Effects of Tar on CPT and Shear Wave Velocity Correlations for the LA Metro Purple Line (D-Line)

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ABSTRACT

The Los Angeles (LA) Metro Purple Line (D-Line) Extension project requires the design and construction of deep station excavations and tunnels for rail transit from downtown to west LA. The tunnel alignment for Reach 2 of the Westside Purple Line Extension 1 construction transects naturally-occurring tar-infused soils, which have been known to cause challenging construction conditions in southern California, as well as many other locations around the world. Two stations in similar geology but located within and outside tar soils were compared. The soil investigations of the tunnels and station excavations consisted of subsurface exploration including deep soil borings, Cone Penetration Testing (CPT), seismic velocity measurements, pressuremeter testing, and gas measurements, among others. The results of CPT and shear-wave velocity testing provide extensive data in tar soils unique to Southern California and an opportunity to increase our understanding of four-phase soil materials and the effects of tar on soil behavior interpretation and engineering properties. CPT correlations for conventional (non-tar-infused) soils were found to be inadequate for tar soils in the Los Angeles basin. The CPT based Soil Behavior Type Index (SBTn) determined in tar soils suggested the presence of much finer-grained material than determined from laboratory testing and field observations. Additionally, the presence of tar soils amplified the difference between CPT correlations for shear wave velocity (V_s) and direct V_s seismic CPT measurements.

INTRODUCTION

The tunnel alignment in Reach 2 of the LA Metro Purple Line (D-Line) Extension (legally referred to as the Westside Subway Extension Project, Section 1, Contract C1045) is located along Wilshire Boulevard, from the La Brea Station to the Fairfax Station (see Figure 1 below). The tunnels in Reach 2 cover a distance of approximately 0.84 miles (1.35 kilometers), with an invert depth from about 65 to 120 feet (20 to 37 meters) below ground surface. A large portion of the Reach 2 alignment crosses through the Salt Lake Oil Field, which contains soil that is partially to nearly completely saturated with bitumen. In this paper, the bitumen-impacted soil is simply referred to as "tar soil."

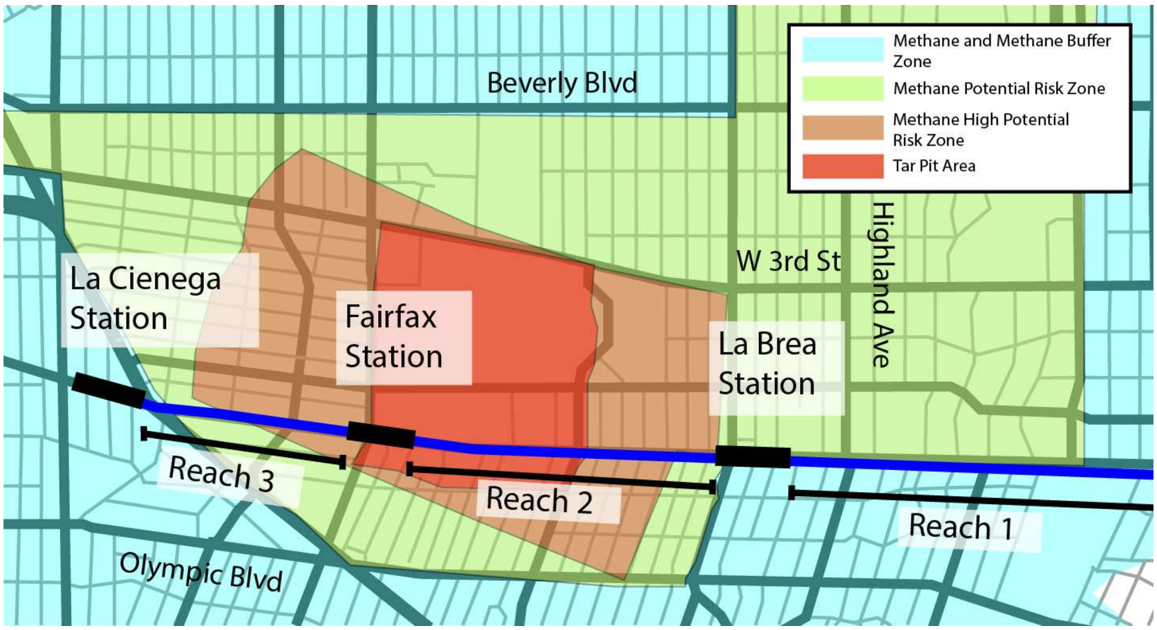


Figure 1. Tar Pit and Methane Zones in the Vicinity of Reach 2 (After City of Los Angeles, 1985)

