Geotechnical Lessons Learned from Construction of a Tire Plant in Karst

By
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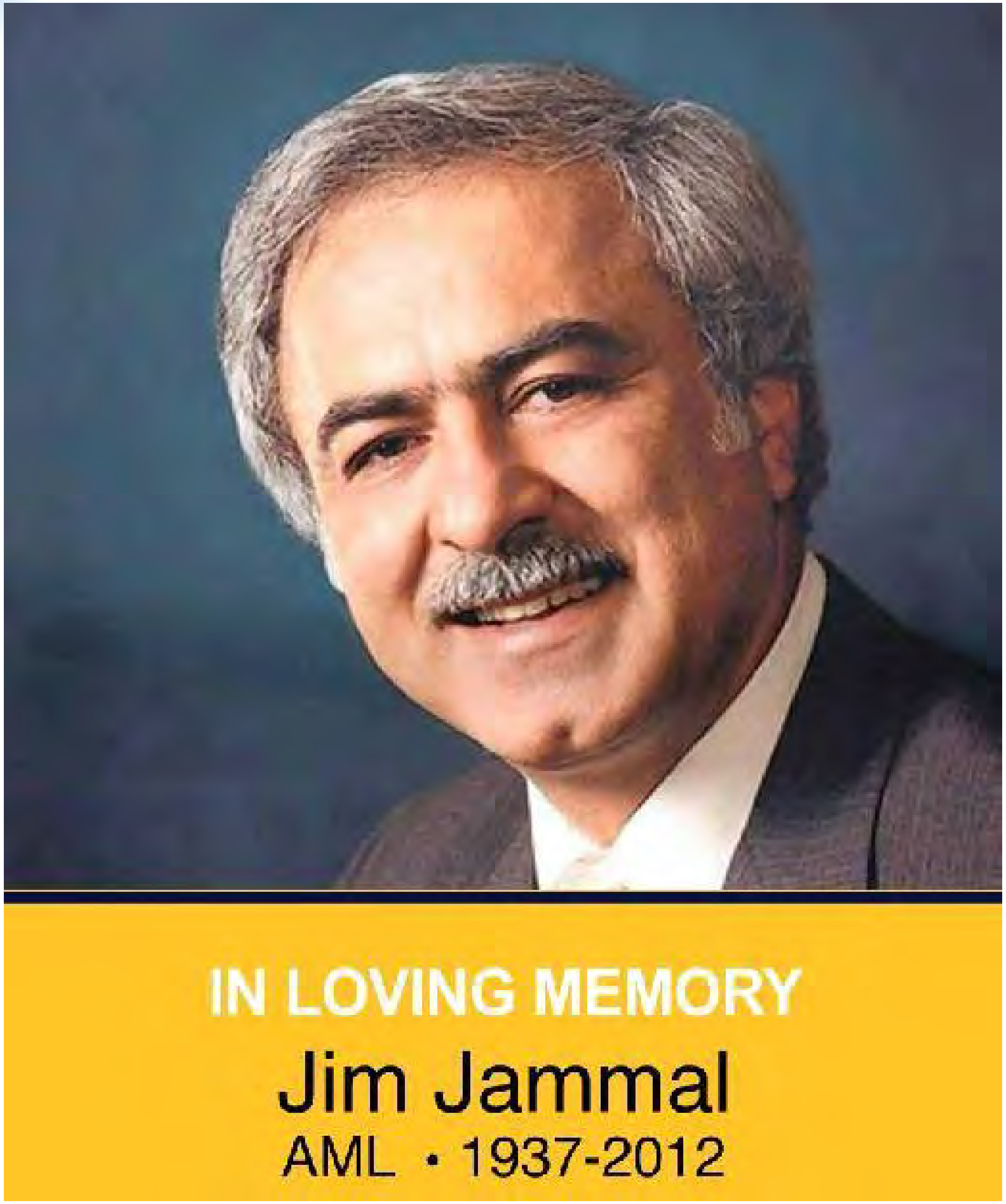
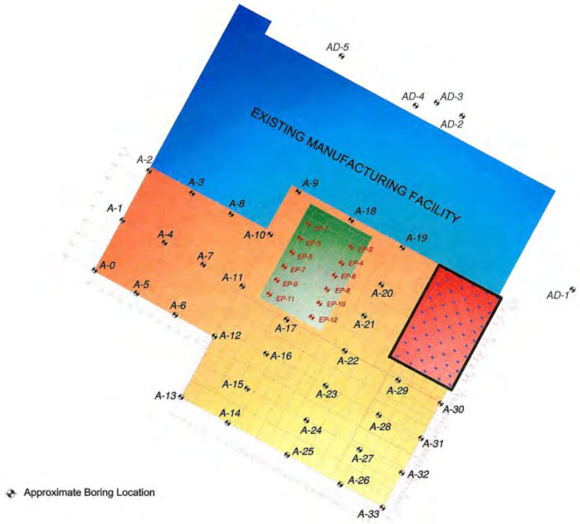
In his career, Jim Jammal would study more than 2,000 sinkholes. Jammal's work changed the understanding of sinkholes…

He was my mentor from 1983 to 1993 and I am a much better engineer for it.



The Winter Park Sinkhole 1981



The NS2 Case History –

A Tire Plant over Karst conditions

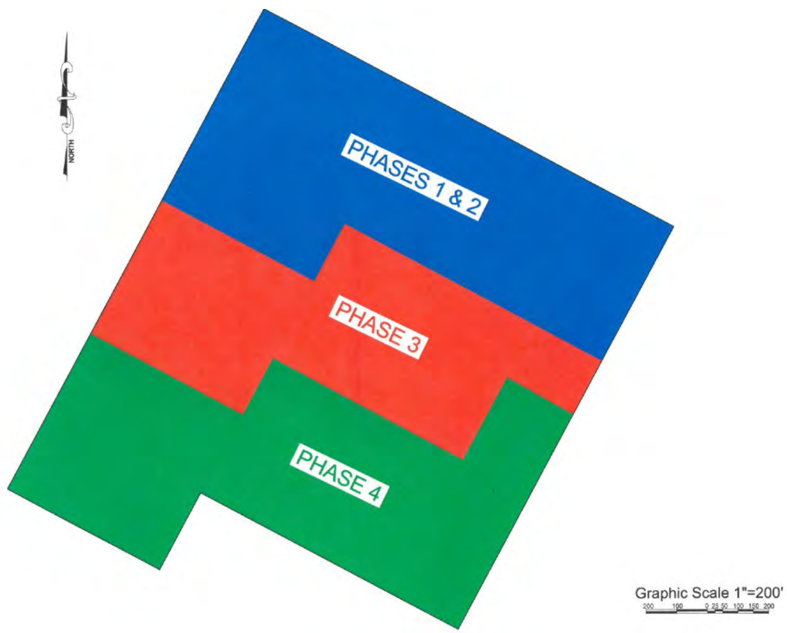
- **NS2 Tires, White, Georgia**
  - Multiphase project with manufacturing & warehouse
  - Two basic areas: plant/warehouse & mixing tower
  - Structural Loads:
    - 1-story concrete tilt wall plant & warehouse:
      - ~150 kips for steel columns
      - 3 to 4 klf continuous wall footings
    - 3-story mixing tower: 2,000 kip columns, cast in place concrete frame
  - Geology: Ridge & Valley with known Karst

NS2 Tires (Project History)

- Phase 1 & 2 – Geotech done by others
  - Mixing Tower foundations: drilled shafts (initially)
  - Plant/warehouse foundations: shallow spread @ 3 ksf
- Trouble installing drilled shafts in mixing tower
  - Mid-way through mixing tower rock dropped off & firm bearing for shafts could not be found at <100 feet.
  - Micropiles substituted for the drilled shafts. Micropiles drilled to bearing in competent rock at 200 to 300 feet.
- Lawsuit ensued over $3M cost overrun & delays

