal) within Balboa Park; and to provide adequate vertical cover for the bore as it descends the west canyon wall and proceed beneath Highway 163. As shown in Figure 5, if the entry point were moved further east, adequate depth could not be achieved before the bore passes beneath the Caltrans ROW. A shallower bore profile would increase the risk of hydrofracture in the canyon bottom as well as potential settlement damage to the roadway. The 16-degree entry angle is near the high end of typical HDD geometry. If the entry point were moved further to the west, the HDD rig would be in conflict with the historic retaining wall (as shown in Figure 6), unless the entry point were also moved north or south. Moving the entry point further north would put more of the HDD rig and support equipment into Upas Street, preventing at least one-way traffic flow. Additionally, moving the entry point further north would cut off access to the staging area from Upas Street, requiring a more disruptive route from Balboa Drive that would affect a larger portion of Balboa Park. Finally, moving the entry point to the south would likely cause the damage or removal of at least two additional trees in Balboa Park.

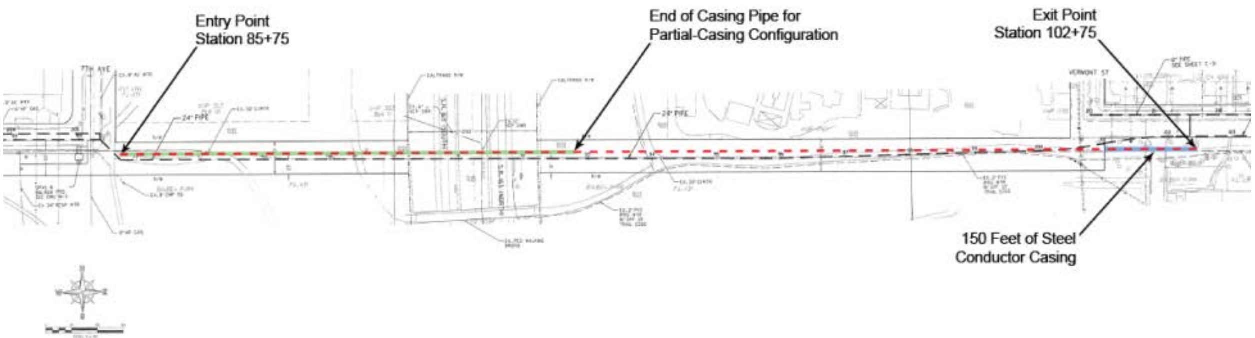


Figure 5. Highway 163 Crossing HDD Bore Plan View

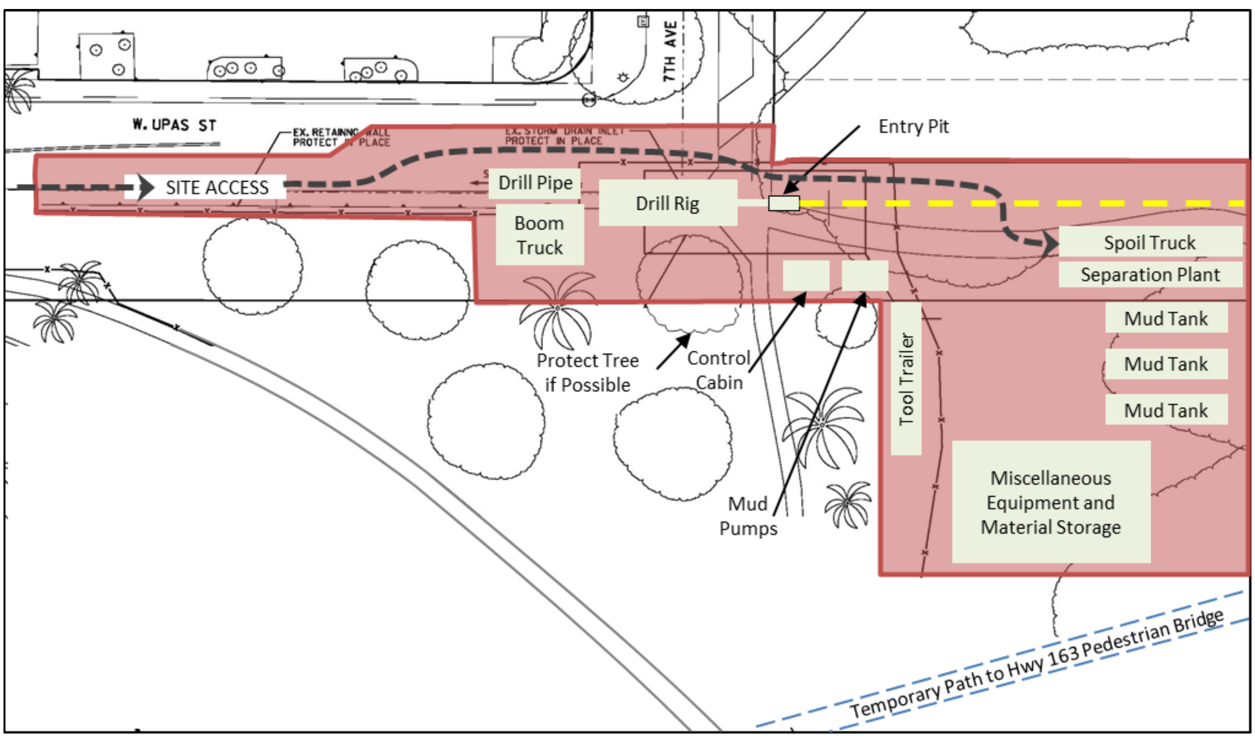


Figure 6. HDD Entry (Rig) Side Work Area and Example Layout (Shaded Area)

The exit location was chosen to reduce disruption to traffic flow in Upas Street and to reduce disruptions to public access to the pedestrian path that crosses Highway 163. The exit point is out of the traffic lanes of Upas Street and approximately 225 feet east of the end of the walking path, so pedestrians can safely cross to the sidewalk along the north side of Upas Street. This geometry provides the shortest (and least costly) crossing that can still provide enough cover at the Boy Scouts' driveway, near Station 102+00, to effectively manage settlement and hydrofracture risk at this point. The resulting bore alignment also remains approximately centered within the existing Upas Street right-of-way.

The maximum depth of the bore was chosen to avoid the gravel layers identified in Borings B-7 and B-8. Specifically, the maximum bore depth was set at elevation 158 feet to stay above the gravels and cobbles noted below this elevation in Borings B-7 and B-8. Gravel and cobbles present significant challenges to HDD pipeline installations and should be avoided if possible.