Tar soils (also termed in literature as oil sands, tar sands, or bituminous soils) are deposits that have been partially saturated with naturally-occurring heavy hydrocarbon that typically has migrated upward from deep petroliferous source rock to near-surface sediments. The hydrocarbon (herein termed "bitumen") is a visco-elastic fluid that has a temperature-dependent behavior. Traditional soil is a three-phase material (solids, water, air); however, the presence of bitumen results in a unique four-phase material (solids, water, gas, and bitumen).

Tar soils are most notably encountered in Athabasca Canada, Los Angeles USA, Eastern Venezuela, and China, and have been documented in nearly every continent around the world. However, the published research on the engineering properties of tar soils is mostly limited to laboratory testing related to petroleum resource extraction in Canada (e.g., Ward & Clark 1950, Dusseault & Morgenstern 1978, and Agar et al. 1987). Published literature on the results and interpretation of in-situ testing in tar soils is very scarce. Examples include Standard Penetration Testing (SPT) of tar soils in Athabasca, Canada (Carrigy, 1967) and load testing results of deep foundation elements embedded in tar soils in Los Angeles, USA (Deane et al., 2018). The testing results indicate high penetration resistance of the dense Athabasca tar soils and high load capacities of the deep foundations in Los Angeles. However, the testing programs were limited and the effects of tar on the results were not conclusive.

Cone Penetration Testing (CPT) is an important site characterization method for large underground projects. It involves the relatively rapid collection of large amounts of continuous data for identifying subsurface stratigraphy, correlations with engineering soil properties, and groundwater conditions. With tar soils, the use of soil borings for site characterization can be problematic with respect to borehole stability and costly/difficult disposal of drilling cuttings. The use of CPTs can be effective in reducing the number of soil borings needed for site characterization. However, there is no available literature on the use of conventional methods of CPT interpretation in naturally-occurring tar soil. Abdelhalim et al. (2021) represents one of the few publications which discusses CPT performed in mixed, oil-contaminated sands at a small-scale. Like similar papers, the study seeks to simulate in-situ conditions near oil mining fields in typical oil export regions (e.g., Saudi Arabia, Iraq, UAE, etc.), and concluded that the presence of oil in sandy soils reduced the cone resistance and sleeve friction. Since processed oil (refined petroleum) and tar can potentially behave very differently in their in-situ conditions (i.e., processed oil has a much lower viscosity, whereas natural bitumen occurs over a range of higher viscosities), the results are used for reference only.

Development of shear wave velocity profiles is a critical step for design and analysis of underground construction, especially in seismically active areas. Shear wave velocity profiles are used for site response analysis as well as the design of the excavation support system and assessment of settlement potential during tunneling. To date, there is no literature available on the effects of tar on shear wave velocity or correlations for shear wave velocity.

SUBSURFACE CONDITIONS

The subsurface exploration for Reach 2 consisted of in-situ and laboratory testing of the tar and non-tar soils. The depth to top of tar varied from about 5 to 55 feet (1.5m - 17m) below ground surface, with the majority of tar soils located within the Lakewood and San Pedro Formations. Table 1 presents the geologic units encountered in Reach 2. The primary soil type is provided in terms of symbols using the Unified Soil Classification System (ASTM D2487).

Table 1. Subsurface Soils Encountered in Reach 2

Geologic Unit		Layer Thickness	Primary Soil Type	Deposition Age	Presence of Tar
Artificial Fill (Af)	-	-	SC, SM, CL	-	None
Older Alluvium (Qalo)	Alluvial deposits	Up to 15 ft (5 m)	CL, CH, SM	Late Pleistocene	None to slightly infused
Lakewood Formation (Qlw)	Marine and non-marine deposits	Up to 40 ft (12 m)	CL, ML, SM	Late Pleistocene	None to fully infused
San Pedro Formation (Qsp)	Marine deposits	40 to 90 ft (12 to 27 m)	SM, ML, SP-SM	Early to Mid Pleistocene	None to fully infused
Fernando Formation (Tf)	Marine deposits	-	Siltstone	Early Pleistocene	Fully infused

The subsurface exploration for the Reach 2 tunnel alignment and stations was performed in 2009 to 2013, and consisted of 16 rotary wash borings, seven sonic core borings, and seven cone penetration tests (CPTs). Seismic measurements, including shear wave velocity tests, were collected at three of the borings (OYO Suspension Logging) and seven of the CPTs (Seismic CPT). The soil borings and CPTs evaluated as part of this paper are presented in Figure 2.