NS2 Tires – Phase 3 Study

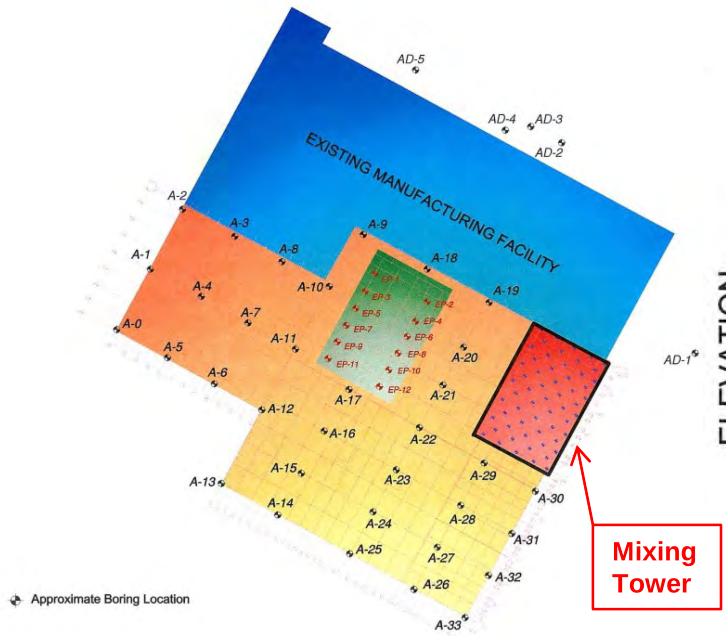
~1,200,000 sf

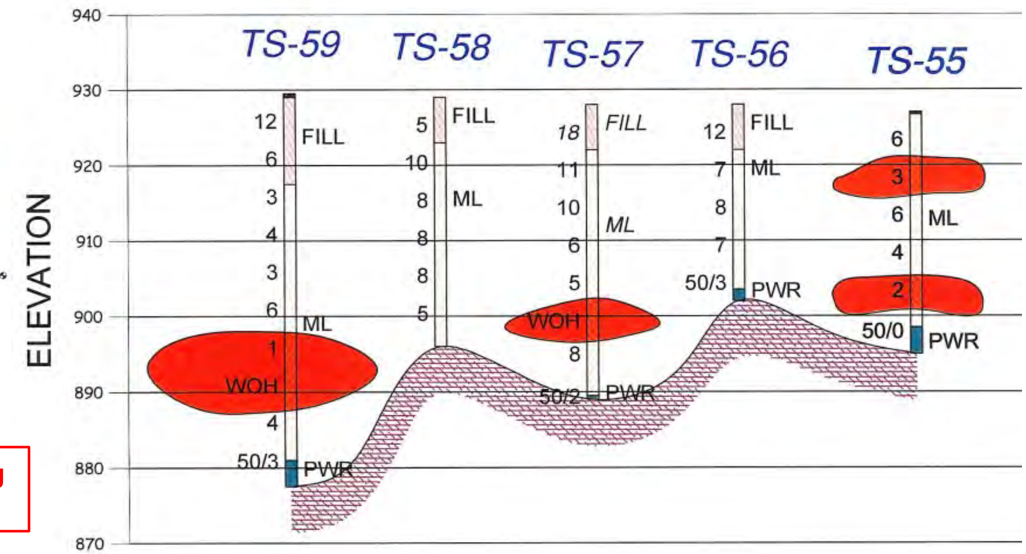


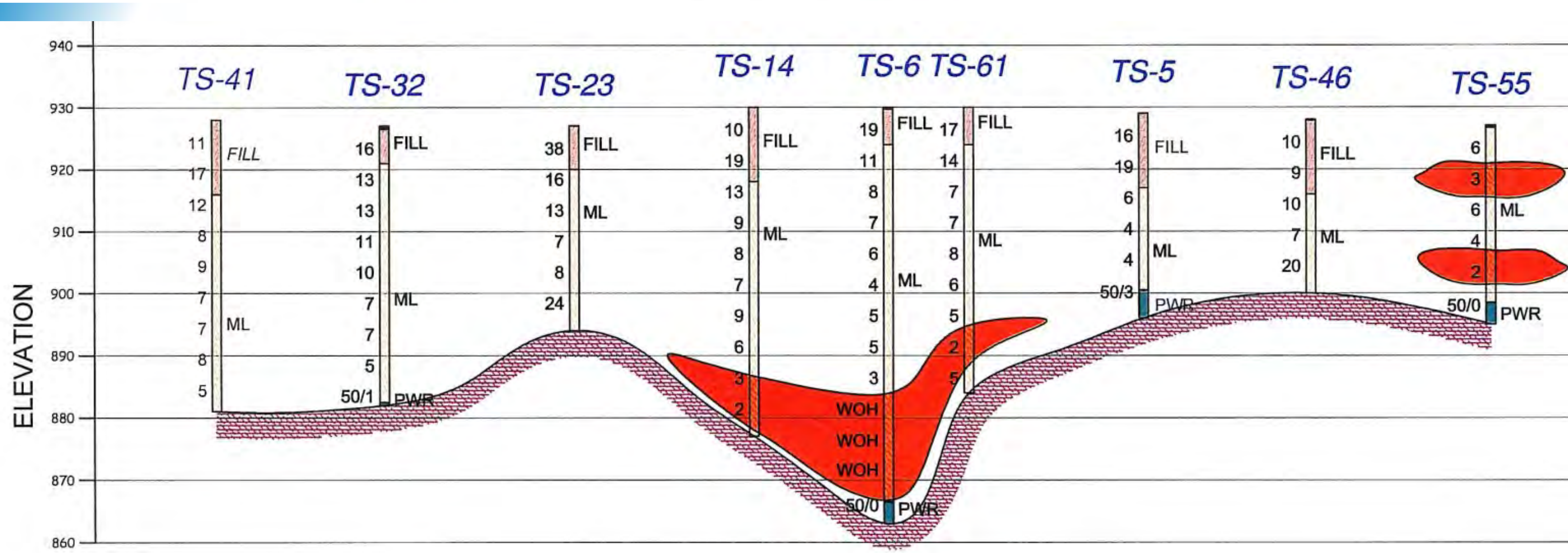
- ECS asked to interview for Phase 3.
  - New design-build team selected by owner
  - Japanese owner and D-B contractor both adverse to risk on Phase 3
  - Major design team concerns were Karst and support of new mixing tower adjacent to troubled Phase 1 & 2 structure.
  - ECS experience with sinkholes and Karst in Florida a big factor in our selection.
  - Another major factor in ECS selection was plan to avoid use of micropiles if at all practical to reduce foundation cost.

- Exploration
  - Extensive exploration conducted with SPT in new mixing tower to define upper rock surface. Most columns drilled. More typical spacing used in 1-story plant.
  - Discussions with Specialty Foundation Contractor evaluated various intermediate foundation options.
  - Additional CPT work done in mixing tower to check settlement of vibropiers, etc.
  - Specialty Foundation Contractor ultimately recommended micropiles or at least some version of cased pile into rock.

Typical Profiles in Phase 3





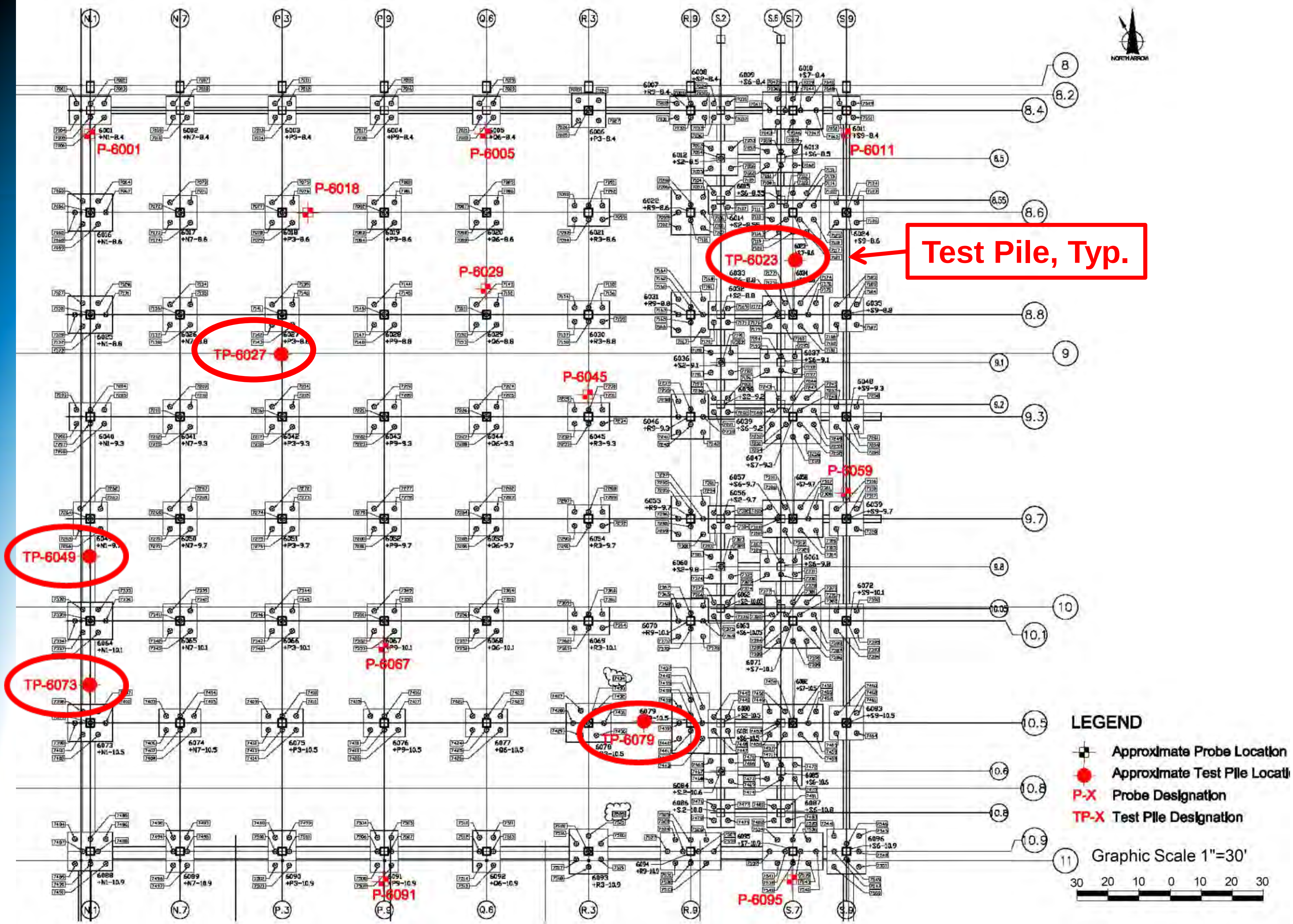


Selected Option: 18” Dia. Auger Cast Piles

1. Cost effective option (~$2M less than micropiles)
2. Able to adjust to highly variable conditions & pinnacled rock
3. Excess grout from ACIP provides indirect benefit of grouting Karst under floor slab on grade
4. Allows for quality assurance testing & live feedback from subsurface conditions

Japanese Thought Process at Work

- Design team wanted savings but nervous about how to “prove” quality and safety of ACIP
- To build confidence we suggested doing 5 test piles in very small area & loading them to 3x design load
- Engineers in Tokyo were looking over the shoulders of ECS & local designers.
- Later we found out that our client had a poor experience with ACIP piles in Pacific Rim.
- We also found out Japanese engineers were trained to consider ACIP piles as “friction” only.



P-6001
P-6005
P-6011
P-6018
TP-6023
Test Pile, Typ.
P-6029
TP-6027
P-6045
P-6059
TP-6049
TP-6073
P-6067
TP-6079
P-6091
P-6095
LEGEND
Approximate Probe Location
Approximate Test Pile Locati
P-X Probe Designation
TP-X Test Pile Designation
Graphic Scale 1"=30'
NORTH ARROW

Comparison of Test & Probe Piles Lengths vs Airtrack Results

Pile Number (nearest column)	Probe or Test Pile Length	Depth to Top of Rock*	Thickness of Top Rock Layer*
6001	41	72	9’
6005	45	45	7’
6011	47	68	0.25’
6018	77	67	1’ @ 42’, 2’ @ 67’
6023	39	41	7’
6027	63	70	19’
6029	84	39	3’
6045	43	43	3’
6049	44	42	7’
6059	79	51	19’
6067	55	64	7’
6073	66	50	3’
6079	44.5	45	2’
6091	66	>98	None Found to 98’
6095	38	56	5’

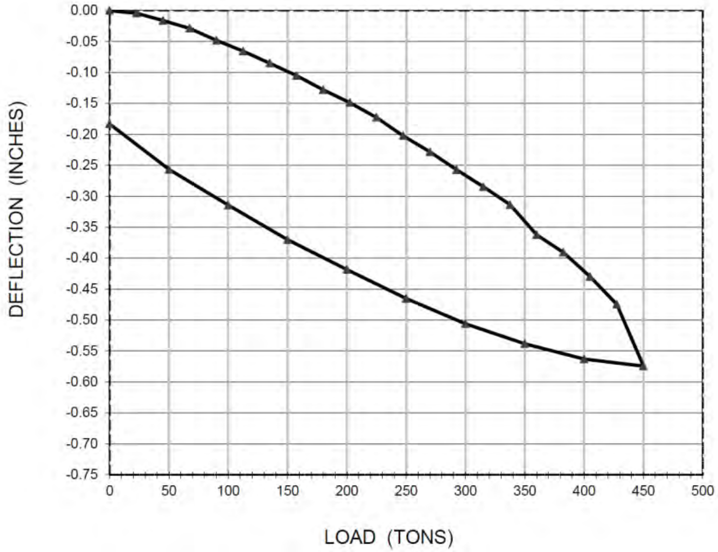
* Estimated from Airtrack drilling at nearby column location.

Test Pile, Typ.

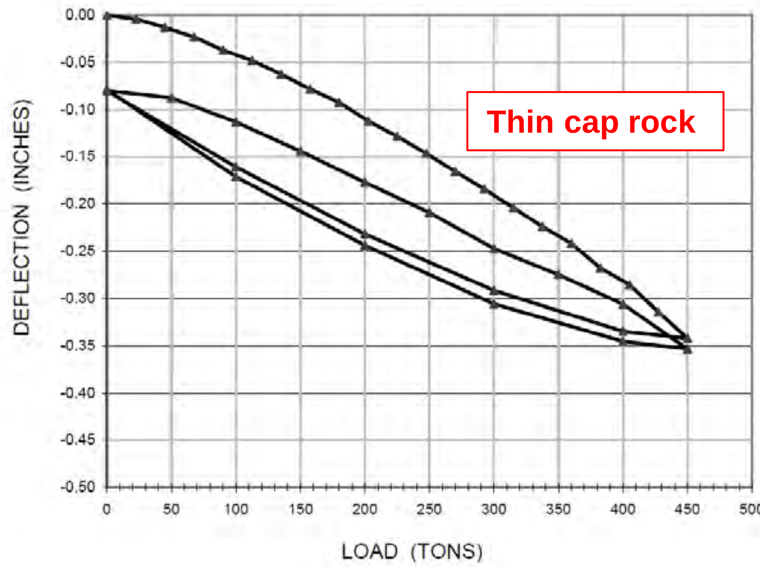
Thin cap rock

Pile Load Testing – Phase 3

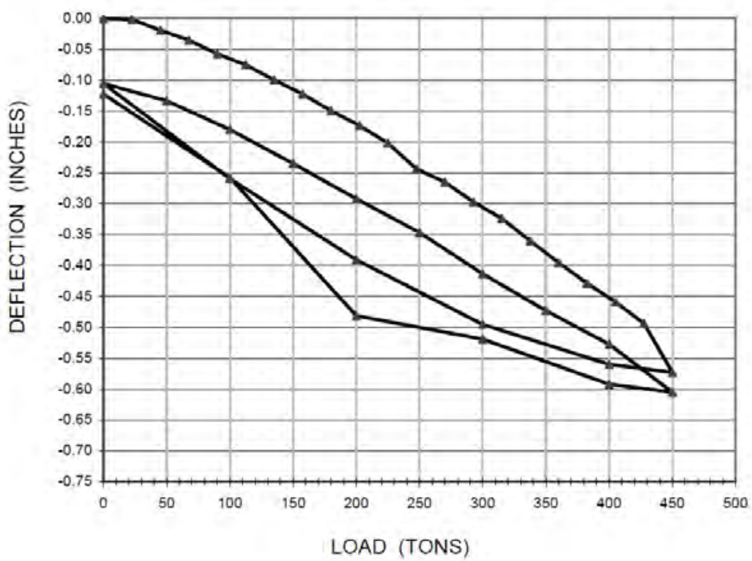
Pile # 6023 (18-inch Dia. Compression Test)
Pile Length - 39 feet