## 5. STAGING AREA CONSIDERATIONS

Due to the size and length of the proposed HDD crossing, a large HDD rig will be required. The typical required staging area for this size rig is 20,000 to 30,000 square feet at the entry side of the bore. The required layout area for the exit side, or pipe side, of the bore is equal to the length of the pipe to be installed, by approximately 20 to 50 feet wide. Ideally, the pipe is completely assembled prior to pullback and is installed without stopping to weld/fuse pipe. Interruptions during pullback increase the risk of bore collapse and/or the pipe becoming stuck within the bore, especially for bores with diameters greater than 36 inches, as will be required for this project. For this project, the risk of collapse is mitigated somewhat by the dense to very dense silty sand conditions expected along most of the bore alignment which should provide a stable bore. However, some risk always remains when pullback is paused.
Adequate space for the rig site staging is available on both sides of the proposed crossing. However, space for pipe fabrication and layout is only available on the east side of the crossing. The jog that occurs in Upas Street as it crosses 6th Avenue would require that the pipe be fabricated in, and strung across, Balboa Park. Further, significant traffic disruption would occur at each cross street of Upas between 6th Avenue and 2nd Avenue. The volume of traffic, and subsequent disruption, on the west side of the crossing makes staging the pipe on this side impractical. Therefore, the entry was located on the west side, with pipe layout planned for the east side, as shown in Figures 4 through 6.

The rig side work area must accommodate the drill rig, drill pipe, control cabin, boom truck or crane, separation plant and spoil truck, mud tanks, equipment trailer, and storage space for other small equipment and materials. Layout of the individual pieces of HDD equipment is flexible and therefore the equipment can be adjusted to irregular shapes; however a minimum length of approximately 75 feet behind the entry point is typically necessary to accommodate the drill rig. An example site layout at the entry side is shown in Figure 6. Ultimately, the actual equipment layout is left to the contractor to avoid negative impacts to their means and methods, but the sample layout illustrates that at least one feasible layout option exists. The staging area limits were chosen to provide the contractor with sufficient working area and reasonable access to the work site, while trying to minimize negative effects to the park, especially tree removal. However, as shown in Figure 6, it is possible that one tree may have to be removed to allow space for the drill rig and support equipment.

The remaining portions of the staging area were selected to be in the open, grassy portion of the park to reduce the impacts to other trees and to expedite restoration after construction. The other significant impact to Balboa Park will be access to the path leading to the Highway 163 pedestrian bridge. The existing and proposed alignments each run beneath this path, and the required staging area will block access to the path from Upas Street and 7th Avenue. A new temporary path will be constructed that provides access to the walking trail at the top of the canyon, to the south of the proposed staging area.