Figure 2. Reach 2 CPTs and Soil Borings Evaluated for this Study. Upper Image: Western Portion of Reach 2, Lower Image: Eastern Portion of Reach 2

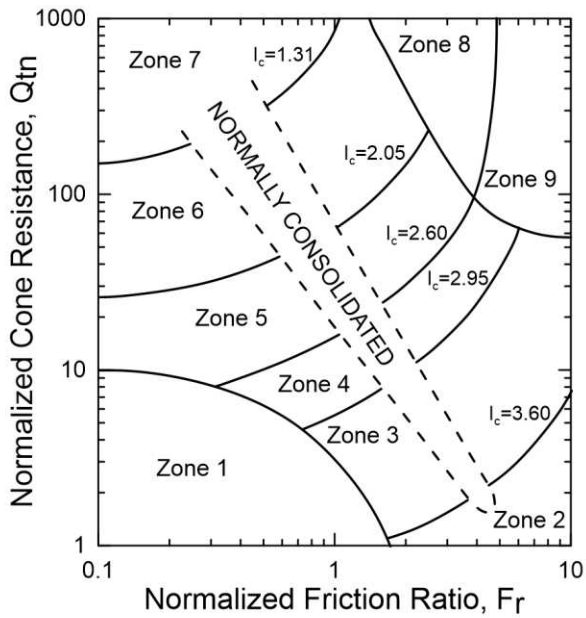
SOIL BEHAVIOR TYPE

The CPT data was evaluated to investigate the effects of tar on the interpreted and physical properties of the soil. For Reach 2, four CPTs were performed in tar soils (C-350, C-103, C-104, C-111) and two CPTs were performed in non-tar soils (C-110, C-101). Robertson (1986) developed a method for predicting soil type based on CPT data termed Soil Behavior Type (SBT). The method has since been updated to include effects of effective overburden stress (SBTn) and pore pressure, resulting in nine Soil Behavior Type zones (Robertson & Cabal, 2015). The Soil Behavior Type Index (I_c) is a numerical representation of boundaries between the soil behavior types in the SBTn chart, although Zones 1, 8, and 9 do not have a corresponding I_c. The SBTn chart and I_c boundaries are presented below.

Following Robertson and Cabal (2015), I_c can be determined as:

$$I_c = ((3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2)^{0.5} \tag{1}$$

from which Q_t = normalized cone penetration resistance $= (q_t - \sigma_{vo})/\sigma'_{vo}$, F_r = normalized friction ratio, in % $= (f_c/(q_t - \sigma_{vo})) \times 100\%$, q_t = cone tip resistance, and σ_{vo} = total stress and σ'_{vo} = effective stress, both at the elevation of tip resistance.



Zone	*Soil Behavior Type*	*I_c*
1	*Sensitive, fine grained*	N/A
2	*Organic soils – clay*	> 3.6
3	*Clays – silty clay to clay*	2.95 – 3.6
4	*Silt mixtures – clayey silt to silty clay*	2.60 – 2.95
5	*Sand mixtures – silty sand to sandy silt*	2.05 – 2.6
6	*Sands – clean sand to silty sand*	1.31 – 2.05
7	*Gravelly sand to dense sand*	< 1.31
8	*Very stiff sand to clayey sand**	N/A
9	*Very stiff, fine grained**	N/A

* *Heavily overconsolidated or cemented*

Figure 3. Cone Penetration Testing Soil Behavior Type Charts (After Robertson & Cabal, 2015)

I_c profiles for two CPTs in non-tar impacted soils and four CPTs in tar impacted soils were developed using Equation 1 and are presented in Figures 4a-b and c-f, respectively for the estimated SBT Zones 2 through 7. Data from the nearest soil boring to each CPT was analyzed separately to determine equivalent SBT profiles based on laboratory testing results and field observations (e.g., using fines content, plasticity index, and boring log descriptions). The latter analysis represents an estimation of the soil behavior type and is indicated in Figures 4a-f as a grey shaded zone in conformance with the range of I_c in Figure 3. In addition, Figure 4 displays the fines content and the tar content whenever determined through lab testing.

