Foundation Supportworks®
PolyLevel® Deep Injection Testing

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Polyurethane foam has been used for numerous applications since it was first patented in 1937. The use of polyurethane foam for shallow soil treatment beneath concrete slabs began in the 1980's, and many patents have been granted for various methods of soil improvement. The use of polyurethane foam for soil strength improvement of deep soils (greater than 2 to 3 feet deep) was a patented process until 2017, which limited the sharing and understanding of the technology until just recently. The deep injection process typically consists of identifying the weak soil zones requiring treatment, determining the lateral and vertical injection point locations, and injecting the foam using specialized equipment. This research was undertaken to document the suitability of polyurethane foam injection for deep treatment of various soil types along with evaluation of different injection methods and polyurethane foam mixtures. Three soil types were evaluated during the current Foundation Supportworks research: loose sand, soft clay, and medium stiff to stiff clay loess.

1.0 Introduction

Polyurethane is not a new material. The chemistry of polyurethanes was discovered and patented in 1937 and has been used extensively in a variety of products and materials. Polyurethanes are best known to the public in the form of flexible foams, e.g., upholstery cushions, mattresses, caulking, weatherstripping, vehicle door and dash moldings, etc. Spray foam insulation and foam filler within shells of watercraft are examples most similar to the line of two-part PolyLevel products. The use of polyurethane foam for deep soil strength improvement was a patented process until 2017, which limited the sharing and understanding of the technology until just recently. There is limited information regarding the installation methodology and suitability of two-part polyurethane foams for deep soil strength improvement, with most of the knowledge base considered proprietary by former patent holders. Much of the available research has shown that polyurethane foam for deep soil improvement is suitable for loose sand soil. However, test results of treatment in cohesive soils are not well documented, and there is conflicting information regarding the effectiveness of deep injection treatment. To better understand the performance of Foundation Supportworks PolyLevel foams for deep soil improvement, three soil types were selected for testing: loose sand, soft clay, and medium stiff to stiff clay loess. The testing was also performed to evaluate the top-down versus bottom-up injection methodology and to compare effectiveness of two different PolyLevel mixtures.

2.0 PolyLevel Polyurethane Foam

The Foundation Supportworks PolyLevel product line consists of different polyurethane foam mixtures for use in a wide range of geotechnical and structural applications. The foam products are two-part urethanes that, when mixed, expand into rigid foam. Additives in the urethane can be used to vary the foam density and speed of reaction, depending upon the application requirements. Polyurethane foam is created by the reaction of a polymeric isocyanate (the "A" or "Iso" side) with a polyol (the "R" or "Resin" side) to form a urethane linkage. Polymeric isocyanates are organic compounds that are specifically manufactured to react with polyols. The A-side varies little between polyurethanes of similar product lines or use groups. Polyols are simply alcohols with multiple hydroxyl groups. The polyols and other additives within the R-side may vary significantly among products to control characteristics such as color, density, and speed of reaction.

Two PolyLevel foam types were evaluated during the testing at the clay site, PolyLevel PL-250 and PL-SI400. The PolyLevel PL-250 foam is recommended for slab stabilization and lifting whereas the PolyLevel PL-SI400 foam is recommended for deep soil strength improvement, PolyLevel PL-SI400 was specially formulated to have slower reaction properties than other PolyLevel foams. The slower reaction time allows the polyurethane foam to travel deeper within the soil prior to the reaction. The material and reaction properties of the PL-250 and PL-SI400 foams are shown in Table 1.

Table 1: PolyLevel Properties

PolyLevel PL-250 and PL-SI400 Typical Material and Reaction Properties		
Property	**PL-250**	**PL-SI400**
Resin Unit Weight	8.88 ±.04 lb/gal	8.88 ±.04 lb/gal
Isocyanate Unit Weight	10.2 lb/gal	10.2 lb/gal
Free-Rise Density	2.5 ±0.1 lb/ft^3	4.0 ±0.1 lb/ft^3
Compressive Strength	34.6 psi	62-67 psi
Water Absorption	0.6 ±0.04 pcf	0.6 ±0.04 pcf
Cream Time @ 77°F	7.5-8.5 sec	8-10 sec
Cream Time @ 100°F	4-5 sec	4-5 sec
Rise Time @ 77°F	35-40 sec	70-80 sec
Rise Time @ 100°F	18-25 sec	40-45 sec

3.0 PolyLevel Equipment and Setup

Special equipment is necessary to properly inject polyurethane foam for deep soil improvement. A custom truck mounted rig was utilized for the polyurethane foam injection. The rig consisted of six primary components that include the generator, air compressor, transfer pumps, proportioner, material hoses, and the injection gun. The material temperature is controlled by heater elements in the proportioner and material hoses. For the deep injections, low material temperatures are preferred to slow down the reaction time. For the testing, the temperature values for the A-side were between 90 and 100° F. and the R-side was set about 5° higher than the A-side. The hose heat was set to the same temperature as the A-side. The two components were mixed with fluid pressures between 1,200 and 1,500 psi. For optimal performance, the A- and R-side fluid pressure were maintained at 200 psi difference or less during injection operations.