On the exit side, Figure 7 shows that there is not adequate length to lay out the full pipe string (1,730+ feet) along the shoulder of Upas Street, even if the full length between Vermont Street and Park Boulevard is used. If the full length of the pipe were pre-fabricated, both the Boy and Girl Scouts driveways, Richmond Street, and at least a portion of Park Boulevard would be blocked for as much as a few weeks. To minimize traffic impacts at these locations, the pipe will instead need to be fabricated and laid out between Richmond Street and Park Boulevard, (see Figure 8) in two or more sections which will then be positioned and welded just prior to pullback, or in the very early stage of pullback. Access to both the Girl Scouts' driveway from Upas Street will be maintained by using this pipe layout option for the entire construction duration except just prior to pullback. During pullback, the Girl Scouts will still have access through their driveway on Richmond Street. Traffic on Richmond Street will be maintained until immediately prior to pullback. At this time, the leading section of the pipe will be positioned for pullback and will need to be hoisted above the intersection using cranes or temporary supports such as storage containers, limiting traffic disruption on Richmond Street. To eliminate impacts to Park Boulevard, the first section of pipe may be pulled approximately 150 to 200 feet into the bore before the second section is positioned and welded to complete the pipe string. Stopping the pullback with a portion of the pipe within the bore would present some risk of the pipe becoming stuck, however the relatively dense ground conditions expected reduce this risk. Finally, to minimize impacts related to the middle school, construction is planned for the summer months when school is not in session.