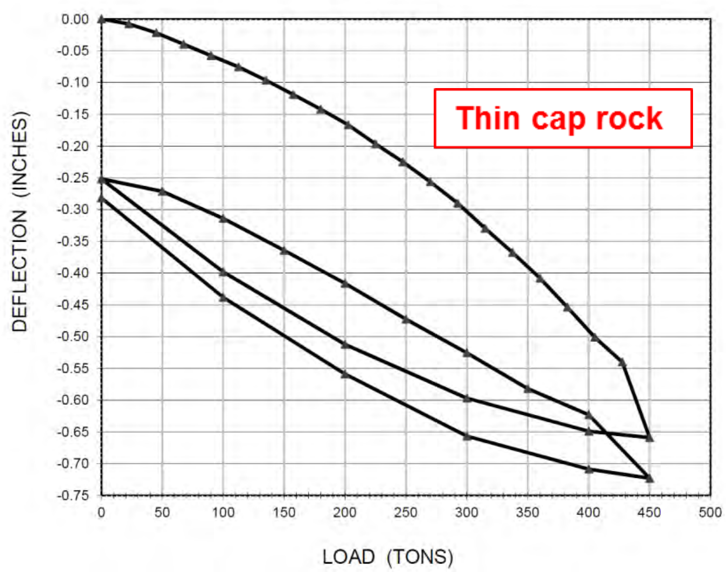
Pile # 6073 (18-inch Dia Compression Test)
Pile Length - 66 feet



Pile # 6027 (18-inch Dia Compression Test)
Pile Length - 65 feet



Pile # 6079 (18-inch Dia Compression Test)
Pile Length - 44.5 feet



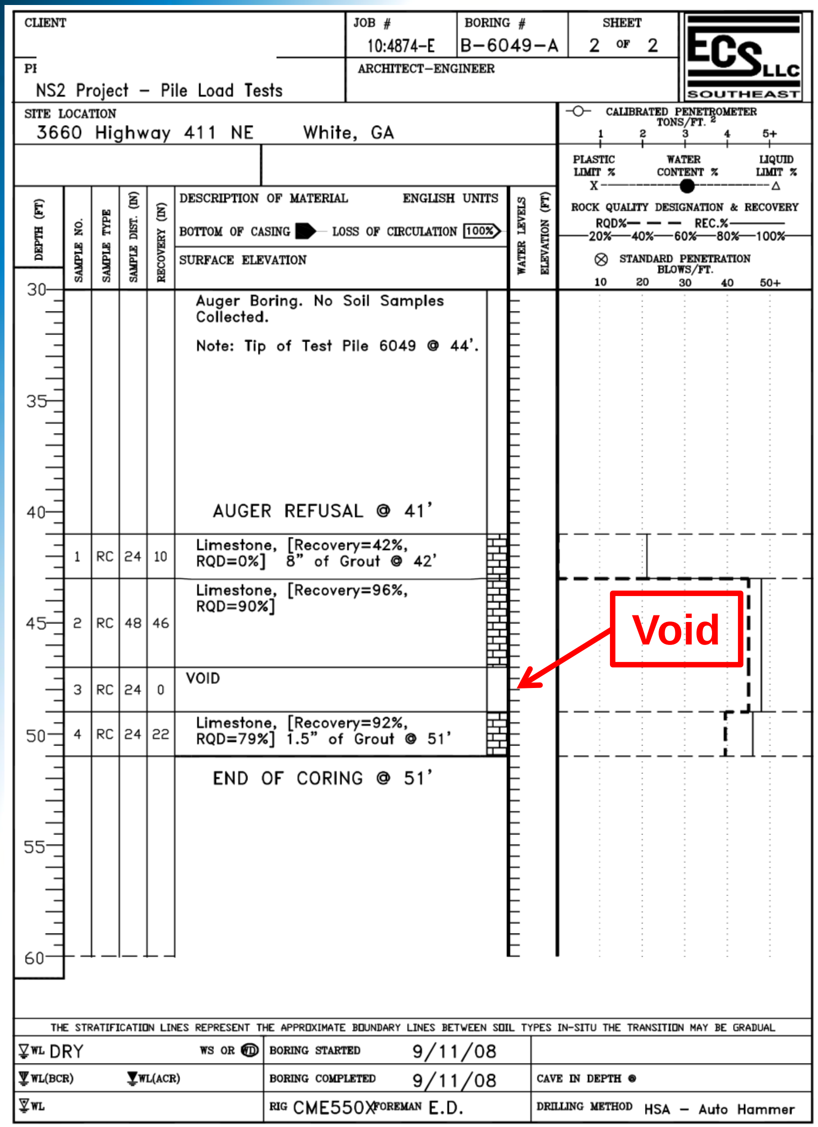
Test Pile Results & Actual Pile Tip - Top of Rock Comparison

Test Pile Number	Maximum Applied Test Load (tons)	Creep at Maximum Load		Actual Test Pile Length	Depth to Top of Rock*	Est. Thickness of Rock Below Pile Tip*
		Initial Load Cycle	Rapid Reload Cycle			
6023	450	0.049”	Apparent breakage at full load	39’	41’	7’
6027	450	0.042”	0.002”	65’	70’	19’
6049	382.5	Test stopped for safety reasons	No reload attempted	44’	42’	7’
6073	450	0.014”	0.017”	66’	50’	3’
6079	450	0.081”	0.042”	44.5’	45’	2’

* Estimated from Airtrack drilling at nearby column location.

Thin Cap Rock

Additional Study at TP # 6049



- During pile load testing TP #6049 showed signs of instability & test was terminated before reaching full test load.
- To confirm TP # 6049 didn't start to fail into underlying rock, SPT boring w/ 10 ft. rock core was drilled.
- Results found pile was sitting on a 6 foot thick seam of rock over a **2 foot void typical of Karst**.

NS2 Tire Phase 3 – Test Piles

Client requested coring of TP # 6049 to inspect interface between pile & pinnacled rock

Pile Contractor said coring the pile couldn't be done. We did it!

Lessons Learned (Phase 3)

- During installation of the probe, reaction, & test piles several lessons were learned:
  - expect high grout takes initially in some areas (150% to 200% of theoretical)
  - expect to twist off some drilling equipment / augers in difficult Karst conditions
  - expect to redrill some piles 3 to 6 times before grout stops flowing into underlying Karst.
  - any redrilled piles will take significantly more grout (300% to 1,200% of theoretical volume).

Lessons Learned (Cont.)

- During installation of the probe, reaction, & test piles several lessons were learned:
  - As production progresses, grout takes were expected to lessen.
  - Earliest piles tend to seal upper rock surface & reduce number of open passages into lower voids in rock.
  - Supporting a pile on thin rock seams 2 to 3 feet thick is practical (see piles 6073 & 6079).

Lessons Learned (Cont.)

- If during production, refusal occurs < 80% of depth to rock in Airtrack borings <u>or</u> at a depth < 30 feet below existing grade:
  - Assess individual pile relative to adjacent piles in cap
  - Determine if that pile needs to be downgraded in design capacity.
  - Check capacity of all tension piles carefully

Lessons Learned (Cont.)

- Strain gauges were installed in the test piles. Results of that testing indicated:
  - Upper soil profile has significant skin friction capacity.
  - Up to 56 percent of ultimate axial load capacity came from upper skin friction
  - Only about 44 percent of total capacity came from end bearing.
  - For piles 44 to 66 foot long, there didn't appear to be much change in end bearing percentage.
  - Deeper piles (>65 feet long) should develop more skin friction due to penetration through dense soil & thin rock layers above refusal.

Lessons Learned (Cont.)

- From strain gauge results during pile load tests the following skin friction values were recommended at NS2 Tires:

SPT N-values in Soil	Allowable Skin Friction (psf)
3 or less	None
4 to 10	300 to 500
10 to 35	500 to 1,100
35 to 50	1,100 to 1,500
Weathered Rock	1,700

NS2 Tire over Karst

Construction of Mixing Tower w/2,000 kip Column Loads

NS2 Tires – Phase 4 Study

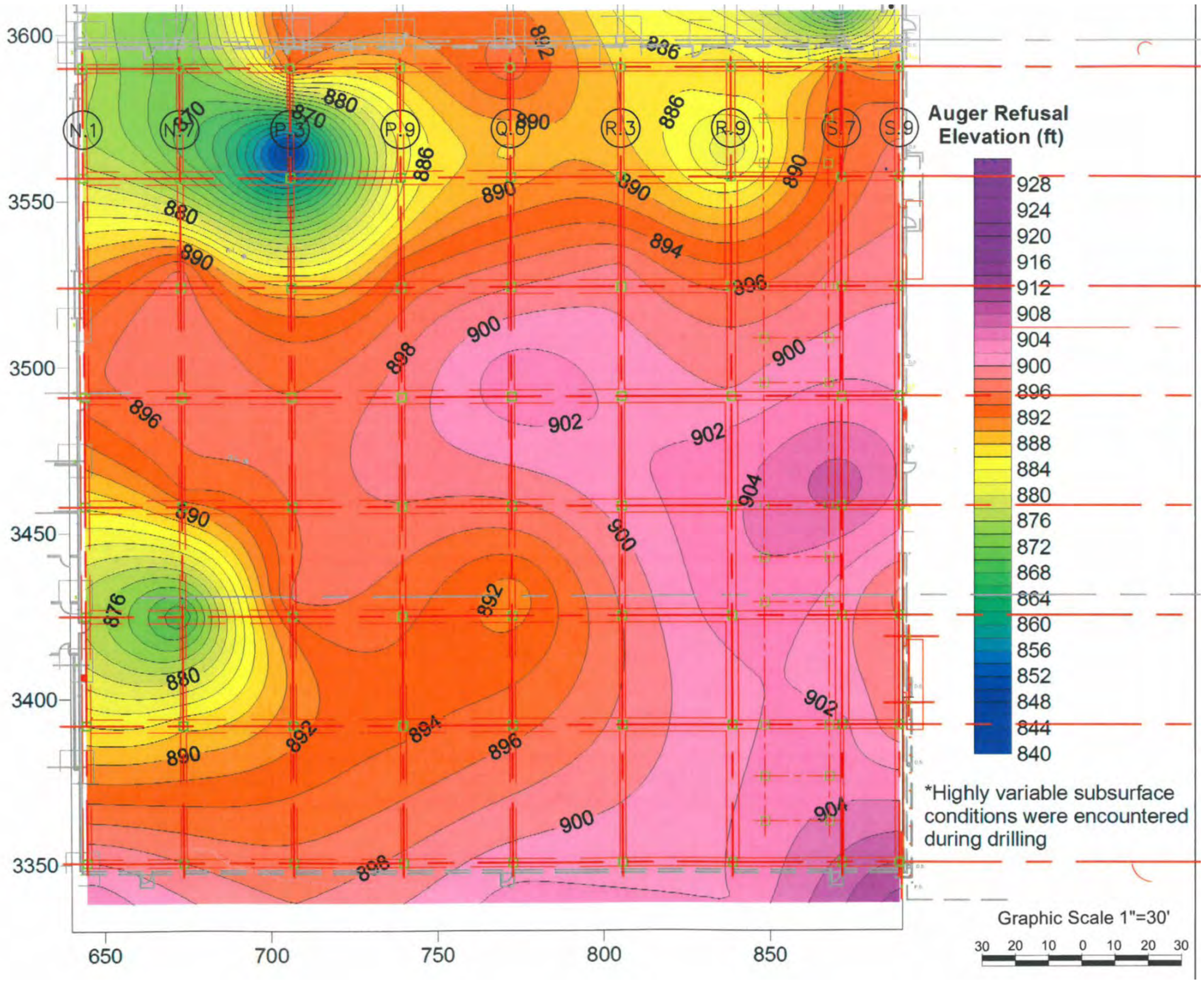
~800,000 sf

Phase 4 Construction including slipping in a new mixing tower.