Injection tubes are used to carry the polyurethane foam as a liquid phase down to the appropriate treatment depth where the reaction occurs. The injection tubes consisted of ½-inch steel conduit (EMT). The stroke counter on the proportioner was used to correlate polyurethane injection quantities at each location.

4.0 Injection Methodology

The injection process can be performed using a bottom-up or top-down methodology. For the bottom-up method, with multiple injection depths at the same location, the deepest injection depth would be treated first, followed progressively upward to the shallowest injection depth. The top-down method would be the opposite approach. In an effort to determine which method produces better treatment results, the research testing evaluated both methods in the sand test area. The PolyLevel was injected at depths of 3 and 6 feet at the locations shown in Section 7. The PolyLevel was injected at each location until any of the following occurred, the quantity reached 70 lb, noticeable surface movement, PolyLevel escaped to surface or there was noticeable back pressure in the injection tube.

5.0 Test Area Soil Properties

Three test areas were established at the Foundation Supportworks facility in Omaha, Nebraska. Loose sand and soft clay test areas were created by excavating the residual soils and replacement with documented sand and clay fill material. The third test area was within the residual clay loess soil at the site. The specific information regarding each of the three sites follows.

5.1 Sand Site: An approximate 7-foot-wide by 16-foot-long area was excavated to a depth of about 9 feet to create the sand site. Medium graded sand conforming to ASTM C33 was placed in the excavation in 2-foot lifts, taking care to place the material in a similar manner across the excavation. Once 7 feet of material had been placed in the excavation, 1-foot lifts were used and a single pass with a plate compactor was performed at each 1-foot lift until surface grade was achieved.

5.2 Clay Loess Site: During a geotechnical investigation, the residual soil at the test site was classified as Peoria clay loess to a depth of about 16 feet underlain by Loveland clay loess. Peoria clay loess can exhibit high collapse potential given the low dry density and wind-blown formation. Laboratory testing of soil samples collected in the Peoria loess showed unconfined compression strengths of 0.9 to 1.3 tons per square foot and dry densities ranging from 86.1 to 94.3 pounds per cubic foot (pcf). Atterberg Limits testing showed a liquid limit of 34 and a plasticity index of 13. An approximate 7-foot-wide by 12-foot-long area was established for the testing.

5.3 Clay Site: The clay site excavation and backfill procedures were similar to the sand site; however, the clay was moisture treated after each two-foot lift by applying water evenly across the excavation. An undisturbed sample taken from the untreated area was laboratory tested for grain size analysis, hydrometer analysis, dry density, moisture content, and Atterberg limits. The grain size and hydrometer analysis showed 3% sand, 76% silt, and 21% clay. The dry density was 101.8 pcf, the moisture content was 16.8%, and the Atterberg limits testing showed a liquid limit of 36 and a plasticity index of 16.

6.0 Soil Strength Testing

A combination of dynamic cone penetrometer (DCP) and helical screw plate testing was used to determine the soil strength prior to and after the polyurethane foam injection treatment. The DCP test allowed the test crew to evaluate the entire depth of the treatment area, whereas the screw plate testing was performed at depths of 4 feet and 7 feet.

6.1 DCP Testing: The DCP instrument is a common tool used to estimate the bearing strength of soil and identify weak soil zones prior to polyurethane foam treatment and for posttreatment testing to determine the effectiveness of the polyurethane foam treatment. The DCP test process involves driving a steel rod with specific shaft and end cone geometry into the soil with calibrated weights dropped from a known distance. The number of blows (drops of the weights) required for the rod to penetrate the soil profile a specific distance determines the DCP Index (DCPI) which can be used to correlate to a California Bearing Ratio (CBR) and ultimate bearing capacity (q_u).

Figure 1: DCP testing at the sand site

The CBR values were determined using the following equations from ASTM D6951: *"Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications"*.