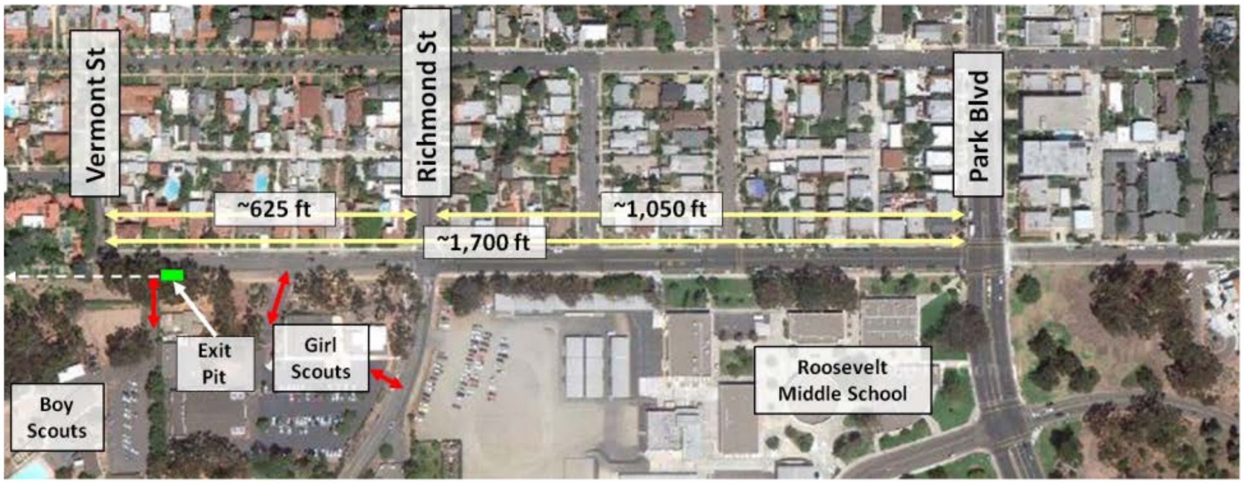

Figure 7. HDD Exit Side

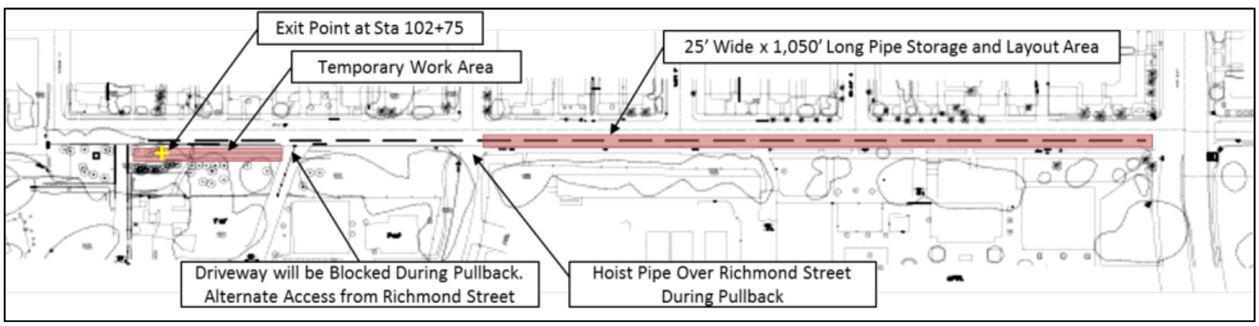

Figure 8. HDD Pipe Layout and Work Area

## 6. PIPE MATERIAL CONSIDERATIONS

Due to the geometry and pullback constraints of HDD crossings, the pipe materials that are primarily used are steel, fusible PVC (FPVC), and HDPE. An important consideration for pipe materials used on HDD projects is allowable bend radius. The entrance and exit points for this bore had to be set back from the canyon walls to allow the pipe to reach the proper depth before passing beneath Highway 163. The allowable radius of the drill pipe and product pipe affect entry and exit setback. Steel pipe cannot be bent through short radius curves without risk of yield or failure in bending. The rule of thumb for steel pipe is that the minimum allowable bend radius in feet is equal to 100 times the pipe diameter in inches. Therefore for a 30-inch to 36-inch steel casing pipe, the required minimum bend radius would be 3,000 to 3,600 feet. The significantly higher flexibility of plastic pipe materials avoids this difficulty, as the minimum allowable bend radius for HDPE and FPVC are much lower. For plastic pipe applications, the minimum bend radius is typically dictated by the steel HDD drill pipe. Drill pipe of the size necessary for this project limits the minimum bend radius to approximately 1,000 feet. A bore designed using steel pipe would have been significantly longer (25% or more) than one that used plastic pipe. For this project steel was considered impractical because of the elevation difference between Upas Street and Highway 163 and the steep sides of the canyon, which required tight vertical curves in the bore design to keep the trenchless crossing length reasonable. FPVC and HDPE pipe were considered the feasible options for the HDD crossing on this project.

The trenchless crossing of CA State Highway 163 requires an encroachment permit from the California Department of Transportation. Caltrans' encroachment permit manual sets forth the requirement that forced flow pipeline crossings passing beneath their facilities must be contained within a redundant casing. This requirement is based on the potential for erosion of the roadbed and creation of a possible sinkhole in the event that the carrier pipeline develops a leak. For pipelines installed by HDD, the manual states that the casing may consist of HDPE pipe, rather than the steel casing required for other trenchless methods. The use of FPVC pipe is not explicitly discussed in the manual, presumably due to its more recent arrival to the marketplace. However, discussions with Underground Solutions, the manufacturer of FPVC, indicate that Caltrans has approved FPVC for use as a casing on a few recent projects.

While a casing is necessary, it is only required beneath the Caltrans ROW. The specifics of the HDD pullback method require that the casing extend the full distance from the drill rig to the highway, but does not have to extend from the highway to the exit point. For this crossing, a partial casing option includes approximately 700 feet of casing pipe extending from the entry point to the east Highway 163 ROW. The remainder of the bore will contain only the un-cased carrier pipe (properly designed for safe installation without casing). This method provides a significant cost advantage be eliminating approximately 1,000 feet of casing material. Additionally, it will provide significant simplification of the pipe fabrication and storage logistics on the east side of the crossing.

For a crossing where the carrier pipe is to be installed within a casing pipe, it is common for the carrier pipe to be preloaded inside the casing prior to pullback and the two pipes are installed together in one pass. However the issues regarding traffic on Richmond Street would make preloading the carrier pipe very difficult, although not necessarily impossible. The casing and carrier pipes could also be pulled in separately. This would require significant width to store both pipe strings, in two pieces each, in Upas Street prior to pullback, but would allow Richmond Street to remain open until the day of pullback. The use of a partial casing provides an alternative which results in the most efficient installation. The casing length is limited to 700 feet, allowing this pipe to be completely fabricated between Richmond Street and Park, leaving 350 feet available for fabricating and preloading the first 1,000 feet of carrier pipe. The remaining approximately 750 feet of carrier pipe will then be fabricated and stored next to the casing and leading carrier segment. In this way only two pipe segments have to be stored in the street. Adequate space for this option requires approximately half of the width of Upas Street between Richmond and Park. This space will be obtained by eliminating parking from the south side of the street and one direction of travel, leaving parking on the north side and forcing opposite-direction traffic onto a parallel street.

