CHAPTER 5 – ANALYSIS AND INTERPRETATION

ANALYSIS OF INTERPRETED BOND STRENGTH DATA

Figure 13 contains the interpreted bond strength data for all sites and installation methods. Mobilized bond stress values in test nails that did not fail are marked with an asterisk (*). It is noted that the values shown correspond to average interpreted bond strength along the bond length of the nail, and may not be representative of larger, localized values along the bond zone. The average interpreted bond strengths are likely affected by the displacement-softening and post-peak reduction of shear strength phenomena that typically occur at the interfaces between structural materials and granular soils (Gómez et al. 2003). Littlejohn et al. (1977) provide an extensive discussion on the variation of mobilized bond stress along tiebacks and anchors that is also directly applicable to soil nails.

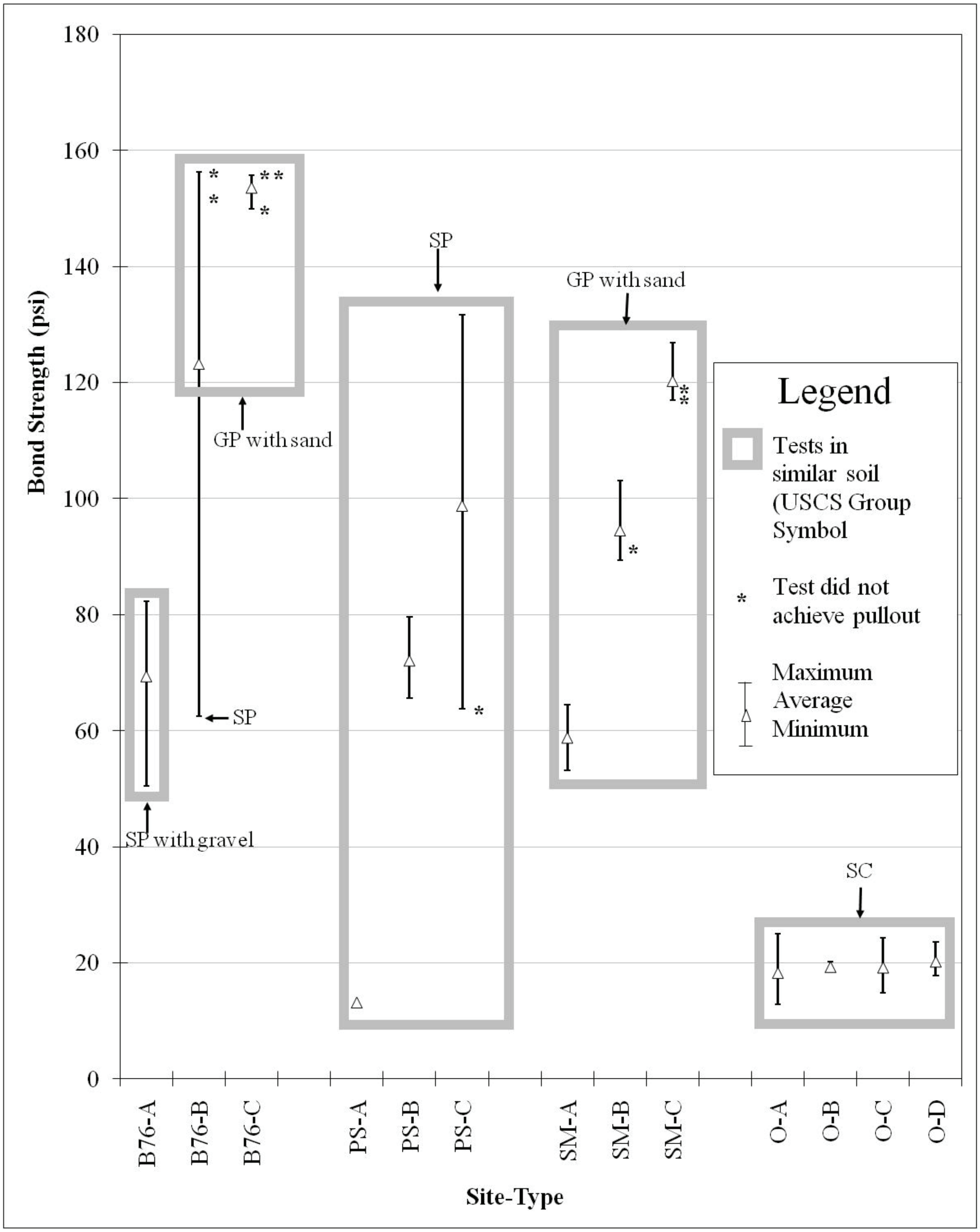

Figure 13. Graph. Interpreted bond strength for the HBSN and SBSN.

As shown on Figure 13, the bond strength along the test nails ranged from approximately 10 psi to a maximum of 155 psi. Two key points are observed in the data and are further discussed in this chapter: (1) The data shows that the bond strength along the HBSNs was generally larger than the bond strength along the SBSNs, especially in clean sands and gravel. (2) The data also shows that the average bond strength calculated based on Equation (2) was generally larger in soil nails debonded according to Method C than in those debonded using Method B.