All borings presented in Figures 4a-f encountered a sandy (SP, SP-SM) portion of the San Pedro Formation that corresponds to Zone 6 (sands – clean sands to silty sands), where the fines content decreases to below 12% (as low as 1.2%). When tar soils are not encountered (Figures 4a and 4b), the CPT-based I_c falls within Zone 6. However, wherever tar soils were encountered (Figures 4c through 4f), the sandy portion of the San Pedro Formation is generally classified by the CPT-I_c as Zone 5 (Sand Mixtures – silty sands to sandy silts). The classification of Zone 6 soils as Zone 5 soils is due to an increase in I_c. An evaluation of the input parameters for I_c from Equation 1 suggests that the presence of tar results in a decrease of total cone resistance and/or increase in sleeve friction; this results in an increase of I_c. This observation implies that the Soil Behavior Type interpretation for conventional soils does not necessarily apply to tar soils. The increase in sleeve friction (compared to the reduction in sleeve friction as observed for CPT in oil sands by Abdelhalim et al. (2021)) is likely associated with the unknown in-situ consistency of the bitumen. A non-liquid consistency of the sticky tar/bitumen material can potentially increase the side friction due to adhesion to the CPT cone. Further evaluation of the soil conditions and corresponding cone penetration data (tip, sleeve, and pore pressure) are needed to develop a CPT interpretation for tar soils. This effort is currently underway and a new testing program to evaluate CPT correlations for tar-infused soils has been developed.