For all soils except CL soils with CBR< 10 or CH soils:

$$CBR=292/DCPI^{1.12} \quad (1)$$

For CL soils:

$$CBR=1/(0.017019*DCPI)^2 \quad (2)$$

Equation 1 was used for the sand test area, and Equation 2 was used for the clay and clay loess test areas. The ultimate bearing capacity (q_u) for all three sites was based on the equation from the Portland Cement Association (PCA) 1955 research paper: *"Design of Concrete Airport Pavement"* as follows.

$$q_u=546.3628*CBR^{0.664} \text{ (psf)} \quad (3)$$

It should be noted that the PCA equation was based on data from much denser soil than was used in the current research and may not accurately represent the actual strength value determined from laboratory testing. To that end, the DCP results should be used for a comparative analysis of percent change in strength between pretreatment and posttreatment testing rather than a finite strength value for each test location.

6.2 Screw Plate Testing: The screw plate testing was performed using a single 8-inch diameter, 3/8-inch thick, Grade 50 steel helix plate with a 1.5-inch round corner, high strength solid steel square shaft. The helix plate had a 3-inch pitch with the leading and trailing edges parallel to within +/- 0.25 inches. The helix plate was formed by cold pressing the steel plate with matching machine dies to form a true helix geometry. The general geometry of a helix plate is shown in Figure 2.

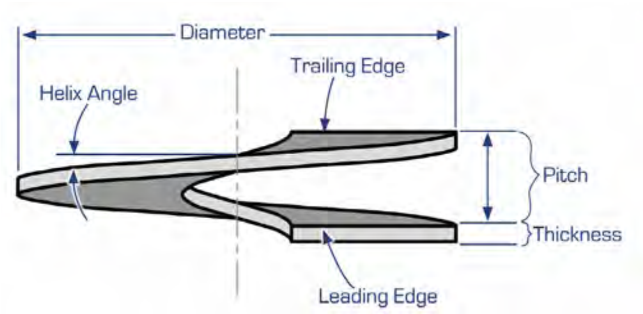

Figure 2: Helix plate geometry

The helix plates were installed to the required test depths using a hydraulic drive head mounted on a mini excavator. The testing was performed with calibrated equipment in general conformance with the Quick Test Method of ASTM D1143: *"Standard Test Method for Deep Foundations Under Static Axial Compressive Load"*. The screw plate test setup is shown in Figure 3.

Figure 3: Screw plate test setup

The ultimate capacity (Q_u) of the screw plate test was determined as the load where a net movement of 10% of the average helix diameter was reached. Net movement is the total pile movement minus the elastic deformation of the steel shaft. With the 8-inch helix plate, a net movement of 0.8 inches was used to define the ultimate capacity. The ultimate bearing capacity (q_u) at each test location was back calculated from the screw pile test results as follows.

$$q_u = Q_u/A_h \quad (4)$$

Where,

q_u = Ultimate bearing capacity (psf)
Q_u = Ultimate Pile Capacity from Screw Plate Test (lb)
A_h = Area of Helix Plate (ft^2)

Rather than performing a screw plate test, the ultimate capacity of a screw plate can also be estimated using the individual bearing capacity equation with known soil parameters as shown below.

$$Q_u = \Sigma A_h(cN_c + q'N_q) \quad (5)$$

Where,

Q_u = Ultimate Pile Capacity (lb)
c = Cohesion at Helix Depth (lb/ft^2)
q' = Effective Vertical Overburden Stress at Helix Depth (lb/ft^2)
A_h = Area of Helix Plate (ft^2)
N_c, N_q = Dimensionless Bearing Capacity Factors

For the clay and clay loess test sites, an N_c value of 9 can be assumed and the equation can be simplified to:

$$Q_u = A_h(9c) \quad (6)$$

Combining equations 4 and 6, one can estimate the cohesion from the ultimate capacity and bearing capacity determined from the screw plate testing as:

$$c = Q_u/(9A_h) = q_u/9 \quad (7)$$

7.0 DCP Test, Screw Plate Test, and PolyLevel Injection Locations

The screw plate tests were performed at depths of 4 and 7 feet and the DCP tests were performed from the ground surface to a depth of about 9 feet. The sand site was also used to evaluate soil strength differences using top-down PolyLevel installation versus bottom-up installation. The clay site was used to evaluate soil strength differences between PolyLevel PL-250 versus PolyLevel PL-SI400. The testing and PolyLevel injection locations for each site are shown in Figures 4, 5 and 6.