The bond strength data was normalized by dividing the bond strength of each test nail at a site by the average bond strength measured in Type A nails (SBSNs) at that same site. The normalized bond strength data is shown in Figure 14. It can be seen that the bond strength along the HBSNs installed using Method B was generally more than 1.5 times larger than the bond strength along the SBSNs installed using Method A. The difference in bond strength is likely due to the effect of the HBSN grouting procedure on the surrounding soil, which results in a larger grout body with considerable surface roughness.

Test HBSNs debonded using Method C generally yielded bond strength values that were significantly larger than those measured in Method B nails. The larger values measured in the Method C nails are likely an artifact of the contribution of the grout annulus left above the bond zone and around the free length of the nails, which is a product of the installation procedure. Consequently, the following discussion focuses on the bond values interpreted from the test SBSNs installed using Method A, and the test HBSNs debonded using Method B.

It is important to note that five of the eight test HBSNs in the gravel did not reach failure. Therefore, in these test nails, the actual average bond strength is larger than that given by the maximum test load.

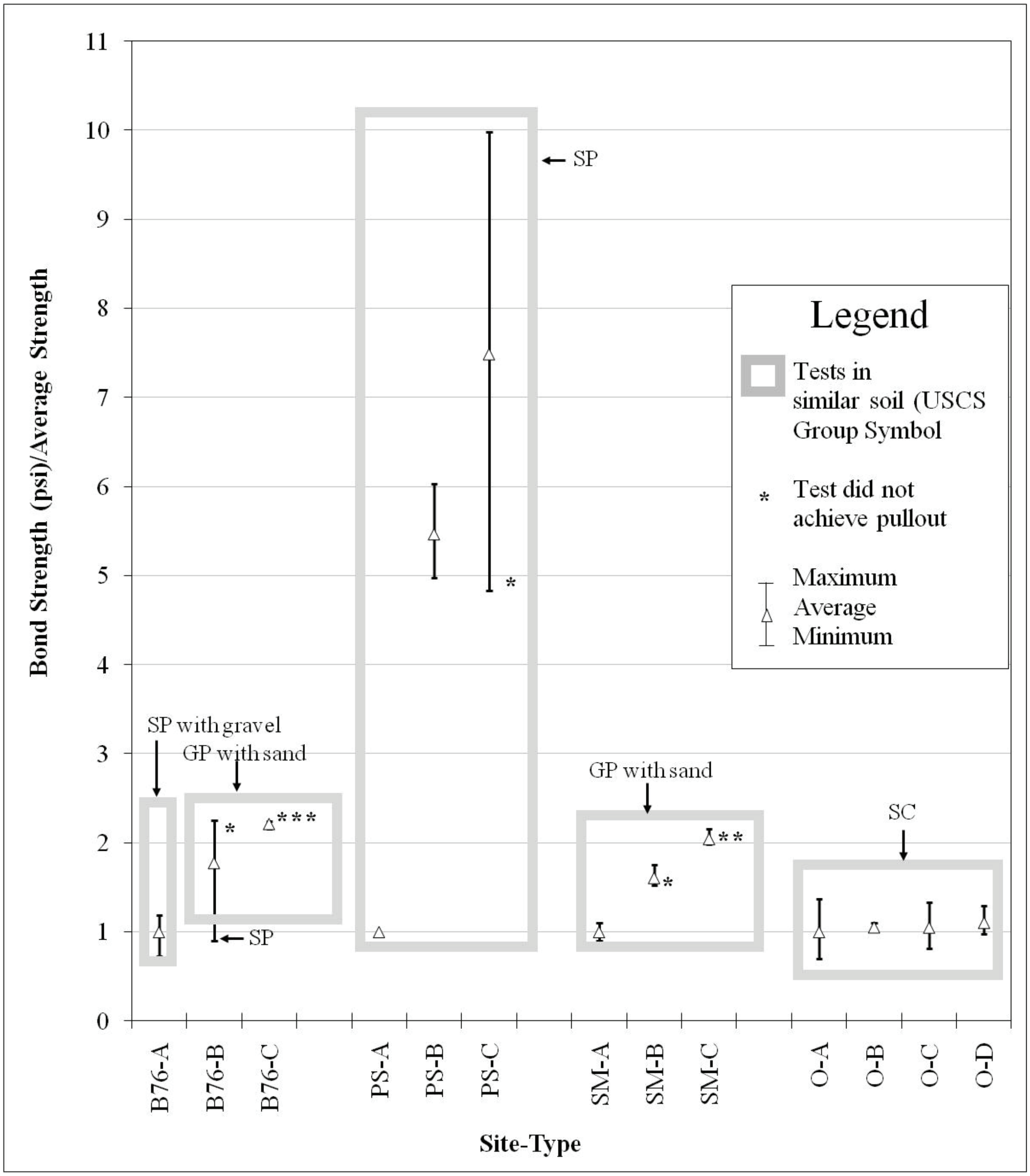

Figure 14. Graph. Normalized interpreted bond strength.