Phase 4 Exploration Results

- Phase 4 drilling found shallower rock than Phase 3 in mixing tower & silo.
- Some very shallow pinnacled rock was found at depths of 5 to 10 feet below grade near equipment pits.
- Phase 4 earthwork included deep fill (30+ feet) in existing detention pond to support warehouse.

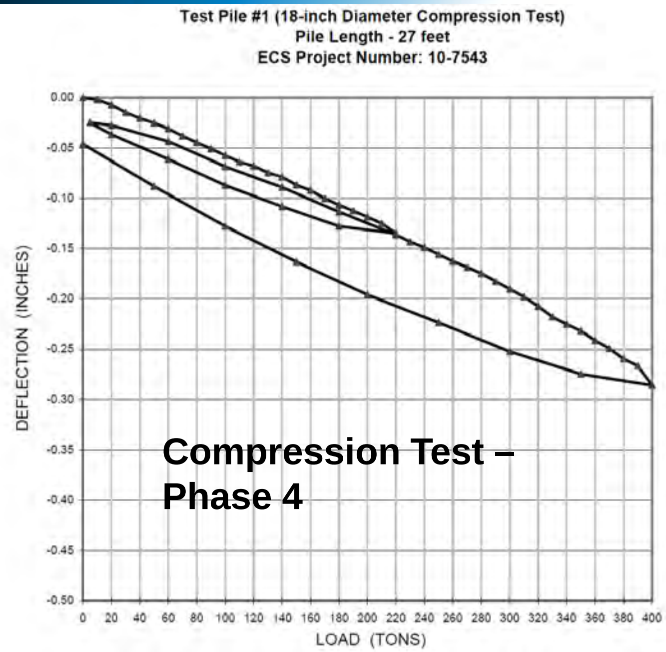
Variability in rock surface – Phase 4 Mixing Tower

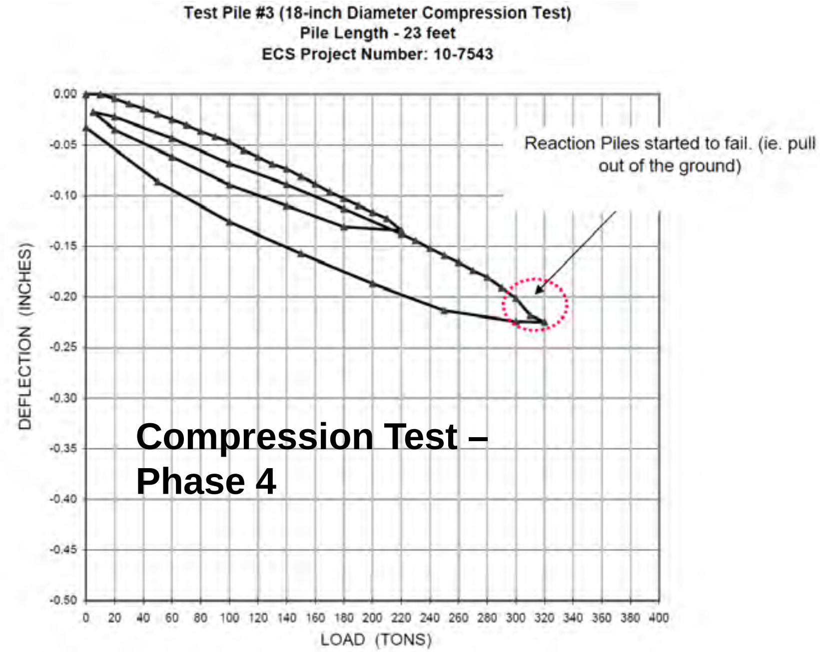


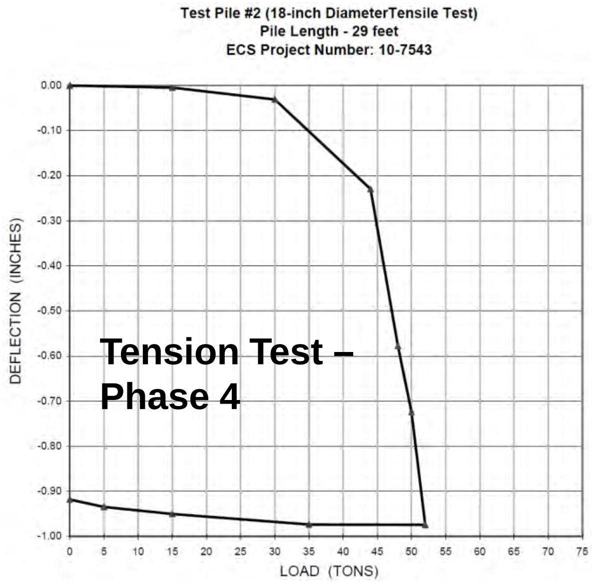
Summary of Test Pile Results – Phase 4

Test Pile Number	Type of Test	Maximum Applied Test Load (tons)	Gross Deflection (in)	Design Allowable Load (tons)	Actual Pile Length
TP#1	Compression	400	0.286	110	27'
TP#2	Tension	52*	0.974	20	29'
TP#3	Compression	310	0.218	110	23'

*Load test stopped due to anchor pile pullout.


Test Pile #1 (18-inch Diameter Compression Test)
Pile Length - 27 feet
ECS Project Number: 10-7543
DEFLECTION (INCHES)
LOAD (TONS)
Compression Test –
Phase 4


Test Pile #3 (18-inch Diameter Compression Test)
Pile Length - 23 feet
ECS Project Number: 10-7543
Reaction Piles started to fail. (ie. pull out of the ground)
DEFLECTION (INCHES)
LOAD (TONS)
Compression Test –
Phase 4


Test Pile #2 (18-inch DiameterTensile Test)
Pile Length - 29 feet
ECS Project Number: 10-7543
DEFLECTION (INCHES)
LOAD (TONS)
Tension Test –
Phase 4

Auger Cast Pile Installation Criteria in Karst

Procedure for installing ACIP piles in Karst

When grout loss occurs during grout placement in a pile, the following procedures apply:

- Remove steel cage & reinforcing steel center bar, if applicable.
- Allow fresh grout to remain in augered hole for a few hours.
- After a few hours, reattempt to install pile using general procedure.
- If grout loss still occurs, fresh grout remains in augered hole until end of day.
- At end of day, grout will be removed from the augered hole by drilling.
- Low strength flowable fill is placed into hole & allowed to “set up” overnight.
- Next day, a 3rd attempt to install the pile using general procedure.
- If grout loss again, fresh grout can remain in hole a few hours.
- Repeat above Steps until pile is constructed by general procedure.

Validation & Acceptance of Auger Cast Piles in Karst – How Do You Prove Pile Is Okay?

ECS	Structural	Kajima				1st Attempt						
						Actual		Est. Refusal - Geo Study			Actual	Calc.
						Drill		80%	Depth	Method	Grout V	Grout V
			Cap #	Line	Pile #	Date	Depth	Criteria**	Criteria (Ft)	Criteria	Actual (CF)	% Min*
1			PC-4	N.7-11.4	4	1/15	61	42	52	Air Track	205	158
1			PC-4	N.7-11.4	5	1/31	55	42	52	Air Track	138	118
1			PC-4	N.7-11.4	6	2/3	56	42	52	Air Track	154	130
1			PC-4	N.7-11.4	7	2/4	56	42	52	Air Track	128	108
1			PC-4	P.3-11.4	8	1/15	35	30	38	SPT	95	129
1			PC-4	P.3-11.4	9	1/16	40	30	38	SPT	108	128
1			PC-4	P.3-11.4	10	1/17	40	30	38	SPT	114	134
1			PC-4	P.3-11.4	11	2/3	44	30	38	SPT	150	160
2			PC-4	P.9-11.4	12	1/15	76	40	50	Air Track	218	136
2			PC-4	P.9-11.4	13	1/16	39	40	50	Air Track	96	117
2			PC-4	P.9-11.4	14	1/17	37	40	50	Air Track	96	123
2			PC-4	P.9-11.4	15	1/18	33	40	50	Air Track	87	124
1			PC-4	Q.6-11.4	16	1/15	34	27	34	SPT	112	155

Lessons Learned

1. Japanese clients respect your opinion, but want proof that what you say is a fact. For this job that meant a bunch of drilling and testing.
2. Sometimes you can innovate by using a weakness of a foundation system as a benefit (i.e. grout loss into Karst was a good thing on this project).
3. Expect high grout takes initially to “treat” the Karst conditions. Expect to re-drill and re-grout individual piles 3 to 6 times before grout will stop flowing out of the hole.
4. Expect to lose some augers during geotechnical study and also during auger cast pile installation. Some piles may need to be abandoned if an auger shears off.

Lessons Learned Cont.

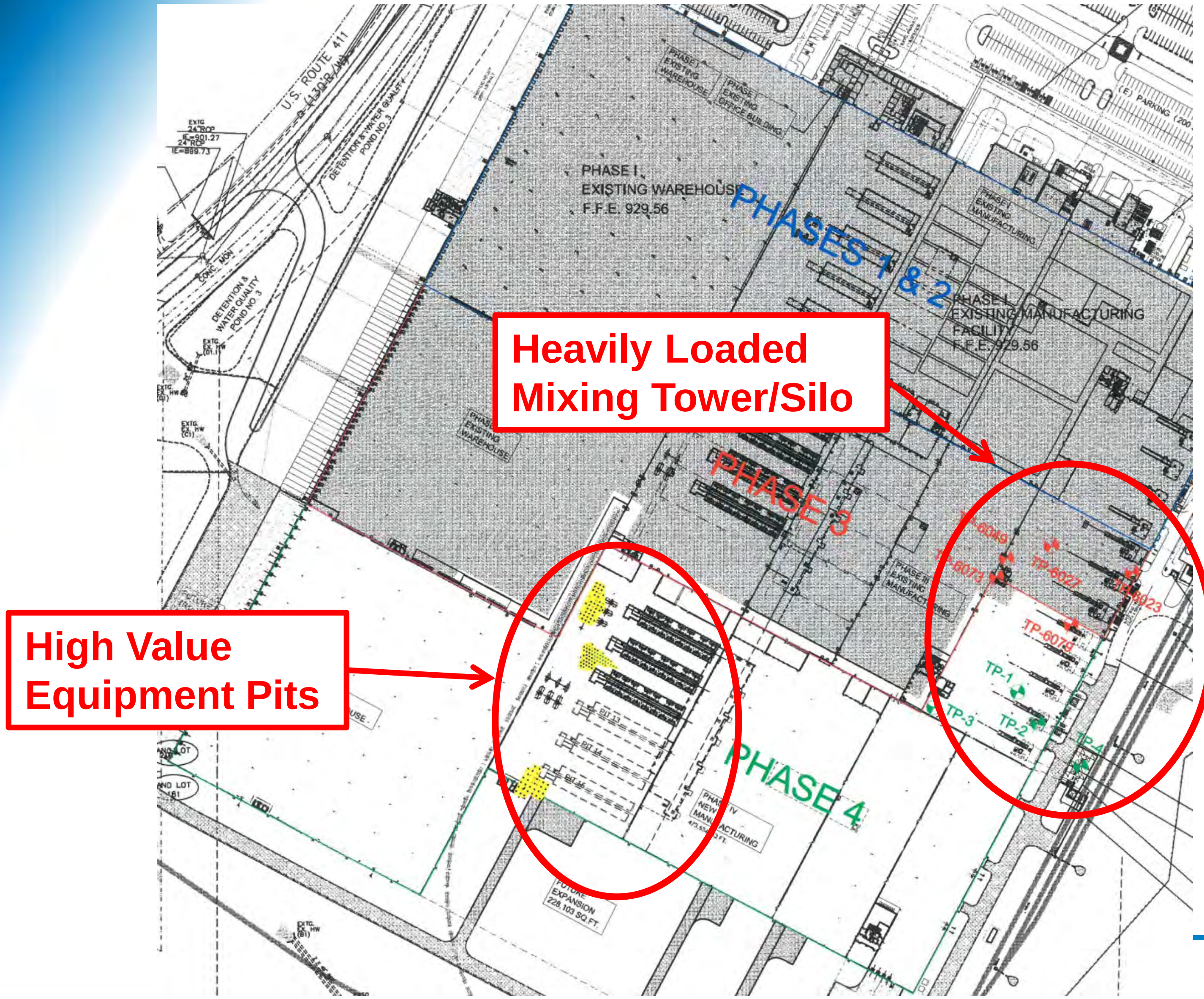
5. Auger cast piles can be excellent end bearing elements even if the rock surface is erratic and steeply sloped.
6. 2 feet of competent limestone can arch over defects or voids in some cases.
7. 10 ft of weathered rock may not be enough to arch over underlying defects.
8. Adding “quality” to every process is extremely important to Japanese clients. In this case history proving each pile was good (in multiple ways) was important to them.