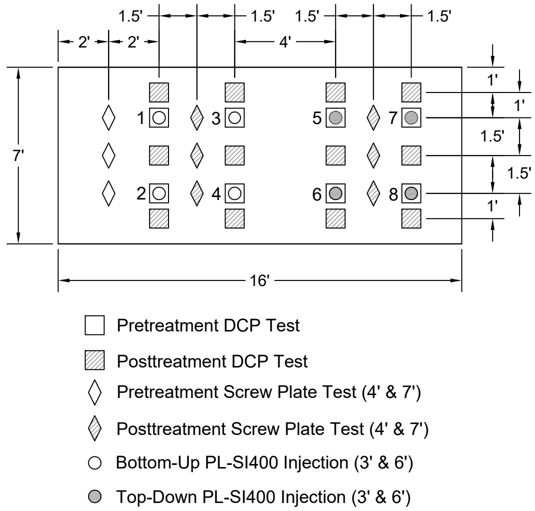

Figure 4: Sand site testing and injection locations

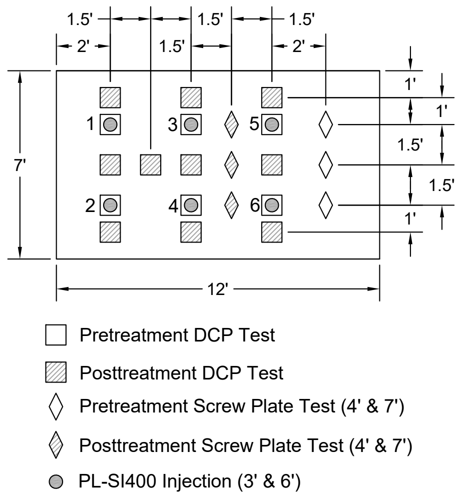

Figure 5: Clay loess site testing and injection locations

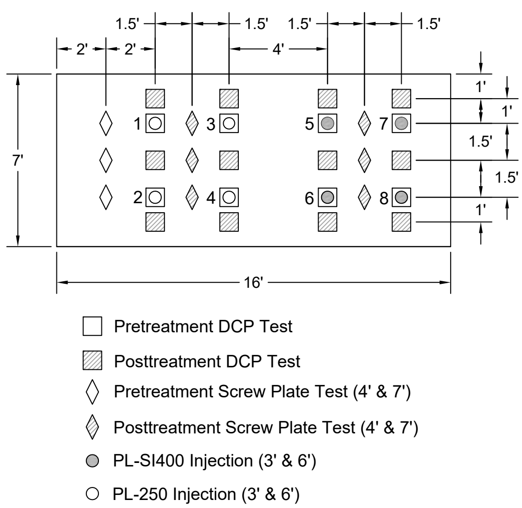

Figure 6: Clay site testing and injection locations

8.0 PolyLevel Injection Data

The PolyLevel injection quantities, injection method and PolyLevel product at each injection location and depth for the sand, clay loess and clay tests sites are shown in Tables 2, 3, and 4, respectively.

Table 2: Sand site PolyLevel injection data

Sand Site				
Injection Location	Depth (ft)	LB of Poly	Injection Method	PolyLevel Product
1	3	27.3	Bottom-Up	PL-SI400
	6	53.8		
2	3	18.8		
	6	70.0		
3	3	14.8		
	6	70.0		
4	3	15.5		
	6	70.8		
5	3	26.8	Top-Down	
	6	65.5		
6	3	16.8		
	6	70.8		
7	3	34.0		
	6	70.8		
8	3	21.8		
	6	70.5		

Total= 718 lb
Top-Down= 377 lb
Bottom-Up= 341 lb

Table 3: Clay loess site PolyLevel injection data

Loess Site				
Location	Depth (ft)	LB of Poly	Injection Method	PolyLevel Product
1	3	6.0	Top-Down	PL-SI400
	6	22.5		
2	3	6.0		
	6	41.0		
3	3	12.5		
	6	50.0		
4	3	16.5		
	6	13.8		
5	3	11.0		
	6	16.8		
6	3	29.0		
	6	50.0		

Total= 275 lb

Table 4: Clay site PolyLevel injection data

Clay Site				
Injection Location	Depth (ft)	LB of Poly	Injection Method	PolyLevel Product
1	3	16.5	Top-Down	PL-250
	6	70.0		
2	3	35.0		
	6	70.0		
3	3	70.0		
	6	59.3		
4	3	12.8		
	6	70.5		
5	3	38.8		PL-SI400
	6	70.5		
6	3	9.0		
	6	26.0		
7	3	14.5		
	6	70.8		
8	3	27.5		
	6	27.8		

Total= 689 lb
PL-250= 404 lb
PL-SI400= 285 lb

9.0 Test Results and Discussion

To evaluate the effectiveness of the PolyLevel treatment, the averages of the aggregate data were used to show the increase in bearing capacity after treatment. The aggregate analysis was selected, given the significant number of test locations. Since the screw plate testing was performed at depths of 4 and 7 feet, the DCP data below a depth of 4 feet was used to compare the DCP and screw plate test results. The DCP data was taken from the ground surface to a depth of about 9 feet, which allowed an analysis of the change in soil strength from a depth of 0-4 feet versus 4~9 feet.