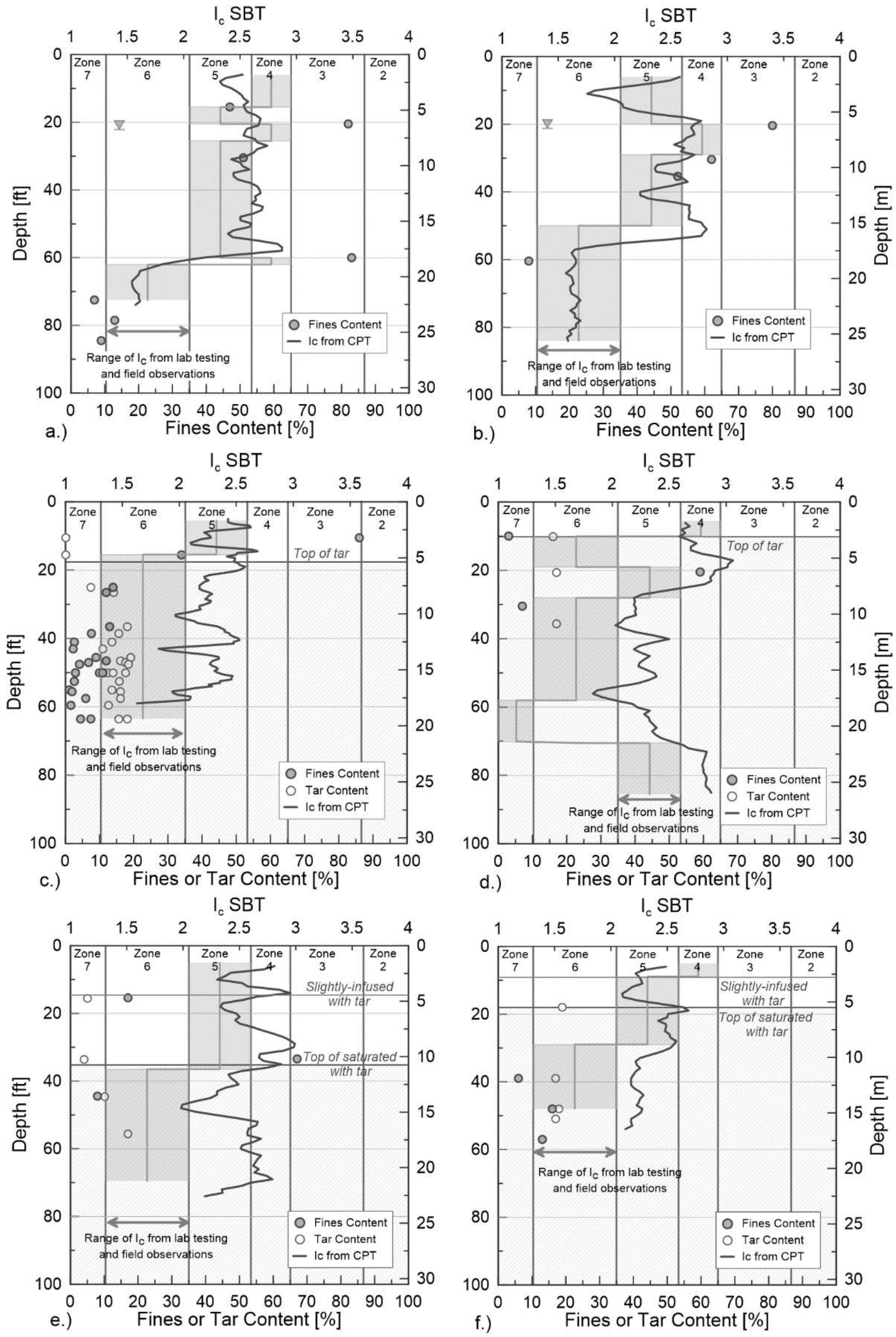


Figure 4. Soil Behavior Type Estimated by CPT Ic and Field Observations/Laboratory Testing for Reach 2 a.) CPT C-110 & Boring G-308 (20 ft, 6 m apart), b.) CPT C-101 & Boring S-104 (220 ft, 67 m apart), c.) CPT C-350 & Borings G-350/S-350/G-351 (33-55 ft, 10-17 m apart), d.) CPT C-103 & Boring G-121 (200 ft, 61 m apart), e.) CPT C-104 & Boring G-123 (110 ft, 34 m apart), f.) CPT C-111 & Boring S-116 (110 ft, 34 m apart).

SHEAR WAVE VELOCITY

Shear wave velocity is a critical engineering soil property for design of underground construction. Direct measurement of shear wave velocity was performed with OYO suspension logging at three locations (two located in tar soils) and seismic CPT (SCPT) at six locations (five in tar soils). Selected V_s measurements are presented in Figure 5 and distinguish between those in soil saturated with tar and not saturated with tar. Above the top of tar, the V_s profiles are shown to be not saturated with tar. The presence of tar does not clearly show an effect on V_s.

Below about 60 ft (18 m) deep, both soil types have V_s within 200 ft/s (60 m/s) of each other. Above 60 ft (18 m) deep, the V_s measurements are quite variable, likely due to the variability of soil type and geologic formation (Older Alluvium, Lakewood, and San Pedro Formations) across Reach 2.

At each SCPT location, four CPT-V_s correlation equations were considered and compared to the direct V_s measurements (Figure 6) to identify the effectiveness of established correlations and their applicability within tar soils. The correlations consider different variables with a combination of CPT tip resistance, sleeve friction, I_c, effective stress, and depth, as shown in Table 2.

Each SCPT measurement was compared to the predicted value at the same depth, and a scatterplot of the data is presented in Figure 7. Many of the non-tar V_s measurements are lower due to the shallower location above the depth of tar (see Figure 6).