Table 8 contains the ranges of bond strength values for gravity-grouted rotary drilled SBSNs given in GEC 7 (FHWA, 2003) for various types of soils that generally correspond to those encountered in the sites chosen for this investigation. The tests on SBSNs yielded bond strength values that are within the range of values given in FHWA (2003) for silty sand and poorly graded sand. However, the test results suggest that the values in FHWA (2003) are conservative for gravelly sand and sandy gravel similar to those tested in this study. The bond strength values interpreted from HBSN tests were all larger than those given by FHWA (2003) for gravity-grouted nails.

Table 8. Range of bond strength by soil type and installation method.

Soil Type	FHWA (2005) Rotary Drilled Grout-to-Ground Nominal Strengths / *Jet Grouted* psi (kPa)	Grout-to-Ground Nominal Strengths			
		Installation Method A psi (kPa)	Installation Method B psi (kPa)	Installation Method C psi (kPa)	Installation Method D psi (kPa)
Silty Sand (SM)	14.5-21.8 (100-150) *55.1* *(380)*	12.8-17.1 (88-118)	18.7-24.4 (129-168)	*not performed	17.8-23.7 (123-163)
Poorly Graded Sand (SP)	14.5-26.1 (100-180) *55.1* *(380)*	13.2 (91)	71.2-79.6 (491-549)	63.7-131.7 (439-908)	-
SP with Gravel	14.5-26.1 (100-180) *101.5* *(700)*	50.5-82.2 (348-567)	-	-	-
GP with Sand	14.5-26.1 (100-180) *101.5* *(700)*	53.2-64.5 (367-445)	62.4-156.3 (430-1059)	116.9-155.7 (806-1074)	-

There was no significant difference between the bond strength values interpreted from the tests performed on the HBSNs and SBSNs in clayey sand at the Olympia Site and those given by FHWA (2003).

Con-Tech Systems Ltd. (CTS), supplier of the Ischebeck Injection Bore bars, has proposed the use of bond diameter magnification factors (Con-Tech, 2005). The CTS method assumes the injection bore process results in a diameter of the as-drilled hole larger than the bit diameter. CTS establishes enlargement factors for various soil types. It is noted, however, that the actual effective enlargement of a hole would depend on drilling parameters such as drilling rate and grout injection pressure. The normalized bond strength values for the tested HBSNs debonded using installation Method B, which are depicted in Figure 14, correspond to this concept of enlargement factor. The normalized bond strength values (Method B) have been reproduced in Table 9, together with the enlargement factors proposed by CTS.

Bond strength values were calculated applying the magnification factors proposed by CTS to the bond strength values interpreted from tests on soil nails installed using Method A. The CTS bond strength values are compared to the bond strength values interpreted from Method B test nails in Table 9. The bond strength values given by FHWA (2005) for pressure grouted micropiles (Type B) are also shown for comparison. To avoid confusion with Method B soil nails, these micropiles are referred to as "pressure-grouted micropiles" throughout this report.

The bond strength values interpreted from data collected from the four sites are consistent with or larger than the bond strength values calculated using the magnification factor proposed by CTS. They are also consistent with or larger than the bond strength values given by FHWA (2005) for pressure-grouted micropiles in similar soils.

Table 9. Bond strength comparison.

Soil Type	Grout-to-Ground Nominal Strengths			FHWA (2005) Grout-to-Ground Nominal Strengths for Pressure-grouted Micropiles psi (kPa)
	Method A psi (kPa)	Method B psi (kPa)	CTS psi (kPa)*	
Silty Sand (SM)	12.8-17.1 (88-118)	18.7-24.4 (129-139)	1.5 (Factor) 19.2-25.7 (132.4-176.9)	Sand (some silt) 10-27.5 (70-190)
Poorly Graded Sand (SP)	13.2 (91)	71.2-79.6 (491-549)	1.5 (Factor) 19.8 (137)	Sand (some Gravel) 17.5-52 (120-360)
SP with Gravel	50.5-82.2 (348-567)	-	1.5 (Factor) 75.8-123.3 (522.3-851)	Sand (some Gravel) 17.5-52 (120-360)
GP with Sand	53.2-64.5 (367-445)	62.4-156.3 (430-1059)	2 (Factor) 106.5-129 (550-667)	Gravel (some Sand) 17.5-52 (120-360)

* Bond strength values were calculated applying the magnification factors proposed by CTS to the bond strength values interpreted from tests on soil nails installed using Method A.

Exhumed Test Nails

Tested nails were exhumed at three of the sites. Exhumed nails were photographed and logged at the Posillico and Sunset Mesa Sites and only partially photographed at the Block 76 site. The appended data reports for the Posillico and Sunset Mesa Sites provide measurements and photographs of the exhumed nails, which show significant differences between the SBSNs and the HBSNs in both the hole diameter and the uniformity of the hole diameter. The cased method of solid bar installation (Method A) results in a relatively uniform diameter equivalent to the outside diameter of the casing. Little to no grout penetration was observed around the SBSNs as would be evidenced by irregularities and cemented soil around the perimeter of the bond zone. The Block 76 data is not included as it is not complete; however, available photographs are included in Appendix 1.