9.1 Sand Site: The pretreatment and posttreatment ultimate bearing capacity results from the DCP data (0~9 feet) are shown in Table 5. PolyLevel Injection locations 1 through 4 were performed using the bottom-up method, and 5 through 8 used the top-down method. The data shows a 171% increase in bearing capacity using the top-down method versus a 48% increase using the bottom-up method. Thus, the top-down injection method is almost three times as effective than the bottom-up method. It should be noted that both areas of the site used similar amounts of PolyLevel foam (see Table 1).

Table 5: Average ultimate bearing capacity data (0~9 feet)

Sand Site-DCP Test Results (0~9 Feet) Average Ultimate Bearing Capacity				
Injection Location	Pretreatment (psf)	Posttreatment (psf)	% Change	Injection Method
1	341	532	56%	Bottom-up Method
2	420	564	34%	
3	376	878	134%	
4	603	607	1%	
Average=	435	645	48%	
5	410	1224	199%	Top-down Method
6	603	693	15%	
7	460	1465	218%	
8	472	1894	301%	
Average=	486	1319	171%	
Average=	461	982	113%	Both Areas

The comparison of the posttreatment soil strength increase between a depth of 0-4 feet versus the depth of 4~9 feet are shown in Table 6. The data suggests that most of the soil improvement occurred below a depth of 4 feet and that the top-down method showed a much higher increase in bearing capacity, compared to the bottom-up method. The lower soil strength improvement in the upper 4 feet was likely due to a lack of confinement at the surface (e.g., pavement or other structures).

Table 6: Comparison of DCP bearing capacity at 0-4 and 4~9 feet

Sand Site-DCP Test Results Average Ultimate Bearing Capacity (% Change)		
Injection Method	Test Depth	
	0-4 Feet	4~9 Feet
Bottom-Up	25%	87%
Top-Down	6%	421%
Both Areas	15%	257%

The percent changes in ultimate bearing capacity from the pretreatment values below a depth of 4 feet for the DCP and screw plate testing are shown in Table 7. Again, the results show a significant capacity increase with the top-down injection method compared to the bottom-up method. With the top-down method, the percent increase was 421% for the DCP testing and 370% for screw plate testing. The data indicates that the soil strength increase due to the PolyLevel treatment was about four to five times the pretreatment soil strength. The data also shows a strong correlation between the DCP and screw plate test results when the entire area is evaluated.

Table 7: DCP versus screw plate test results (% change)

Sand Site-Test Results DCP (4~9') and Screw Plate (4' and 7') Average Ultimate Bearing Capacity (% Change)		
Injection Method	Test Type	
	DCP	Screw Plate
Bottom-Up	87%	192%
Top-Down	421%	370%
Both Areas	257%	285%

The pretreatment and posttreatment ultimate bearing capacity values for the DCP and screw plate tests are shown in Table 8. The data shows a significant variation in values between the DCP and screw plate results, indicating a poor correlation between the two test methods. It is interesting to note that the percent difference in strength across the entire site (Table 7) shows a strong correlation between the two test methods, but the actual bearing capacity values show a poor correlation. This would suggest that although the methods do not yield similar bearing capacities, both methods are suitable for determining percent change.

Table 8: DCP versus screw plate test results (bearing capacity)

Sand Site-Pretreatment vs Posttreatment Test Results DCP (4~9') vs Screw Plate (4' and 7') Average Ultimate Bearing Capacity (psf)				
Injection Method	Pretreatment		Posttreatment	
	DCP	Screw Plate	DCP	Screw Plate
Bottom-Up	329	3095	616	9050
Top-Down	342	3095	1780	14537
Both Areas	335	3095	1198	11793

The method used to determine capacity from the screw plate tests should be considered a more accurate estimation of capacity than the DCP testing since the screw plate tests were performed with calibrated equipment using the methodology in ASTM D1114. This indicates that the equation used to determine ultimate bearing capacity from the DCP data is not appropriate for the test site, and more research is needed to determine an appropriate equation.