## 7. PIPE STRESS EVALUATION

To analyze the pipe material options and pipe wall stiffness requirements, we conducted preliminary pullback and pipe stress analyses for different casing and carrier pipe alternatives. A minimum of two to three inches of annular space is typically necessary between the ID of the casing pipe and the OD of the carrier pipe to allow for safe installation of the carrier. The external fusion beads on the carrier pipe and the internal fusion beads on the casing pipe are typically removed when small clearances are used between casing and carrier. For a 24-inch nominal diameter FPVC carrier (25.8” OD), an approximately 29-inch ID casing pipe is necessary. Nominal 30-inch diameter DR21 DIPS FPVC provides the necessary casing ID. To provide similar capacity with an HDPE carrier pipe, a 30-inch OD, DR 9 (PE4710) pipe is required. To provide a casing pipe with an ID of at least 33 inches, 42-inch OD HDPE is required. The thickest DR currently available in 42-inch HDPE is DR 13.5. Due to the favorability of the partial-casing option, each of the carrier pipes was evaluated for full installation loads (as though the product pipe were being installed without a casing) to ensure safety during the pre-loaded, partial-casing installation where much of the carrier pipe will be exposed to pullback forces.

The pullback calculations were performed based on a combination of the methods laid out in the Plastics Pipe Institute’s Handbook of Polyethylene Pipe, and J.D. Hair and Associates’ 1995 engineering design guide entitled “Installation of Pipelines by Horizontal Directional Drilling”. These methods estimate the loads that the pipeline will experience as it is pulled into the bore and analyze the combined tensile and bending stresses, as well as buckling failure potential of the pipe resulting from these loads. The loads are estimated by calculating the expected frictional drag due to the friction between the pipe and the wall of the bore, the fluidic drag as the pipe is pulled through the drilling fluid in the bore, the effects of the weight of the pipe, and the additional force arising from capstan effect as the flexible pipe string is pulled through bends in the bore. The analysis of the fluidic drag component of these calculations was based on an approach described by Duyvestyn, 2009.

We assumed that the pipes will be filled with water as they enter the bore during installation but that they will be empty on the ground surface. For plastic pipe it is desirable, and often necessary, for the pipe to be full of water during pullback to reduce the buoyant uplift forces, thereby reducing the friction between the pipe and the borehole. The water is also typically necessary to resist the external hydrostatic pressure from the drilling fluid which could lead to an unconstrained buckling failure of the pipe. We also assumed that the pipe will be supported by rollers and/or cranes during installation.

The results of the pullback load analysis using HDPE and FPVC pipe for the HDD crossing are summarized in Table 1. Observations from previous projects indicate that startup loads can be as much as 1.5 to 2 times the calculated steady state loads. Therefore, we applied a conservative factor of two to the steady state pull loads to account for static friction and gelling of the drilling fluid that can be observed when resuming after pull stoppages.

**Table 1: Pullback Load Analysis for HDD Installation (Startup Loads, 2x Steady State)**

| Location | 42" DR 13.5 HDPE Loads (pounds) | 30" DR 9 HDPE Loads (pounds) | 30" DR 21 FPVC Loads (pounds) | 24" DR 18 FPVC Loads (pounds) |
|---|---|---|---|---|
| **End of Straight Section/Beginning of Second Radius** | 412,000 | 190,000 | 211,000 | 121,000 |
| **End of Second Radius/Beginning of Straight Tangent** | - * | 203,000 | - * | 132,000 |
| **Exit Point** | - * | 195,000 | - * | 132,000 |
| **Maximum Allowable Pull Load (FS = 2.5)** | **437,000** | **321,000** | **409,000** | **307,000** |

* - These locations are not applicable to the casing pipe in a partial-casing configuration.

Stresses resulting from the pullback force, and additional tensile stress resulting from the pipe bending through the vertical curves, were analyzed at potentially critical points along the bore and compared to the recommended allowable stress. The results of these analyses are summarized in Table 2. The allowable stress values published by the respective manufacturers of both HDPE and FPVC pipe incorporate a recommended factor of safety of 2.5. Therefore, if the ratio of the combined calculated tensile stress to the allowable stress is equal to or less than 1.0, the pipe is considered to be in a safe condition. The most critical combined stress location in the bore typically occurs at the end of the second vertical curve.