NS2 Tires – Phase 4

~800,000 sf

Grouting & Sinkhole Remediation at Equipment Pits

Effect of Karst in another area…



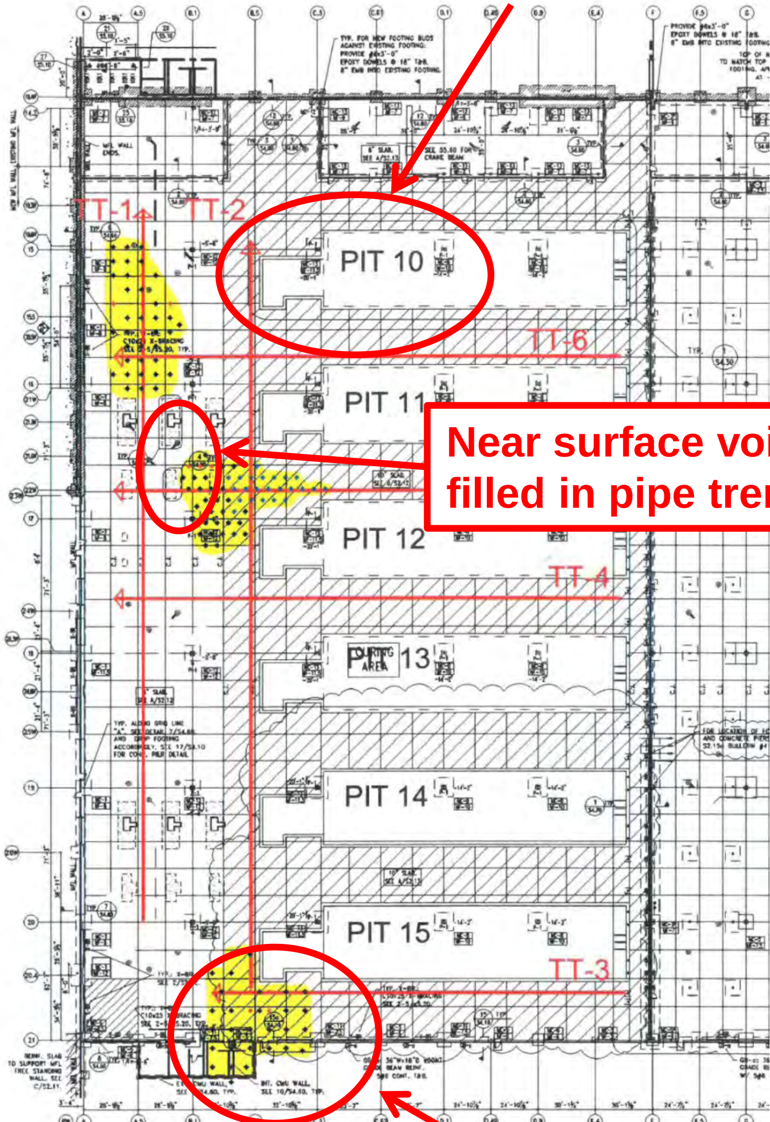

Circular crack pattern
at Pit 10 after 3” rain


Pit 12 Grouting


Distress at Equip.
Pit 11 after 3” rain

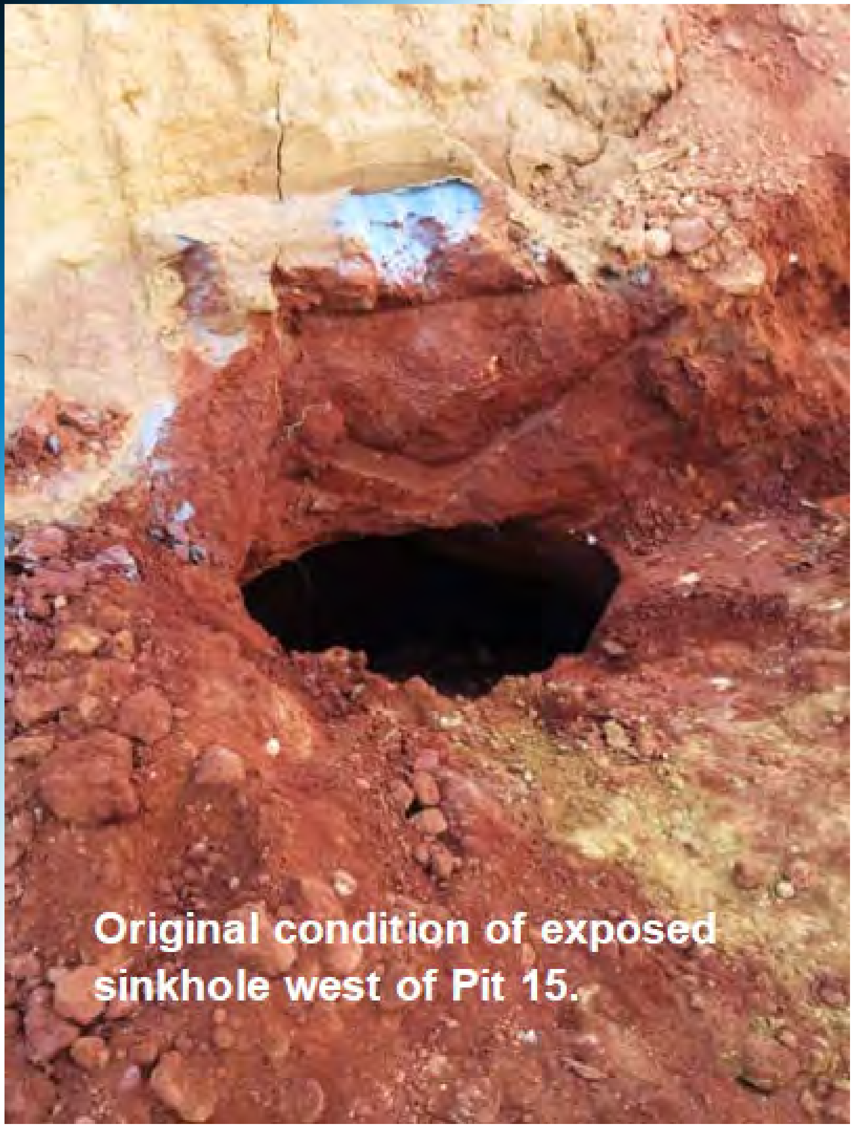

Pit 11

Pit 10 – Circular Cracking in Mud Slab

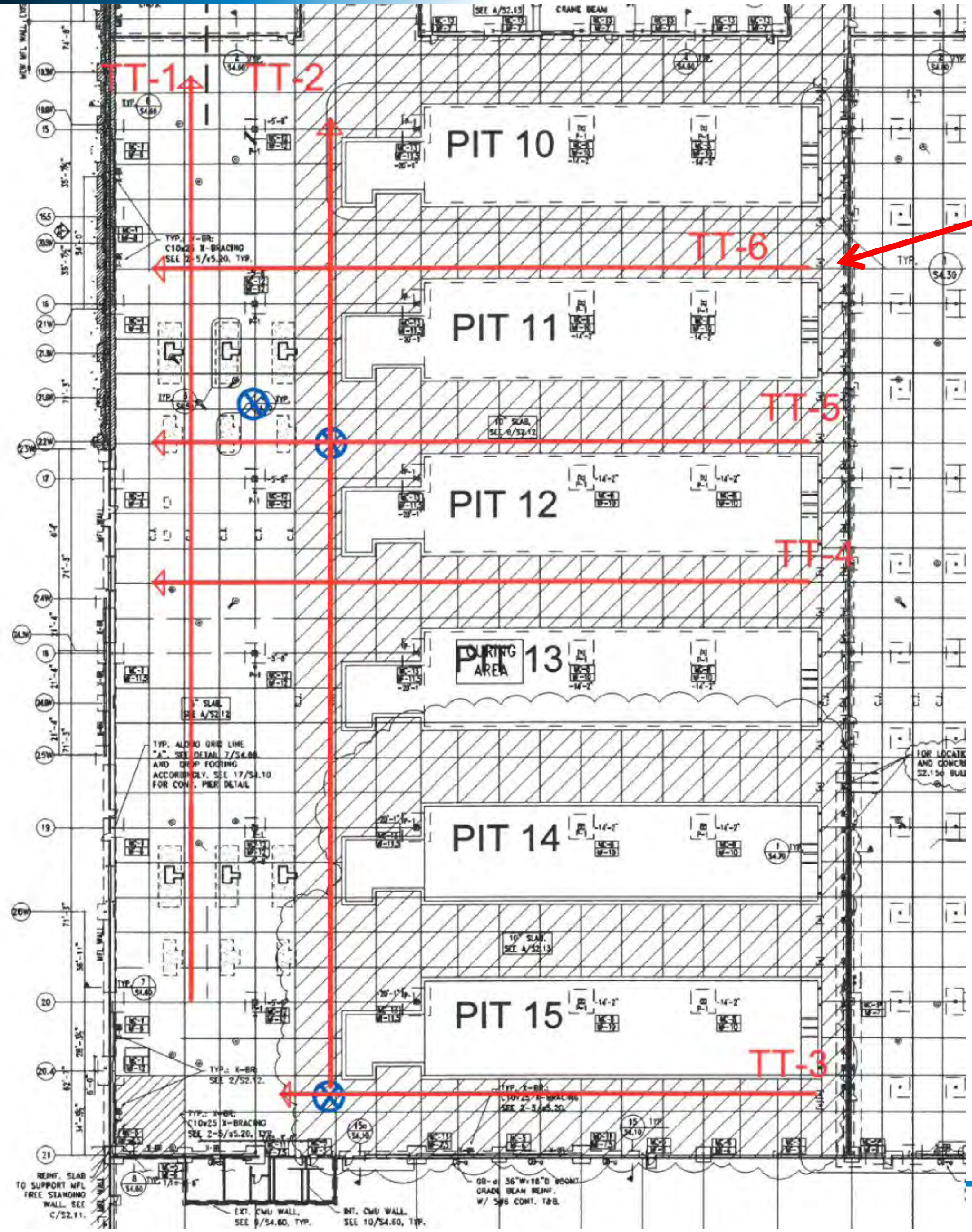


Near surface void filled in pipe trench

Void at shallow depth filled this area


Original condition of exposed sinkhole west of Pit 15.