9.2 Clay Loess Site: The pretreatment and posttreatment ultimate bearing capacity results from the DCP data (0~9 feet) are shown in Table 9. All injection locations used the top-down method with PolyLevel PL-SI400 foam. The data shows a very small loss in soil strength overall.

Table 9: Average ultimate bearing capacity data (0~9 feet)

Clay Loess Site-DCP Test Results (0~9 Feet)			
Injection Location	Average Ultimate Bearing Capacity (psf)		% Change
	Pretreatment	Posttreatment	
1	1655	1767	7%
2	2388	1975	-17%
3	1470	1394	-5%
4	NA[1]		
5	1575	1862	18%
6	1635	1639	0%
Average=	1744	1727	-1%

[1]DCP refusal @ 5 foot depth during pretreatment testing

The comparison of the DCP soil strength percent increase between a depth of 0-4 feet versus the 4~9 foot depth is shown in Table 10. The data shows that there was a loss in soil strength in the upper 4 feet. This is likely due to the collapsable nature of loess soil and the lack of confinement at the surface. There was little soil improvement below a depth of 4 feet.

Table 10: Comparison of DCP bearing capacity at 0-4 and 4~9 feet

Clay Loess Site-DCP Test Results Average Ultimate Bearing Capacity (% Change)	
Test Depth	
0-4 Feet	4~9 Feet
-9%	4%

The percent change in ultimate bearing capacity calculated for the DCP and screw plate testing below a depth of 4 feet is shown in Table 11. The results show a 4 to 5 percent increase in soil strength and the data also shows a strong correlation between the two test methods.

Table 11: DCP versus screw plate test results (% change)

Clay Loess Site-Test Results DCP (4~9') and Screw Plate (4' and 7') Average Ultimate Bearing Capacity (% Change)	
Test Type	
DCP	Screw Plate
4%	5%

The ultimate bearing capacity values for the DCP and screw plate tests are shown in Table 12. The data shows a significant variation in values between the DCP and screw plate results by a factor of about six.

Table 12: DCP versus screw plate test results (values)

Clay Loess Site-Pretreatment vs Posttreatment Test Results DCP (4-9') vs Screw Plate (4' and 7') Average Ultimate Bearing Capacity (psf)			
Pretreatment		Posttreatment	
DCP	Screw Plate	DCP	Screw Plate
2249	13897	2468	14636

The cohesion results were calculated from the DCP and screw plate testing below a depth of 4 feet (see Eqn. 7) and are shown in Table 13. The unconfined compression testing at the clay loess site (pretreatment) showed cohesion values of about 900 to 1300 psf, which indicates that the screw plate testing is a more accurate predictor of capacity than the DCP testing.

Table 13: DCP and screw plate average cohesion values

Clay Loess Site-Pretreatment vs Posttreatment Test Results DCP (4-9') vs Screw Plate (4' and 7') Average Cohesion Using Nc=9 (psf)			
Pretreatment		Posttreatment	
DCP	Screw Plate	DCP	Screw Plate
250	1544	274	1626

9.3 Clay Site: The pretreatment and posttreatment ultimate bearing capacity results from the DCP data (0~9 feet) are shown in Table 14. All injection locations used the top-down method, but there were separate areas to evaluate the effectiveness of PolyLevel PL-250 foam versus PL-SI400 foam. The DCP data for the 0~9 foot depth shows a slightly higher percent change in capacity for the PL-SI400 foam versus the PL-250 foam. It should be noted that more foam was injected at the PL-250 side versus the PL-SI400 (404 lb versus 295 lb); however, the additional foam at the PL-250 side may be attributed to PL-250 foam extending into the pretreatment screw plate test area.

Table 14: Average ultimate bearing capacity data (0~9 feet)

Clay Site-DCP Test Results (0~9 Feet) Average Ultimate Bearing Capacity				
Injection Location	Pretreatment (psf)	Posttreatment (psf)	% Change	Poly Type
1	273	1271	366%	PL-250
2	248	1470	494%	
3	295	648	120%	
4	286	1242	335%	
Average=	275	1158	321%	
5	342	737	116%	PL-SI400
6	302	1339	344%	
7	145	1500	935%	
8	150	1301	765%	
Average=	235	1219	419%	
Average=	255	1188	366%	Both Areas

The comparison of the DCP soil strength percent increase between the 0-to-4 foot depth versus the 4~9-foot depth is shown in Table 15. Based on the data, the PL-SI400 showed a much higher increase in bearing capacity than the PL-250 (by a factor of about 2). Significant improvement was shown below a depth of 4 feet with strength increases of 484% and 759% at the PL-250 and PL-SI400 areas, respectively. The data shows much less increase in capacity in the upper 4 feet compared below 4 feet. Again, the lower bearing capacity in the upper 4 feet is likely due to a lack of confinement at the surface similar to the other test sites.