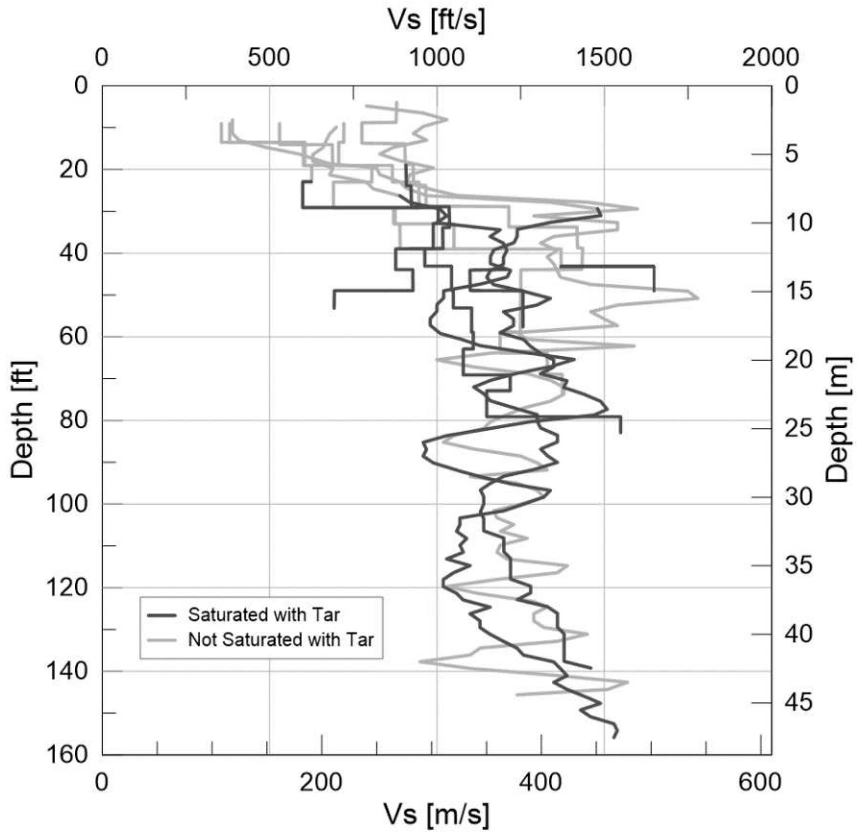


Figure 5. Comparison of Shear Wave Velocity Profiles from Seismic CPTs and OYO Suspension Logging in tar-infused and non-tar soils

Table 2. CPT-Vs Correlation Equations

Correlation	Age of Deposits	Soil Type	V_s Equation (m/s)	Location
Eq. 1 Robertson (2009)	Quaternary	All	$\left[\left(10^{(0.55I_c+1.68)}\right)\ (q_t-\sigma_v)/p_a\right]^{0.5}$	Worldwide
Eq. 2 Andrus et al. (2007)	Holocene & Pleistocene	All	$\left[\left(10^{(0.55I_c+1.68)}\right)\ (q_t-\sigma_v)/p_a\right]^{0.5}$	California, Japan, South Carolina
Eq. 3 Mayne (2006)	Quaternary	All	$118.8\log(f_s)+18.5$	Worldwide
Eq. 4 Piratheepan (2002)	Holocene	All	$32.3q_c^{0.089}f_s^{0.121}D^{0.215}$	California, Japan, Canada