Comparison of the effects due to the various installation methods (Methods B, C and D), indicates there was significant evidence of limited soil mixing, irregular bond diameter (Table 10), and grout penetration. For the gravel site (Sunset Mesa) large cobbles and boulders were engaged with the bar, which likely generated a “deadman effect” during testing. Typical bonding to gravel at the Sunset Mesa Site is shown in Figure 15.

Table 10. Range of bond zone diameters measured from exhumed nails.

Location	Number of Nails Exhumed	Soil Type	Method A	Methods B and C
Sunset Mesa Site	12	GP with sand	~8"	~8" to ~18"
Posillico Site	12	SP	~7" to 8"	6¼" to 9½"

HBSNs debonded using Method C presented a significant annulus of grout around the debonded free length. This annulus can absorb part of the load that was intended to be transmitted entirely to the bond zone, which is discussed in the following section.

Figure 15. Photograph. Exhumed HBSN at the Posillico Site.

Discussion on Interpreted Bond Values

Based on the test results and observations, the effect of the hollow bar installation process creates an enlarged bond zone. It appears that the enlarged bond zone diameter is due to scour of the soil caused by the grout flow, and permeation of the grout into the granular materials. The resulting grout body has an irregular surface with significant roughness, and has an average diameter that is typically larger than the nominal drill bit diameter.

Additionally, the process of installation of the hollow bar is not likely to induce loosening or decompression of the soils.

In SBSNs, the average diameter of the grout body will depend on the internal roughness of the borehole. An SBSN grout body diameter that is significantly larger than the nominal diameter is most likely an indication of significant loss of soil during drilling. This indication may in turn suggest that there was significant disturbance or loosening of the soils during soil nail installation. Consequently, an SBSN grout diameter that is larger than a nominal drill bit diameter does not necessarily result in a larger capacity of the soil nail. Larger diameter drill holes in Method A test nails were observed at the Posillico Site. Loosening of the poorly graded soils may have been responsible for the low bond strength values interpreted from the tests. The interpreted bond stress values were even lower than those given in GEC 7 (FHWA 2006).

With SBSNs where there is no significant soil disturbance, the grout body diameter will be somewhat similar to the nominal drill bit diameter, and there will be little or no permeation of the grout into the soil. Thus, the average load-transfer ratio, defined as the load shed from the grouted element per unit length (bond strength times the nominal drill hole diameter), will be lower than that of a correctly installed hollow core bar where scouring and permeation of the soils take place.

In medium stiff to hard, fine-grained soils, the scouring and permeation effects of the hollow core bar are minimized. Thus, average load-transfer ratio values would likely be similar to those for correctly installed SBSNs.

In summary, the enhanced grout body shape and the reduced disturbance of the soils are considered to be the two main phenomena that contribute to the enhanced capacity of the HBSNs with respect to that of the SBSNs.

It is important to note, however, that there is insufficient information to evaluate the relative contributions of these factors. The drilling parameters are believed to play a significant role in these factors, and these drilling parameters will vary from project to project. Thus, an estimate of what portion of the bond strength gain in a hollow core bar is due to the increased diameter is not possible at this time.

The Doughnut Effect

The average bond strength values interpreted from tests on HBSNs debonded using Method C are larger than those for Method B soil nails. It is assumed that the difference in average bond strength is a testing artifact, herein referred to as Doughnut Effect, which is inherent to the Method C installation.

Soil nails installed using Method C have a significant annulus of grout around the debonded length of the nail. The load applied to the soil nail through the hollow bar is transferred directly to the bond zone below the free length of the soil nail. However, as the bond zone displaces along its longitudinal axis during loading, it tends to compress the annulus of grout around the free length of the nail. If the grout-filled annulus was small enough that it could not withstand significant compressive force, then this effect would be limited. However, the grouted annulus in the tested nails can likely withstand significant compressive forces. Therefore, a significant portion of the load transferred to the bond zone is transferred back to the annulus of grout along the free length of the nail. A schematic diagram of the forces resulting from the Doughnut Effect is show as Figure 16. Consequently, the actual bond zone length of the soil nail is longer than intended. Therefore, Equation (2) overestimates the average bond strength of Method C nails shown in Figure 13 and in Table 9.