Table 15: Comparison of DCP bearing capacity at 0-4 and 4~9 feet

Clay Site-DCP Test Results Average Ultimate Bearing Capacity (% Change)		
Poly Type	Test Depth	
	0-4 Feet	4~9 Feet
PL-250	60%	484%
PL-SI400	120%	759%
Both Areas	90%	597%

Table 16: DCP versus screw plate test results (% change)

Clay Site-DCP Test Results Average Ultimate Bearing Capacity (% Change)		
Poly Type	Test Type	
	DCP	Screw Plate
PL-250	484%	162%
PL-SI400	759%	200%
Both Areas	597%	181%

The ultimate bearing capacity values for the DCP and screw plate tests are shown in Table 17. The data shows a large variation between the DCP and screw plate results (by a factor of about six). Again, this indicates a poor correlation between test methods.

Table 17: DCP versus screw plate test results (values)

Clay Site-Pretreatment vs Posttreatment Test Results DCP (4~9') vs Screw Plate (4' and 7') Average Ultimate Bearing Capacity (psf)				
Poly Type	Pretreatment		Posttreatment	
	DCP	Screw Plate	DCP	Screw Plate
PL-250	257	2734	1501	7154
PL-SI400	181	2734	1554	8195
Both Areas	219	2734	1527	7674

The cohesion results are calculated from the DCP, and the screw plate tests (see Eqn. 7) and are shown in Table 18. Again, there are significant difference in values between the DCP and screw plate test results. The cohesion values calculated from the screw plate testing are more in line with what would be expected at the site.

Table 18: DCP and screw plate average cohesion values

Clay Site-Pretreatment vs Posttreatment Test Results DCP (4~9') vs Screw Plate (4' and 7') Average Cohesion Using Nc=9 (psf)				
Poly Type	Pretreatment		Posttreatment	
	DCP	Screw Plate	DCP	Screw Plate
PL-250	29	304	167	795
PL-SI400	20	304	173	911
Both Areas	24	304	170	853

10.0 PolyLevel Below Grade Formations

Subsequent to the posttreatment testing, excavation of the test areas was performed to identify the PolyLevel structure below grade. The sand and clay test areas were able to be excavated to show the formations; however, the clay loess test area had small fissures of PolyLevel due to the stiff-to-medium-stiff nature of the soil and were not able to be uncovered without damage. Excavation images of the three test areas are shown in the figures below.

Figure 7: Posttreatment excavation-sand site

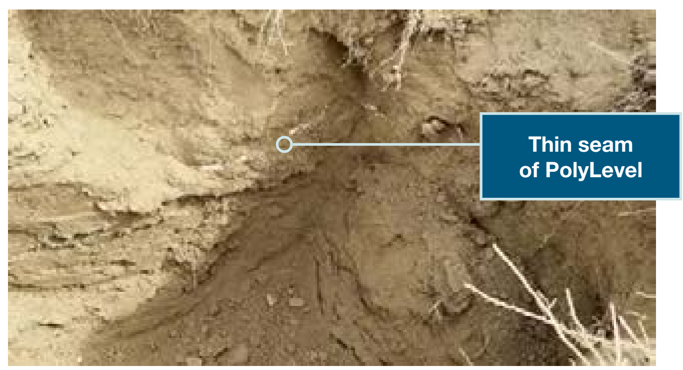

Figure 8: Posttreatment excavation-clay loess site

Figure 9: Posttreatment excavation-clay site

11.0 Conclusions

11.1 Sand Site: The test results show a significant increase in soil strength from the deep injection treatment in the loose sand. The top-down method of PolyLevel injection showed much higher soil strength improvement than the bottom-up method. The DCP and screw plate test data did not correlate well between test methods indicating that more research is needed to determine a more accurate correlation between the DCP results and bearing capacity. Some specific items to note from the results are:

- Similar amounts of polyurethane foam were injected at the top-down and bottom-up injection areas (377 lb versus 341 lb).
- Similar percentages of total foam were injected deep versus shallow with both methods (about 75% deep versus 25% shallow).
- Higher bearing capacity was achieved using the top-down method (about two times more bearing capacity than the bottom-up method).
- Significant increase in bearing capacity was indicated from the 4~9-foot versus 0–4 foot depth across the site, based on the DCP test results (see Table 6).
- Low strength increases in the upper 4 feet may be due to lack of confinement and is typical at all three test sites.
- Based on the DCP test results, there is a much higher bearing capacity increase below 4 feet with the top-down method versus the bottom-up method (421% versus 87%).
- Similar to the DCP testing below a depth of 4 feet, the screw plate testing shows a higher bearing capacity increase with top-down method compared to the bottom-up method (370% versus 192%).
- The screw plate and DCP test results correlate well with each other if one considers the entire site to the full depth; however, there is poor correlation between the test methods for most of the data analysis.