**Table 2: Pipe Stress/Buckling Analysis for HDD Installation**

| Location | HDPE Casing | HDPE Carrier | FPVC Casing | FPVC Carrier |
|---|---|---|---|---|
| | **Install Buckling Stress F.S.** | **Buckling Stress F.S.** | **Buckling Stress F.S.** | **Buckling Stress F.S.** |
| **End of First Radius/Beginning of Straight Section** | 1.6 | 6.4 | 3.7 | 6.2 |

Additionally, unconstrained buckling stresses resulting from the heavy drilling fluid outside the pipe were compared against the critical buckling stress capacity of the pipe to determine the risk of buckling failure. The buckling stress condition for both casing and carrier pipe was evaluated for the installation condition of a full static column of water inside the pipe, a full static column of drilling fluid outside the pipe, plus an additional 10 psi of dynamic fluid pressure arising from fluid moving within the bore during pullback. For HDPE pipe, the elastic modulus used in the installation evaluation condition was the 12-hour load duration modulus (63,000psi for PE4710). FPVC does not experience creep strain and therefore uses a constant modulus for all loading durations.

Tables 1 and 2 show that pull loads and pipe stresses for the FPVC pipe option and the HDPE carrier pipe are all within safe limits. Table 2 indicates that the predicted buckling stresses for the installation of 42-inch DR 13.5 HDPE casing exceed safe limits (factor of safety less than 2.0). The buckling stress risk will be mitigated by requiring an open pullback for the casing pipe. An open pullback uses a pull head that allows drilling fluid to flow through into the annular space between the casing pipe and carrier pipe. This type of installation mitigates the buckling risk by balancing the drilling fluid pressure both inside and outside the casing pipe resulting in zero net-hydrostatic pressure on the casing pipe. The carrier pipe will be installed using a conventional closed pull head, with water ballasting to resist buckling. Therefore, HDPE can be safely used as a casing pipe in a partial-casing configuration. An important result arising from the pipe stress evaluation is that all pipe options must be installed full of water (or using open pullback installation for casing pipes) to resist the external drilling fluid pressures during pullback.

## 8. SETTLEMENT RISK EVALUATION

The risk of settlement-induced damage to structures and facilities overlying the bore is a potential concern for most trenchless construction. For the HDD crossing of Highway 163, the critical feature that could be subject to settlement damage is the highway itself. However, the low vertical cover at the Boy Scouts' driveway makes this location an additional risk area.

Systematic settlements associated with HDD are primarily caused by the collapse of the overcut, or annular space, between the casing pipe and the excavated bore. The overcut is necessary for HDD to facilitate pullback of the pipe by reducing the frictional contact area of the pipe and soil, by allowing the drilling fluid to act as a lubricant around the product pipe, and to account for incomplete removal of some of the spoil from the bore. During drilling, or after pipe pullback is completed, the soil surrounding the bore may collapse or squeeze onto the pipe. The movement of soil into the annulus can result in settlements above the bore. Systematic settlement risks are reduced by limiting the radial overcut that the contractor is allowed to use (within reasonable limits), as well as by filling the annulus with bentonite based drilling fluid during drilling.

To evaluate the settlement risk for the crossing, a settlement analysis was performed using an empirical approach first developed by Schmidt (1969) and Peck (1969), and extended to soft ground open shield tunneling by Cording and Hansmire (1975). The method was adapted to microtunneling by Bennett (1998) and has proven useful for evaluating settlement risks for other trenchless methods, including HDD (Wallin, Wallin, and Bennett, 2008). The method approximates the shape of the settlement trough above the HDD installation using an inverted normal probability distribution curve. The maximum predicted settlement occurs above the centerline of the bore, and decreases to near zero at locations near the edge of the settlement trough. The maximum estimated settlement is directly proportional to the volume of material "lost" to a collapsing annular space or overexcavation, and inversely proportional to vertical clearance above the bore. (Increased vertical clearance results in the predicted settlement trough becoming wider and shallower.)

The percentage of annular space volume that results in actual settlement is affected by three factors: soil mass loosening, soil strength (arching), and drilling fluid and/or grout left in the annulus. Soil mass loosening occurs in dense soils when the soils dilate, or become less dense, as they collapse into the annular space around the pipe. The dense to very dense granular soils expected along the crossing will exhibit soil loosening behavior. Soil loosening behavior, or dilation, decreases settlement above the bore. Arching is a phenomenon where the interaction of the individual soil particles physically prevents the soil from collapsing completely onto the pipe. The high internal friction of the very dense granular soils leads to arching within the soil mass, further reducing observed settlement. Finally, the volume of the annulus that contributes to settlement can be reduced by the solids volume of the drilling fluid remaining in the annulus. Considering these three factors and the soil conditions encountered in the geotechnical investigation, it is likely that little or none of the annular space will contribute to settlement more than a few feet above the bore.