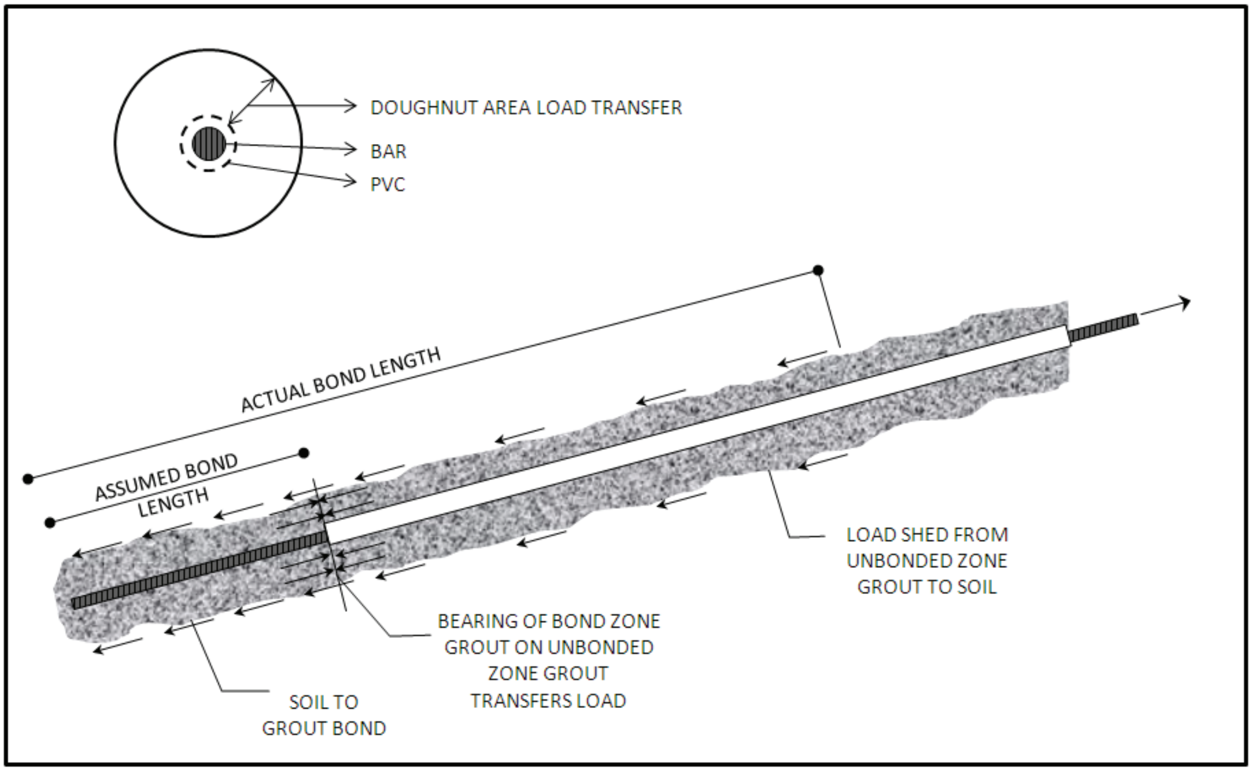

Figure 16. Schematic. Geometry and resistance mechanism of the Doughnut Effect.

The extent to which the annulus along the free length is capable of transferring load to the ground would depend on several factors such as grout-to-ground bond strength along the free length, the compressive strength of the grout, confinement of this grout, the size of the doughnut, and lack of confinement due to the proximity to the excavation face.

It is noted that, for this investigation, 4.5-inch bit diameters were used compared to the 2.5-inch OD smooth PVC sheath. Therefore, given the enlargement of the drill hole, the grout annulus may have been 1.0 to 2.0 inches thick, or even thicker. Such an annulus would be capable of transferring significant axial loads. If a larger PVC bondbreaker or smaller bits are used, the grout annulus may be 0.5 to 1-inch thick, and may not be able to transfer large loads to the free length of the nail. However, such load transfer may still be significant and must be considered for interpretation of the tests.

Based on the data presented in Figures 13 and 14, the Doughnut Effect was not significant in Method C nails installed at the Olympia Site. As noted in Table 7, grout was partially flushed from the unbonded length at this site. It is then possible that the grout annulus did not provide significant added resistance.

The Doughnut Effect may not be significant in Method D nails, where re-drilling of the initial grout may prevent the existence of a significant, intact grout annulus. The remaining grout annulus is likely a relatively thin soil-grout shell of lower strength than the structural grout. It is also possible that the action of drilling deteriorates the pre-installed grout sufficiently to prevent the pre-installed grout from being able to transfer significant axial loads. This method was tried in a relatively fine-grained material where limited scour and grout penetration occurred.

Strain Gauge Data

For the soil nails installed at the Olympia Site, the axial load along the test soil nails during testing was interpreted from the data from strain gauges installed inside the HBSNs. The axial load is shown in Figures 17 through 19. It is important to note that the load tests also included unload-reload cycles. Therefore, the axial load response may have been affected by locked-in axial loads. For simplicity, the plots do not include axial loads during unloading-reloading.