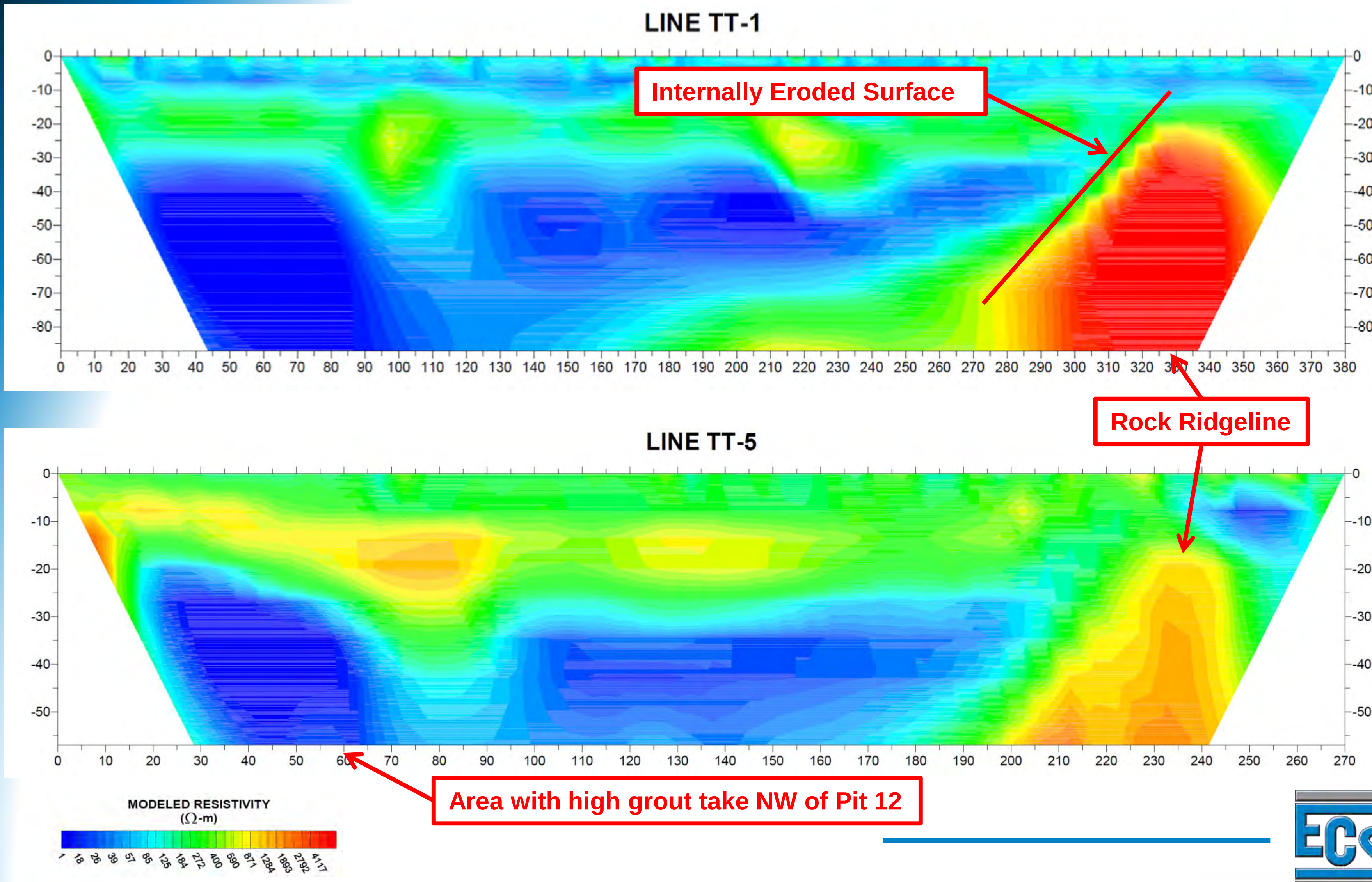

Filling of sinkhole with flowable fill.



ER Transect

Approximate Location of void or very high grout take

ERI Results at Equipment Pits



Grouting NW of Pit 12.

Note the rebar for impending slab pour.

Example of Daily Field Reports

Summary of Services Performed (field test data, locations, elevations & depths are estimates) & Individuals Contacted.

The undersigned arrived on site, as requested, to observe Jensen's Line Pumping continue grouting injection points for pressure grouting operation located west of curing pit 10 between column lines A/B.1 and 15/16.

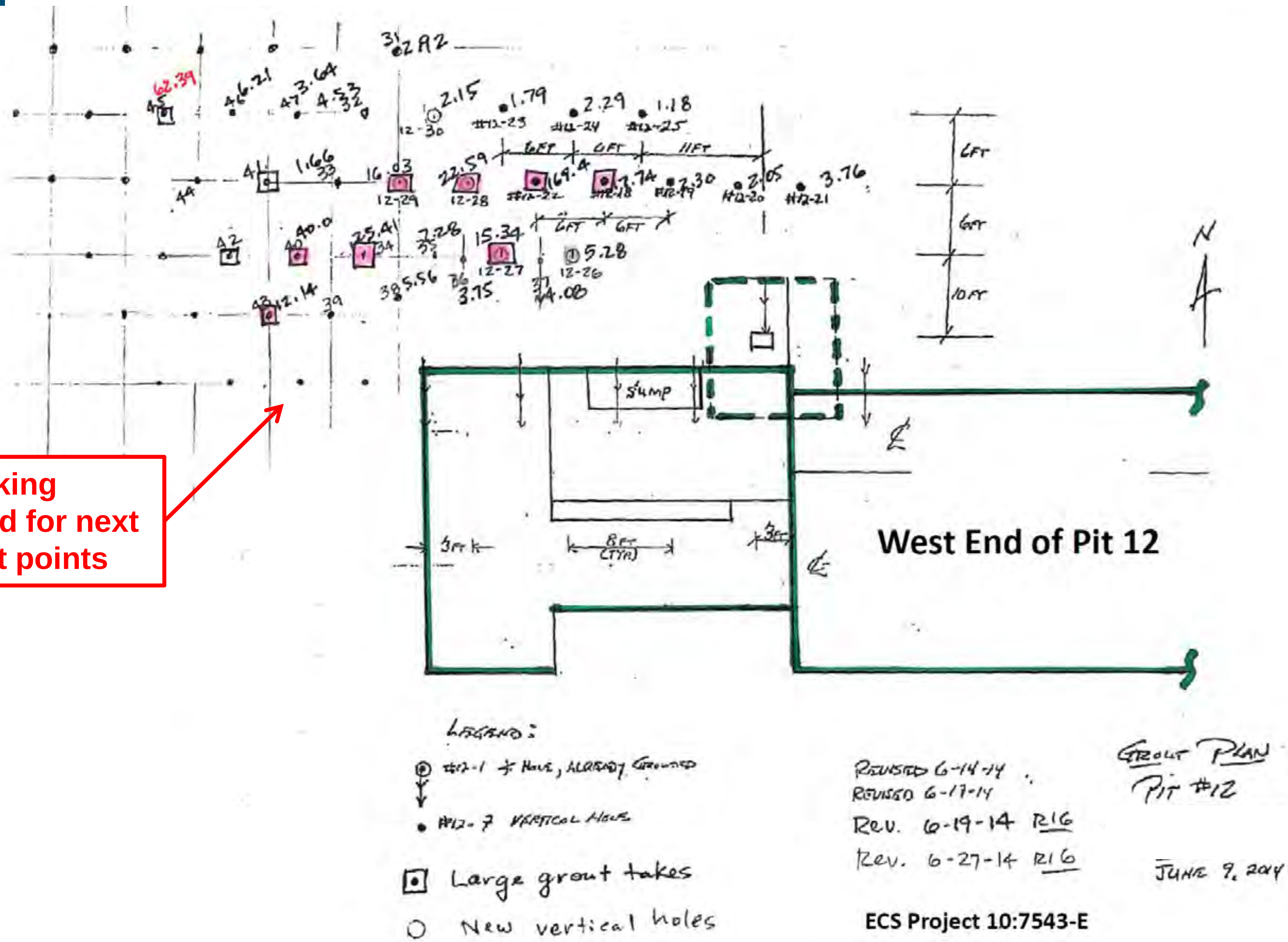
Jensen's Line Pumping placed 4,000 psi compaction grout at the following locations on this day:

Pit 10:
The contractor placed 10.85 cy of grout at 10-111.
The contractor placed 4.08 cy of grout at 10-113.
The contractor placed 0.35 cy of grout at 10-114.
The contractor placed 0.57 cy of grout at 10-116.
The contractor placed 4.38 cy of grout at 10-118.
The contractor placed 9.82 cy of grout at 10-120.

Add comments to help interpret results as program develops

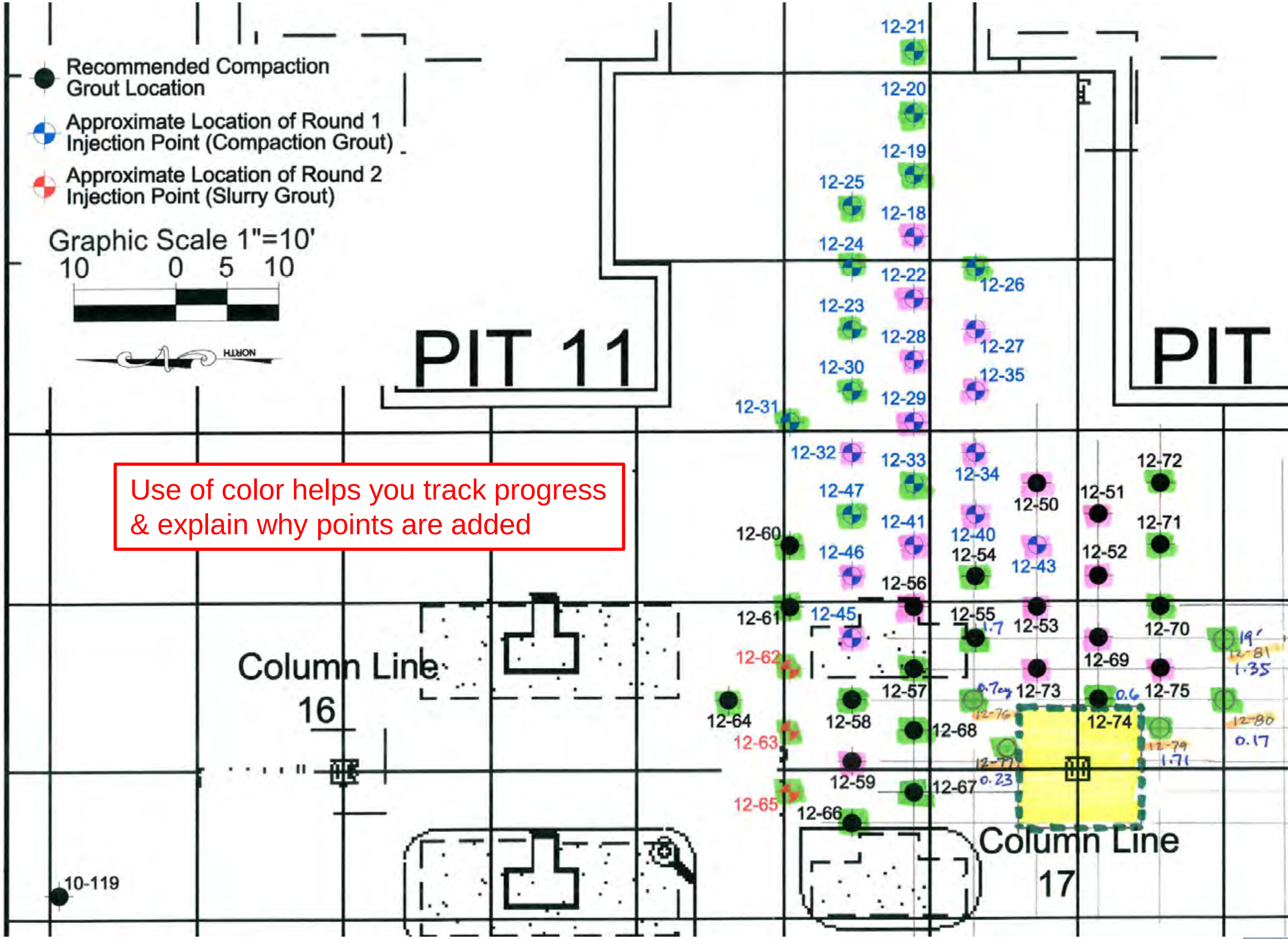
[Engineers Note:] In well compacted fill or competent natural soil typical grout takes should be about 1 to 2 cy for the shallow depth (<50 feet) being treated. It is our experience that grout takes above 3 cy likely indicate very soft or raveled soil conditions associated with Karst geology and on-going internal soil erosion.