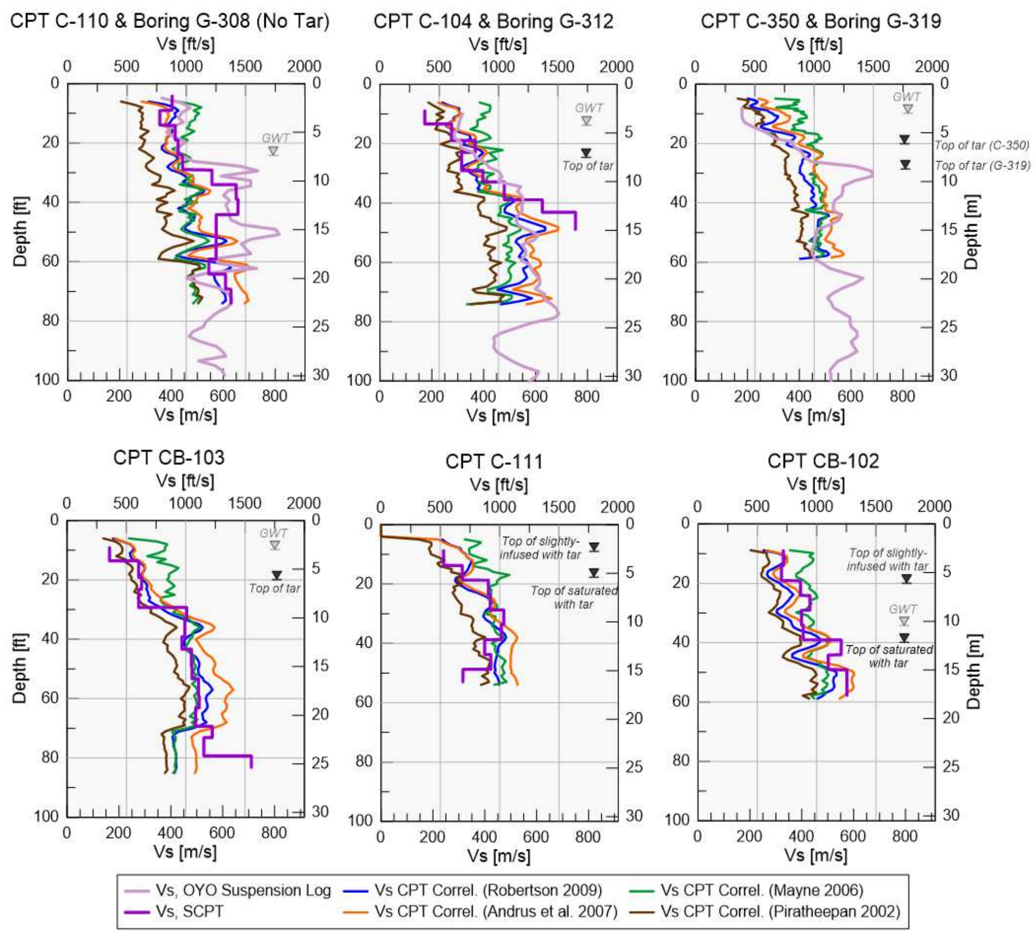


Figure 6. Shear Wave Velocity Profile Measurements and CPT-Vs Correlations

The difference between each V_s measurement and the respective predicted value for each of the four equations was calculated (ΔV_s) and is shown in Figure 8a for non-tar soils and 8b for tar soils. The V_s-CPT correlations within the dataset (tar and non-tar soil) tend to overpredict V_s at lower values (less than about 700 ft/s, 200 m/s) and underpredict V_s at higher values (greater than about 1000 ft/s, 300 m/s).

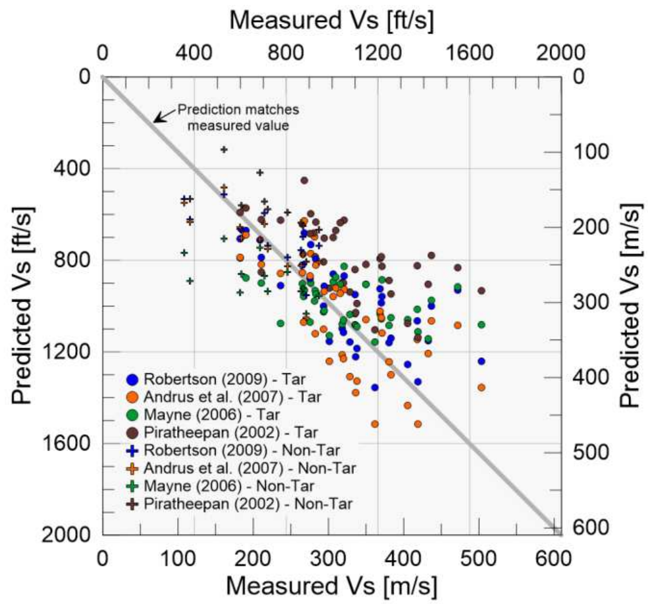


Figure 7. Shear Wave Velocity (V_s) Measured by Seismic CPT and Predicted by CPT data