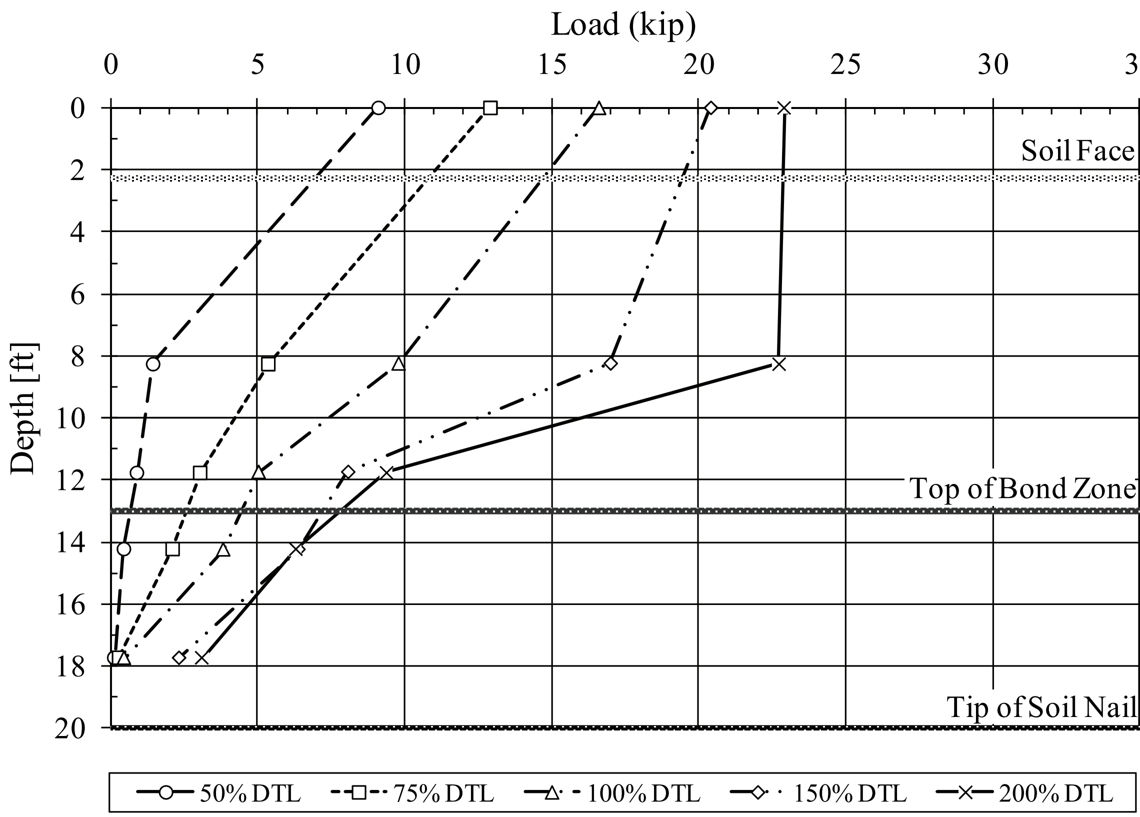

Figure 17. Graph. Load distribution from strain gauges in HBSN B1 (Olympia Site).

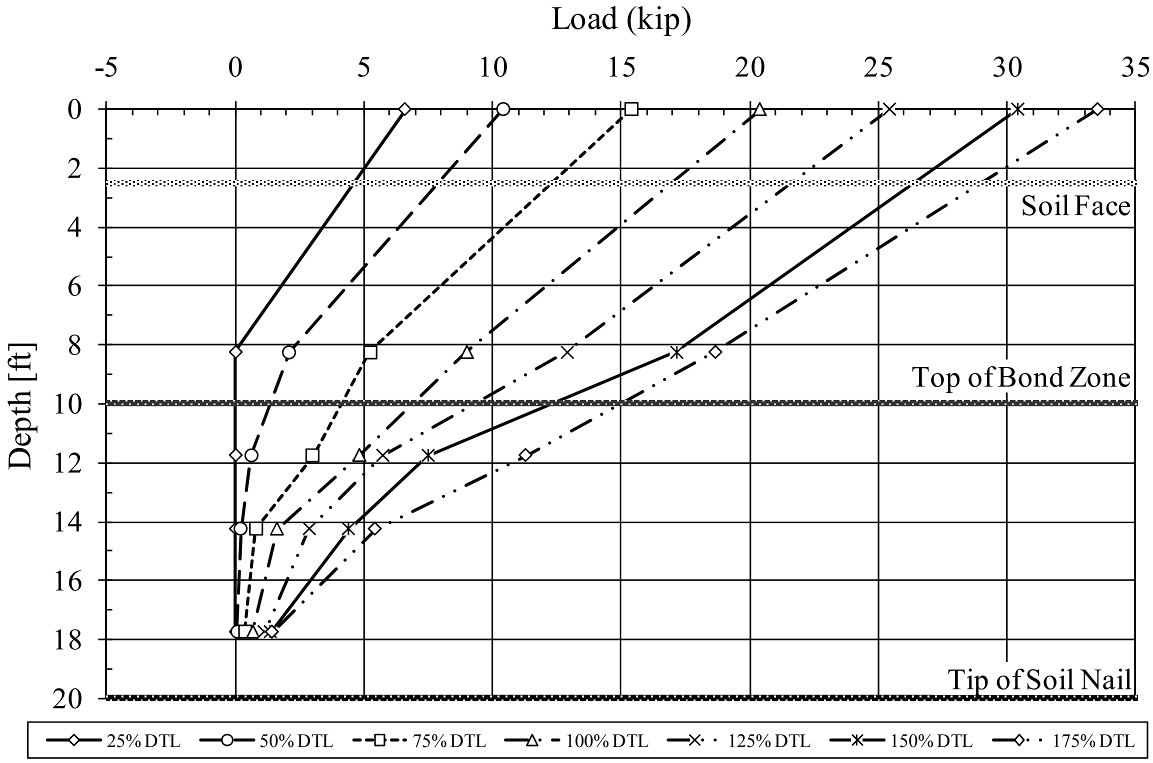

Figure 18. Graph. Load distribution from strain gauges in HBSN C2 (Olympia Site).