Directing/Tracking Grout Program



Thinking ahead for next grout points

Working Grout Pattern NW of Pit 12

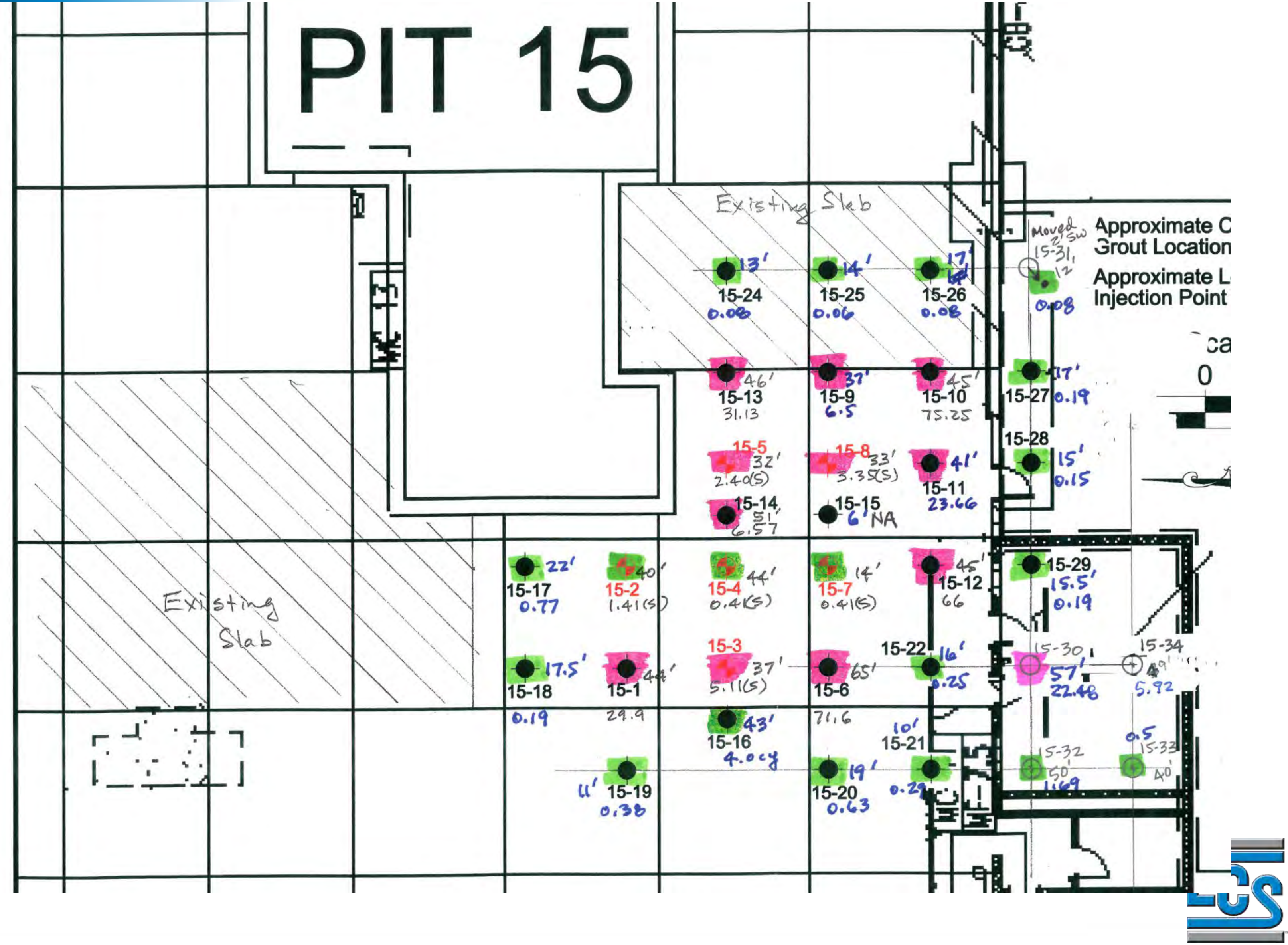


Use of color helps you track progress & explain why points are added

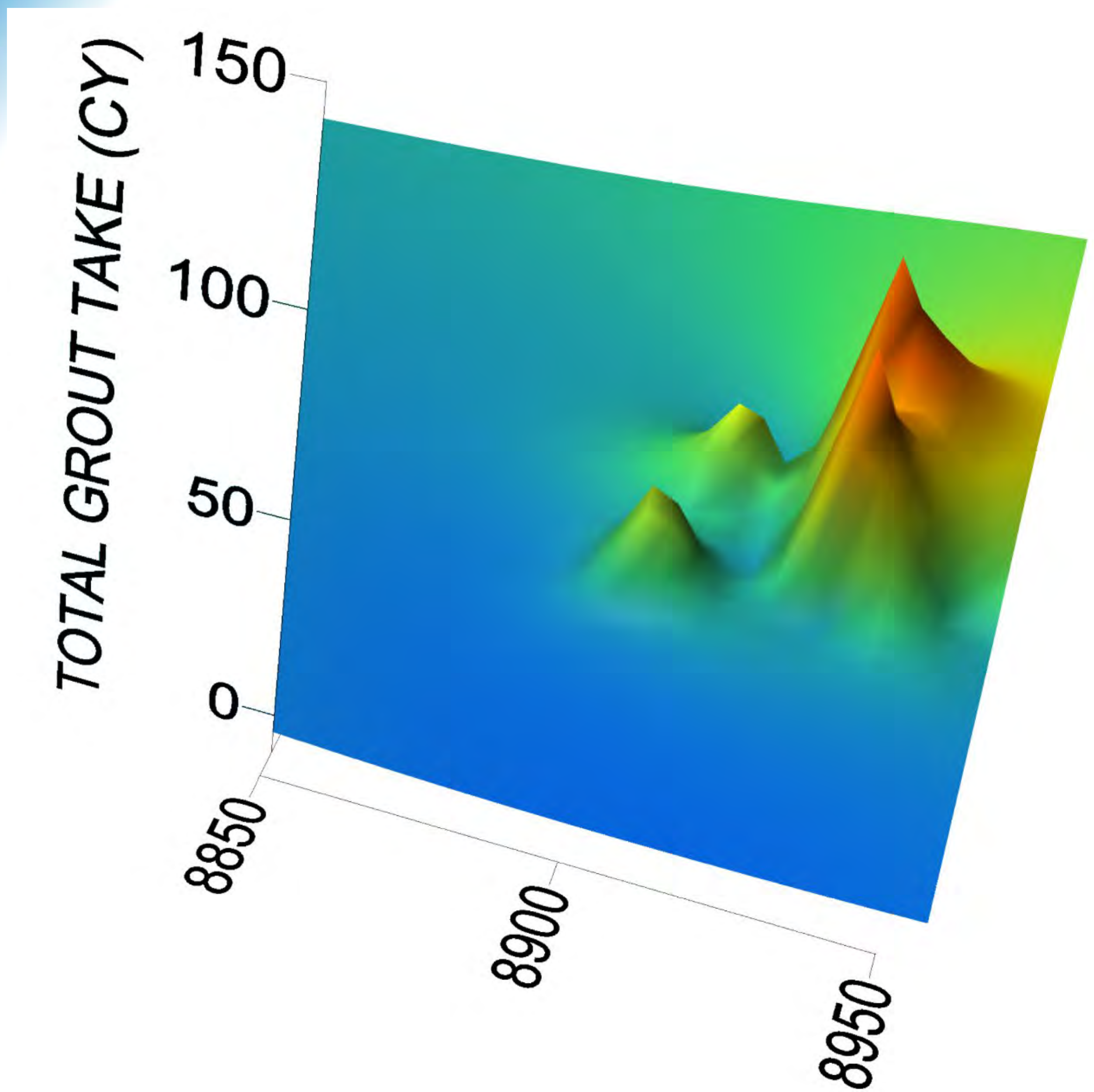
Daily Tracking of Grout Take in Tabular Form

Table 2 - Grout Injections: Slab Area North & West of Pit 12 SECOND ROUND OF INJECTIONS: Starting 11/1/2014					
Grout Injection No.	Inclination	Slurry (S) or Compaction (C)	Initial Casing Depth (ft)	Total Grout Take (cy)	Ave. Grout Take (cf/LF)
12-50	Vertical	C	50	**9.33**	**5.0**
12-51	Vertical	C	44	Abandoned	NA
12-51A	Vertical	C	53	**7.99**	**4.1**
12-52	Vertical	C	64	**17.50**	**7.4**
12-53	Vertical	C	58	**5.49**	2.6
12-54	Vertical	C	50	2.55	1.4
12-55	Vertical	C	45	1.69	1.0
12-56	Vertical	C	Lost Augers	Abandoned	NA
12-56A	Vertical	C	45	**5.42**	**3.3**
12-57	Vertical	C	60	2.05	0.9
12-58	Vertical	C	54	2.13	1.1
12-59	Vertical	C	42	**7.07**	**4.5**
12-60	Vertical	C	49	3.34	1.8
12-61	Vertical	**S**	46	2.88	1.7
12-62	Vertical	**S**	41	0.38	0.3
12-63	Vertical	**S**	49	0.46	0.3

Working Grout Pattern Pit 15



Grout Take at Pit 15



Daily Tracking of Grout Take in Tabular Form

Table 3 - Grout Injections at Southwest of Pit 15

Grout Injection No.	Inclination	Slurry (S) or Compaction (C)	Initial Casing Depth (ft)	Total Grout Take (cy)	Ave. Grout Take (cf/LF)	Remarks
15-1	Vertical	C	44	29.89	18.3	
15-2	Vertical	S	40	1.41	1.0	Slurry, possible Void 26' to 38'
15-3	Vertical	S	37	5.11	3.7	Slurry Grout
15-4	Vertical	S	44	0.41	0.3	Slurry Grout
15-5	Vertical	S	32	2.40	2.0	Slurry, possible Void 13' to 16'
15-6	Vertical	C	65	71.60	29.7	
15-7	Vertical	S	14	0.41	0.8	Slurry Grout
15-8	Vertical	S	33	3.35	2.7	Slurry, possible Void 7' to 33'
15-9	Vertical	C	37	6.50	4.7	
15-10	Vertical	C	49	72.25	39.8	
15-11	Vertical	C	41	23.66	15.6	
15-12	Vertical	C	45	66.00	39.6	
15-13	Vertical	C	49	31.13	17.2	
15-14	Vertical	C	56	6.57	3.2	Compaction; Heave at 42'
15-15	Vertical	C	6	NA	NA	To shallow to grout
15-16	Vertical	C	43	4.00	2.5	
15-17	Vertical	C	22	0.77	0.9	

Use color to help client separate good from bad

Summary of Grouting at NS2 Phase 4

Location	Total Grout (CY)	Ave. Grout (CY/Hole)	Biggest Grout Take (CY)	Biggest Grout Take (CF/LF)
Pit 10	107	1.8	9.4	11.0
Pit 11	82	1.9	4.8	4.0
Pit 12	76	4.5	34.6	26.7
NW of Pit 12	**646**	**10.8**	**169.4**	**114.3**
W of Pit 10	211	5.3	35.9	22.5
SW of Pit 15	**363**	**10.7**	**72.3**	**39.8**
Total Grout	**1,484**			

Ultimate Grout Cost : $1,000,000

Lessons Learned (Phase 4 Grouting)