The carrier pipe for this project will be either 24-inch nominal diameter FPVC pipe or 30-inch HDPE pipe. To meet Caltrans' encroachment requirements, this pipe will be installed within either an FPVC or HDPE casing with an outside diameter of 32 or 42 inches, respectively. Our settlement analysis for Highway 163 assumed the most conservative case of the 42-inch OD casing pipe, installed with a 6-inch radial overcut (54-inch diameter completed bore). The analysis assumed a soil friction angle (φ) of 32°, corresponding to the fine silty sand soils encountered in the geotechnical investigation. We assumed that approximately 10% of the annular space volume will contribute to settlements above the bore.

For the Boy Scouts' driveway analysis, we used the same conservative assumption of a 54-inch bore. However, the relevant pipe diameter at this location would be the carrier pipe OD of 30 inches, due to the partial-casing option. We used the same friction angle (φ) of 32°; however the net volume of annular space contributing to settlement was increased to 25% due to the lower earth cover, and subsequent reduction in soil mass bulking and arching capacity.

Maximum expected settlements were estimated for the Highway 163 roadway where the bore has a minimum of 32 feet of vertical cover, and for the Boy Scouts' driveway where the bore has a minimum cover of 16 feet. The maximum estimated settlement of Highway 163 due to the proposed HDD bore is approximately 0.4 inches for a vertical clearance of 32 feet. This level of settlement represents a low risk of damage to Caltrans' facilities. At the Boy Scouts' driveway where only 16 feet of vertical cover exists above the bore, maximum settlements are estimated to exceed 2.5 inches. This is due primarily to the very large annulus. Additionally, during the drilling process the low earth cover presents an unacceptable settlement risk that could endanger motorists using the driveway if the bore were to collapse. To mitigate this risk, the driveway would have to be closed during most of the bore construction. Alternatively, the bore will be stabilized by installing a steel conductor casing after the pilot bore is complete. The casing prevents settlement or collapse of the soils above the bore during subsequent reaming and pullback, providing for safe access to the driveway during construction.

## 9. HYDROFRACTURE EVALUATION

Hydrofractures, or inadvertent drilling fluid returns to the ground surface, are a serious concern for any HDD crossing. An analysis of the hydrofracture risk for this project was performed based on the Delft Cavity Expansion Model, (Bennett and Wallin, 2008, Staheli, et. al., 1998; Delft Geotechnics, 1997; Luger and Hergarden, 1988). The cavity expansion model provides a rational method to calculate the maximum allowable drilling fluid pressure that the soil can withstand before plastic yield, or hydrofracture, occurs at any point along the bore. The maximum allowable pressure is the safe upper bound value of allowable drilling fluid pressures for the HDD bore, and is dependent on depth of earth cover and the soil characteristics. The calculations assume homogeneous soil properties within each layer.

The minimum required pressure to return the soil cuttings back to the surface was evaluated using the Bingham Plastic Model and assuming laminar flow conditions. The laminar flow approach generates a conservative result since the conditions will more likely be a combination of laminar and turbulent flow. The minimum required pressure is dependent on the length, depth, and diameter of the bore, as well as the drilling fluid properties.

The results when using this method for analyzing hydrofracture risk are primarily dependent on the geotechnical conditions and the bore geometry. Representative average geotechnical parameter values were selected based on review of geotechnical borings B-5 through B-9. The engineering properties of the crossing included predominantly dense to very dense silty sand. The soil parameters used in the analysis were as follows: soil friction angle (φ) 32°; cohesion (c) 0 pounds per square foot (psf); shear modulus (G) 225,000 psf; and unit weight (γ) 108 pounds per cubic foot (pcf). Groundwater was assumed to be at an elevation of 150 feet. The results of the evaluation of hydrofracture risk for the proposed geometry of the pilot bore are shown in Figure 9.

Two adjustments were made to the ground surface used in the analysis. First, it was indicated by IEC that the upper approximately 10 feet of soil beneath Highway 163 may consist of non-engineered fill placed many decades ago. To account for the reduction in hydrofracture resistance due to the fill, half of this presumed fill depth was removed from the analyzed ground surface. The second adjustment was made to address the risk associated with the side canyon that runs parallel to the proposed bore, south of the pedestrian path, between Highway 163 and Vermont Street. Along this section of the bore, the drilling fluid may take a shorter path to the ground surface by coming out along the side slope of the canyon south of the bore, rather than directly above the bore. To account for this risk, cross-sections were prepared every 50 feet along this section of the bore and the shortest radial distance to the ground surface at each section was then used to generate the ground surface. Each of these adjustments is shown in Figure 9 above.