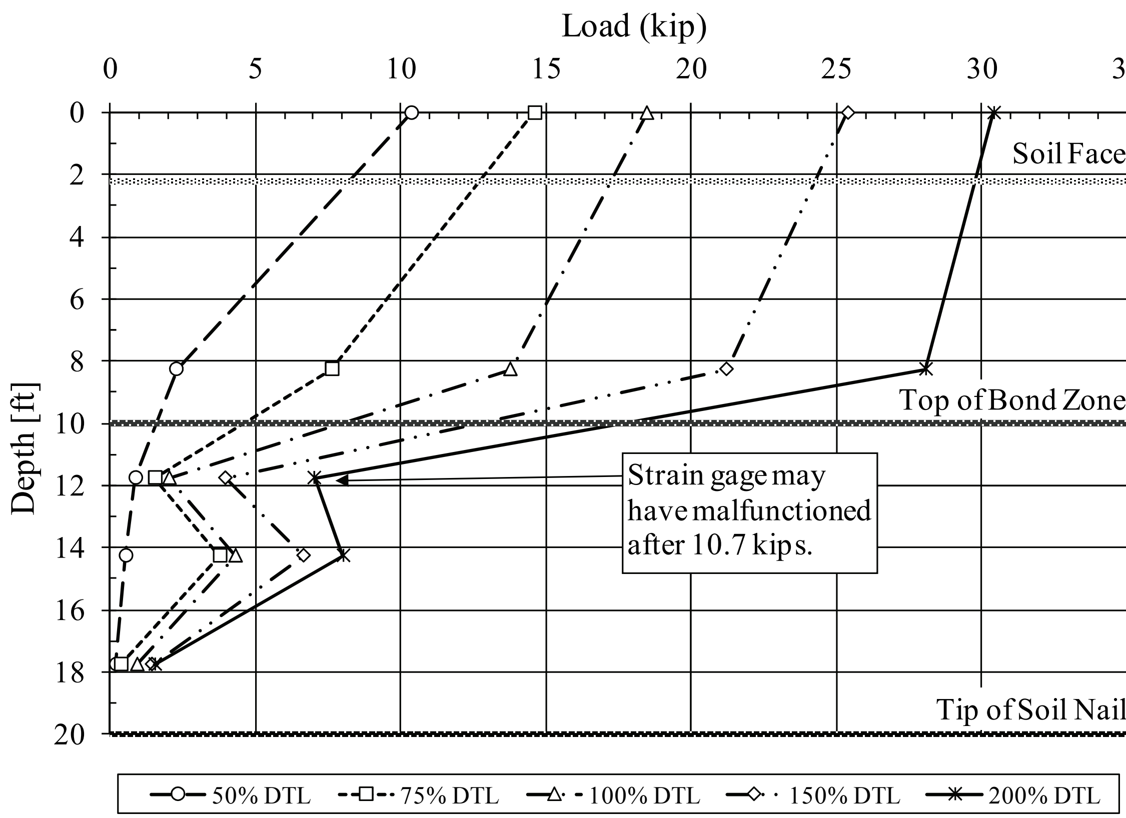

Figure 19. Graph. Load distribution from strain gauges in HBSN D2 (Olympia Site).

Based on the information presented in Figures 17 through 19 only, it would appear that the intended free length was not fully debonded from the surrounding soil in any of the test nails. The plots in the figures show that the axial load in the intended free length was less than the applied load, thus indicating that there was load transfer from the soil nail to surrounding ground.

Figure 20 shows the evolution of the interpreted axial load in the intended free length during testing. During the first test load increment, the strain gauges did not show a significant response to the applied load at the nail head. However, during subsequent test load increments, soil nails installed following Methods B and D showed interpreted axial load increases that followed almost a one to one relationship with the applied test load increments. This suggests that the test soil nails installed using Methods B and D were sufficiently debonded from the surrounding soil.