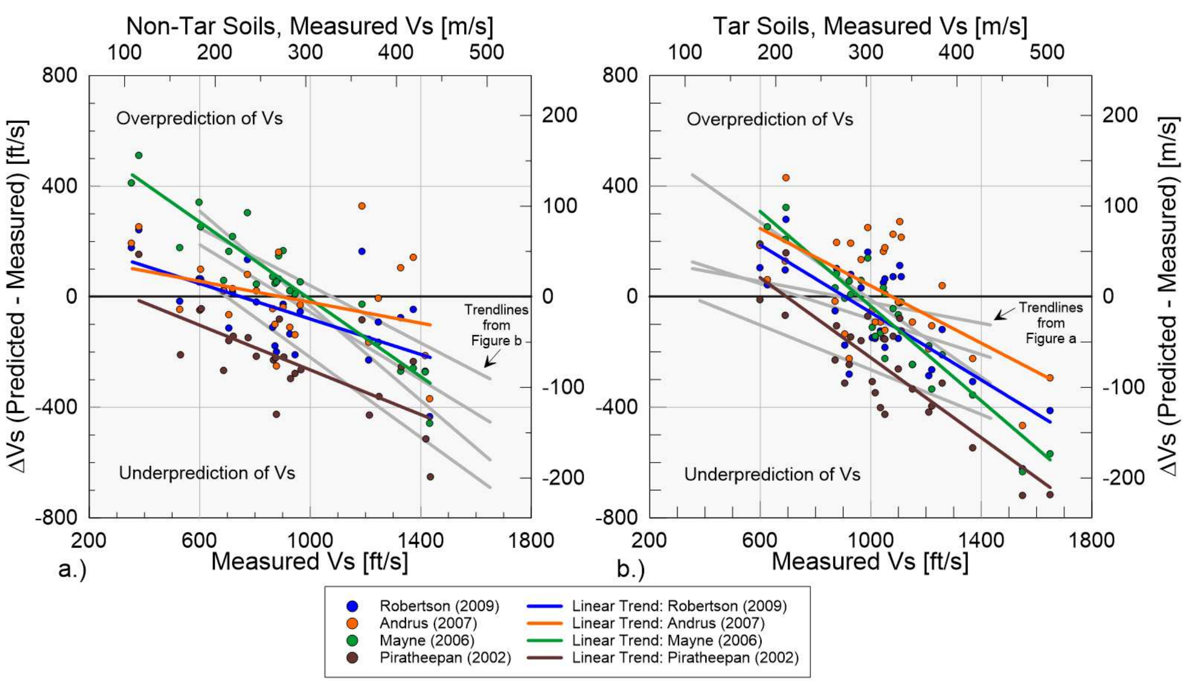


Figure 8. Comparison of Measured and Predicted Shear Wave Velocity (V_s) for Non-Tar (a) and Tar Soils (b).

For non-tar and tar soils, the V_s-CPT correlations utilizing I_c and q_t (Eqs. 1 and 2) result in the best prediction of V_s, as I_c accounts for soil behavior type and q_t accounts for pore pressure effects. As shown in Table 3, the slopes of the linear regression for each equation are greater for tar soils than non-tar soils, while the average ΔV_s is generally similar. This suggests that the presence of tar decreases the effectiveness of the V_s-CPT correlations.

Table 3. Linear Regression for Vs-CPT Prediction Equations of Non-Tar and Tar Soils

Correlation	Non-Tar Soils			Tar Soils		
	Avg. Δ	Equation Linear Regression (US Units)	r^2	Avg. Δ	Equation Linear Regression (US Units)	r^2
Eq. 1 Robertson (2009)	-49	$\Delta V_s = -0.32 * V_s + 241$	0.41	-79	$\Delta V_s = -0.61 * V_s + 555$	0.54
Eq. 2 Andrus et al. (2007)	-3	$\Delta V_s = -0.19 * V_s + 168$	0.13	21	$\Delta V_s = -0.52 * V_s + 559$	0.38
Eq. 3 Mayne (2006)	58	$\Delta V_s = -0.70 * V_s + 690$	0.88	-67	$\Delta V_s = -0.86 * V_s + 822$	0.86
Eq. 4 Piratheepan (2002)	-222	$\Delta V_s = -0.41 * V_s + 140$	0.50	252	$\Delta V_s = -0.72 * V_s + 503$	0.70

CONCLUSIONS

The effects of naturally-occurring tar on engineering properties and in-situ characterization were evaluated from CPT and shear wave velocity data as part of Reach 2 of the Purple Line (D-Line) Extension LA Metro project. The data reviewed included tar and non-tar soils encountered as part of the Reach 2 subsurface exploration. The following findings were made:

- The Soil Behavior Type (SBT) determined from conventional Cone Penetration Testing (CPT) methods does not necessarily apply to tar soils. In sandy tar soils, the SBT interpreted from CPT is finer grained than as determined by laboratory testing and field observations, which may be caused by an increase in total cone resistance or decrease in sleeve friction. In contrast, for sandy non-tar soils, the SBT interpreted from CPT is representative of the soil type.
- Shear wave velocity (V_s) measurements were performed by OYO suspension logging at three locations (two in tar soils) and seismic CPT (SCPT) at five locations (four in tar soils). At depths greater than about 60 feet, the V_s was measured to be similar for tar and non-tar soils. At depths less than about 60 feet, the V_s was measured to be widely varying, and effects of tar need to be further investigated.
- Four methods for estimation of shear wave velocity (V_s) based on CPT data were compared for tar and non-tar soil. Each direct measurement of V_s from SCPT was compared to the predicted values. The correlations tended to overpredict V_s at lower measured V_s and underpredict at higher measured V_s. This trend was amplified for tar soils.

Further analysis to improve the interpretation of CPT data in tar infused soils is needed. For this purpose, an additional experimental and analytical program has been developed, and is currently underway by the authors. This additional study will focus on quantifying the offset of SBT, the change in P-wave velocity, potential effects on shear wave velocities, and the change in effective soil permeability due to the presence of tar.

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