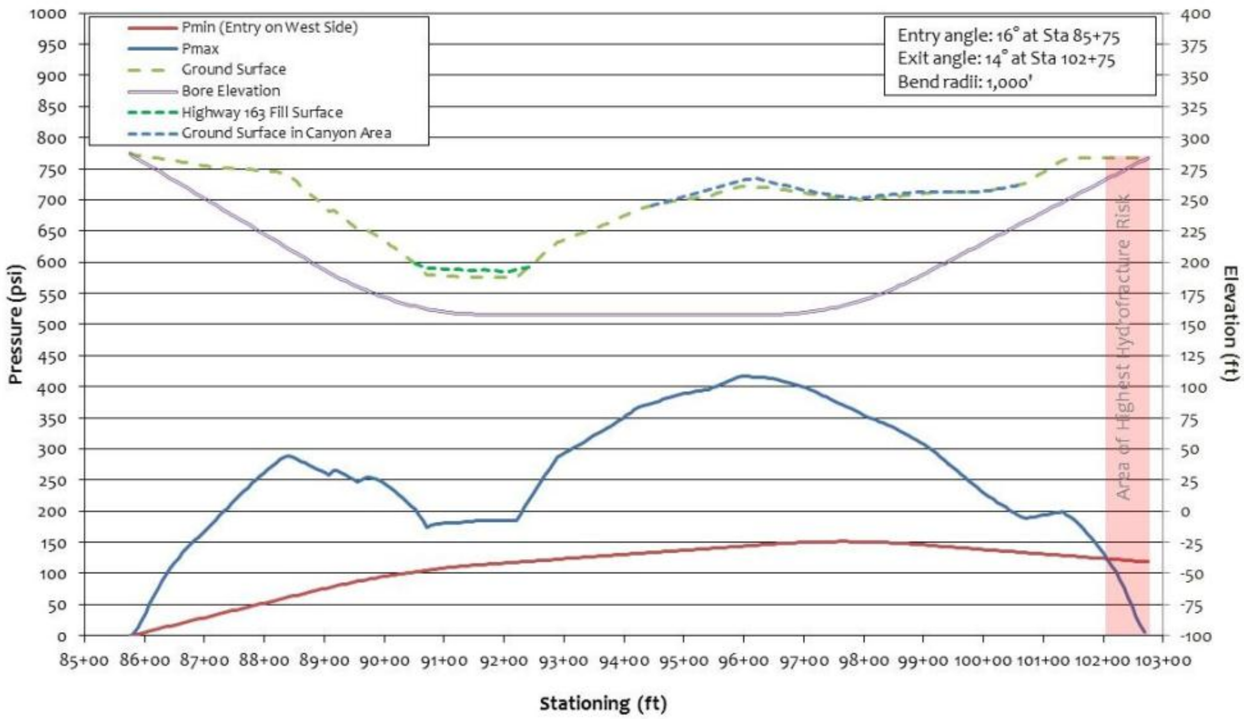


Figure 9. Evaluation of Hydrofracture Risks - Comparison of Maximum Allowable and Minimum Required Drilling Fluid Pressures for the Pilot Bore of the CA Highway 163 Crossing

The results shown in Figure 9 indicate that the risk of hydrofracture is low for the portions of bore with low earth cover, both beneath Highway 163, and beneath the pedestrian trail near Station 100+00. Because the depth of cover decreases toward the exit point, there is an elevated risk of hydrofracture approximately 75 feet before the exit point. This risk is typical for all HDD bores and will be mitigated through common measures including specifying that the Contractor have tools and equipment on-site for rapid containment and clean-up of any inadvertent fluid returns. The contractor will also be asked to develop a detailed Surface Spill and Hydrofracture Contingency Plan for the project that describes the planned response in the event of an inadvertent drilling fluid return. Additionally, the conductor casing included for protection of the Boy Scouts' driveway from excessive settlement will also provide containment of drilling fluid in this section of the bore, preventing hydrofracture.

## 10. CONCLUSION

Through the use of careful design evaluations, advanced logistical planning, and some unique design features, it is anticipated that the Upas Street Replacement Pipeline crossing of CA Highway 163 will provide the City of San Diego with a valuable upgrade to their water transmission system while protecting some of the unique features of the historic Balboa Park neighborhood.

Design of the Upas Street crossing of CA Highway 163 has been completed, however construction is not anticipated until 2016 due to City of San Diego phasing and budget planning.

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