11.2 Clay Loess Site: The test results generally show no improvement in soil strength in the medium stiff to stiff clay loess. This was expected since previous research by Foundation Supportworks showed no improvement in similar soil types and in-situ strengths. Similar to the other test sites, the DCP and screw plate test data did not correlate well between test methods, indicating that more research is needed to determine a more accurate correlation between the DCP results and bearing capacity. Some specific items to note from the results are:

- There was significantly less foam quantity used per injection location compared to the sand and clay sites (average of about 23 lb per location versus 43-45 lb at the other two sites).
- There was a higher percentage of foam at the deep injections; however, this did not result in much more soil strength improvement below a 4-foot depth.
- The posttreatment DCP tests showed a 1% loss of bearing capacity when considering the full depth results across the site.
- The posttreatment DCP testing showed a 9% loss in soil strength in the upper 4 feet, which is likely due to the collapsable nature of loess deposits and the lack of surface confinement.
- The screw plate and DCP test results correlate well with each other based on the percent change in bearing capacity; however, the actual bearing values are off by an approximate factor of six (see Table 12).
- The average pretreatment cohesion value calculated from the screw plate testing was close to the cohesion values based on the unconfined compression strength testing during the pretreatment geotechnical investigation. The cohesion calculated from the DCP testing was lower than the screw plate and laboratory testing values by a factor of about 4 to 6. This would indicate that the screw plate testing is a better predictor of capacity than the DCP testing.

11.3 Clay Site: The test results show a significant increase in soil strength from the deep injection treatment in the soft clay. The PL-SI400 treatment area showed slightly higher soil strength improvement than the PL-250 treatment area, based on the DCP testing across the entire site. However, the DCP and screw plate testing performed below a depth of 4 feet showed that the PL-SI400 had a significantly higher increase in soil strength as compared to the PL-250 foam. As with the other sites, the DCP and screw plate test data did not correlate well, and more research is needed to determine a more accurate correlation between the DCP results and bearing capacity. Some specific items to note from the results are:

- More polyurethane foam was injected at the PL-250 area than the PL-SI400 area (404 lb versus 285 lb).
- Similar percentages of total foam were injected deep versus shallow at both foam areas (about 68% deep, versus 32% shallow).
- Based on the DCP data from 0~9 feet, there is a slightly higher percent increase in bearing capacity at the PL-SI400 test area compared to the PL-250 test area (419% versus 321%).
- Based on the DCP data, significantly higher increase in bearing capacity occurred below a depth of 4 feet compared to above 4 feet. However, the screw plate testing showed less of an increase (see Table 16).
- The lower increase in soil strength above 4 feet may be due to lack of surface confinement and is typical at all three test sites.
- Based on the DCP test results, there is a much higher bearing capacity increase below 4 feet with the PL-SI400 foam versus the PL-250 foam (759% increase versus 484%).
- The screw plate testing showed less of an increase in soil strength than the DCP data: 200% increase with PL-SI400 foam compared to a 162% increase with the PL-250 foam.
- There was poor correlation between the DCP and screw plate test results with the results differing by a factor of about 6 to 10.
- The screw plate cohesion results seem more in line with what would be expected rather than the cohesion results calculated from the DCP tests (see Table 18).

11.0 Recommendations for Further Research

- The DCP and screw plate tests generally did not correlate with each other at any of the test sites. Further research is needed to evaluate the correlation of the DCP Index to ultimate bearing capacity for both clay and sand sites.
- Other soil types and soil strengths should be evaluated for polyurethane foam deep injection treatment.
- The lack of confinement at the test sites likely influenced the soil strength improvement in the upper soils. Further research should evaluate deep injection treatment with concrete pavement confinement.
- The effect of injecting more polyurethane should be evaluated. The injection procedure used in this research limited the foam quantity to 70 lb at each location. There were seven injection locations at the sand site and six locations at the clay site that could have taken more than 70 lb of foam, which may have resulted in higher soil strength improvement.
- The vertical and horizontal injection locations were spaced at 3 feet for this research. The effect of different spacings between injection locations should be evaluated.

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