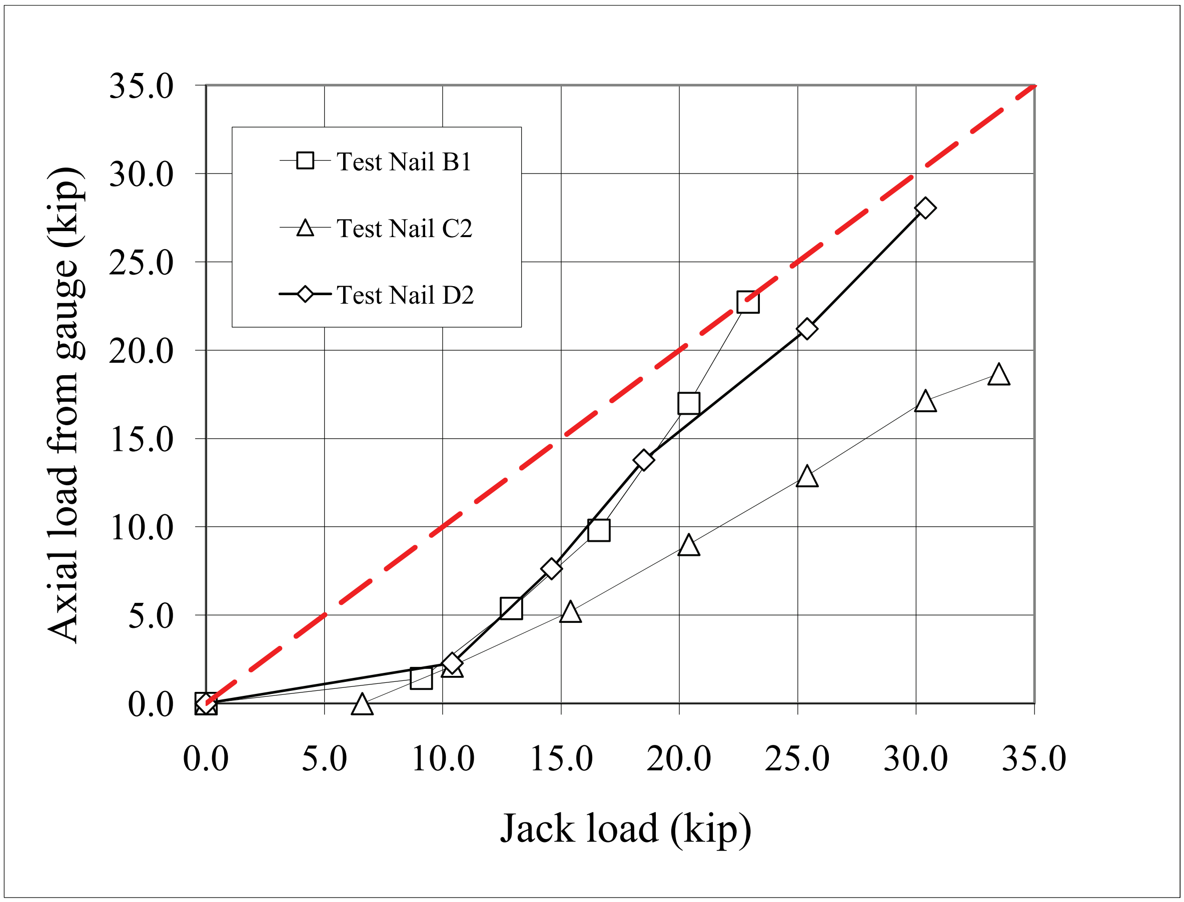

Figure 20. Graph. Measured load within the free length of the soil nail from the Olympia Site.

Figure 20 also suggests that with Method C, installation debonding was not as efficient as with Methods B and D. However, debonding was also significant as the axial load increments in the intended free length were approximately 60% of the applied test load increments. Even though there may have been significant debonding of the bar with respect to the grout annulus, a significant Doughnut Effect, described previously, may still exist.

Figures 17 through 19 also allow the calculation of the bond stresses along the bond zone of the tested soil nails. Table 11 compares the values of bond strength calculated from the strain gauge data to the average bond strength values from Table 10. It is observed that the calculated average bond strength from Table 10 generally matches the maximum interpreted bond strength from the strain gauges. This is consistent with the relatively linear axial load distribution along the bond zone depicted in the figures. It is noted that these test nails were loaded to geotechnical failure. In a soil nail that does not reach geotechnical failure, strain gauge data is useful in providing information to determine the actual bond strength of the soil nail.

Table 11. Comparison of strain gauge data to deformation data.

Nail Number	Calculated Average Bond Strength from Displacement Data (psi)	Calculated Average Bond Strength from Strain Gauge (psi)	Maximum Interpreted Bond Strength from Strain Gauge within Bond Zone (psi)
B1	19.2	11.6	5.3
C2	14.9	10.9	13.7
D2	17.8	14.6	10.8

The similarity between the maximum and the average bond strength in Table 11 is also consistent with a negligible Doughnut Effect in the Olympia Site Method C nails discussed in the preceding section.

The results inferred from the strain gauge readings prompt the following conclusions:

- All three installation methods followed for the hollow core bars (B, C, and D) provided significant debonding.
- Method C debonding was less efficient than the debonding achieved using Methods B and D. However, the use of strain gauges in the intended free length of Method C soil nails could allow adequate interpretation of the test results.
- There was no significant Doughnut Effect in Method C nails at the Olympia Site, possibly due to partial flushing of the unbonded zone (only performed at this site).