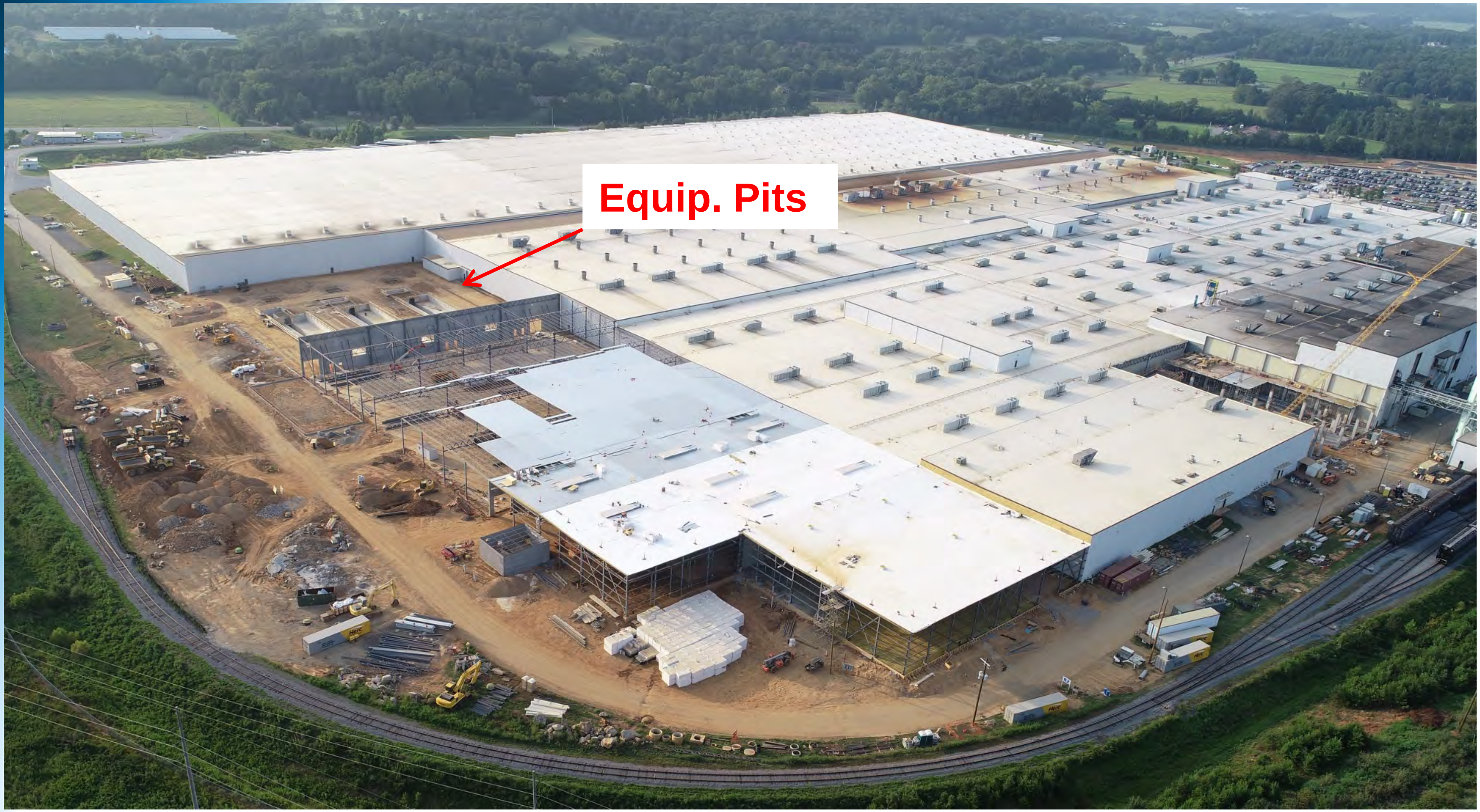
- Nobody likes sinking money into the ground to protect against an unknown risk.
- Low mobility grouting allows you to best control the area & depth being treated.
- At NS2 site, deepest injection pipes (below ~30 ft depth) took most of the grout.
- When highly variable lengths & grout takes occur – add extra points to be sure area is treated.
- Be sure to track total grout take in CY & CF/LF. Tracking per foot grout take normalizes results.
- Grout takes and problem areas matched well with ERI study results.

NS2 Tires – Phase 5

~390,000 sf

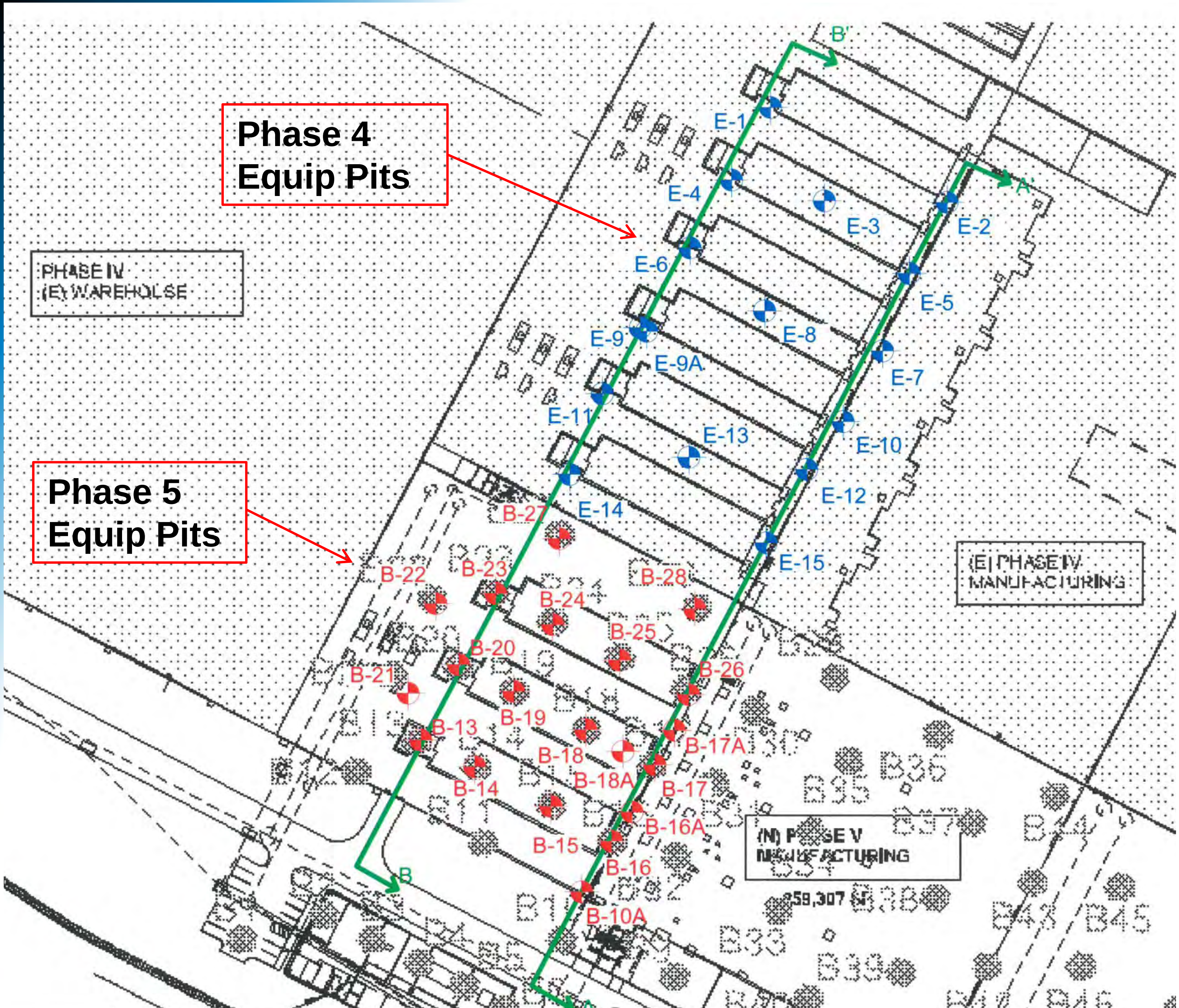
Grouting & Sinkhole Remediation at Equipment Pits (again)

Phase 5 Under Construction



Lessons Learned from Phase 5

- Even lightly loaded equipment pit structures can be critical to Owner.
- To mitigate risk of ground relaxations & damage a decision to support to Phase 5 equipment pits on ACIP piles was made.
- Structural engineer designed piles to support the pits in the air without soil.
- Pile installation at pits went smoothly with few re-drills and moderate grout takes.
- Then a sinkhole appeared…



Phase 4
Equip Pits
Phase 5
Equip Pits
PHASE IV
(E) WAREHOUSE
(E) PHASE IV
MANUFACTURING
(N) PHASE V
MANUFACTURING
B'
A'
B
A
E-1
E-2
E-3
E-4
E-5
E-6
E-7
E-8
E-9
E-9A
E-10
E-11
E-12
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E-14
E-15
B-10A
B-13
B-14
B-15
B-16
B-16A
B-17
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B-18
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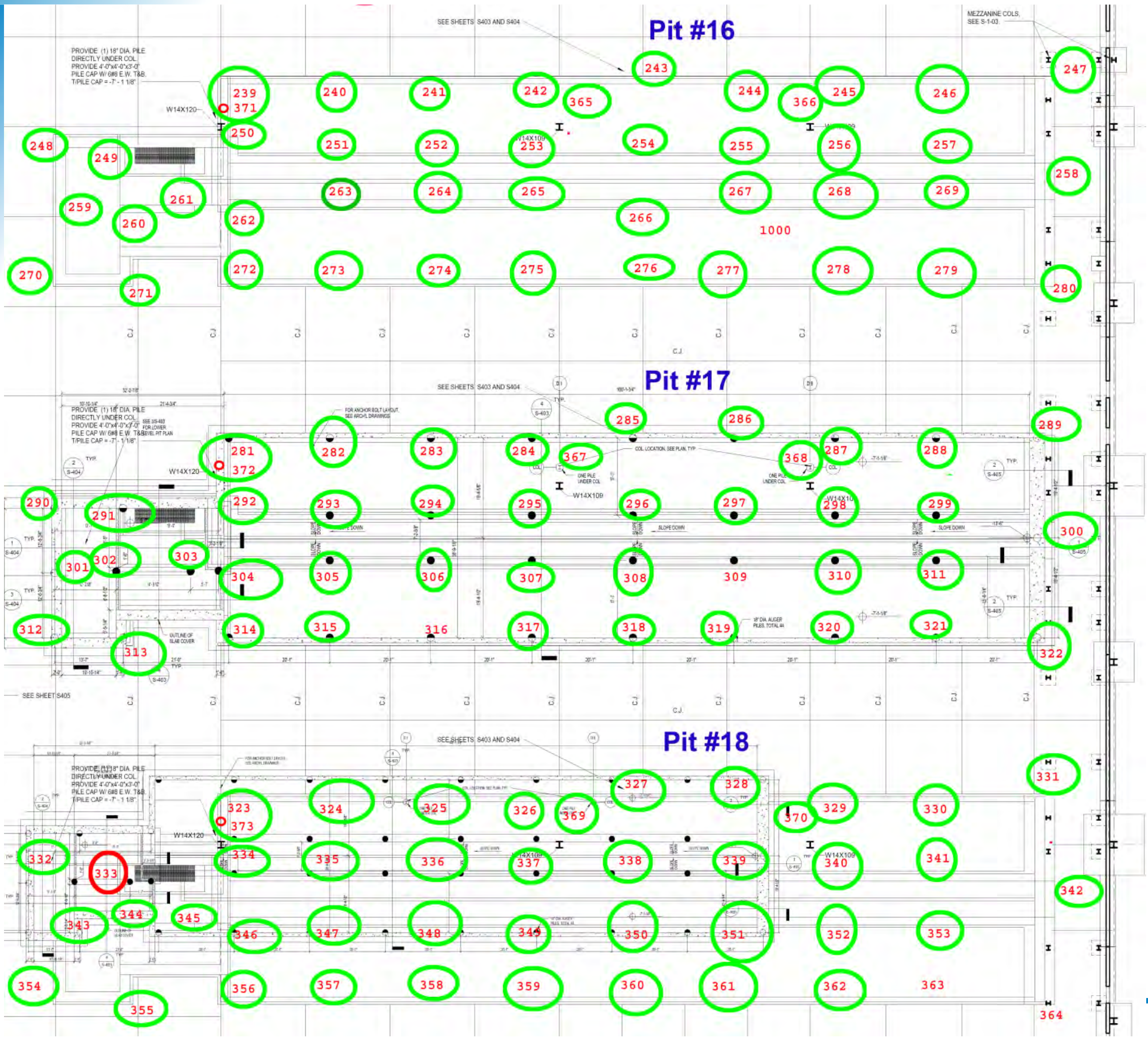
B-28

Phase 5 Equipment Pit Layout w/piles

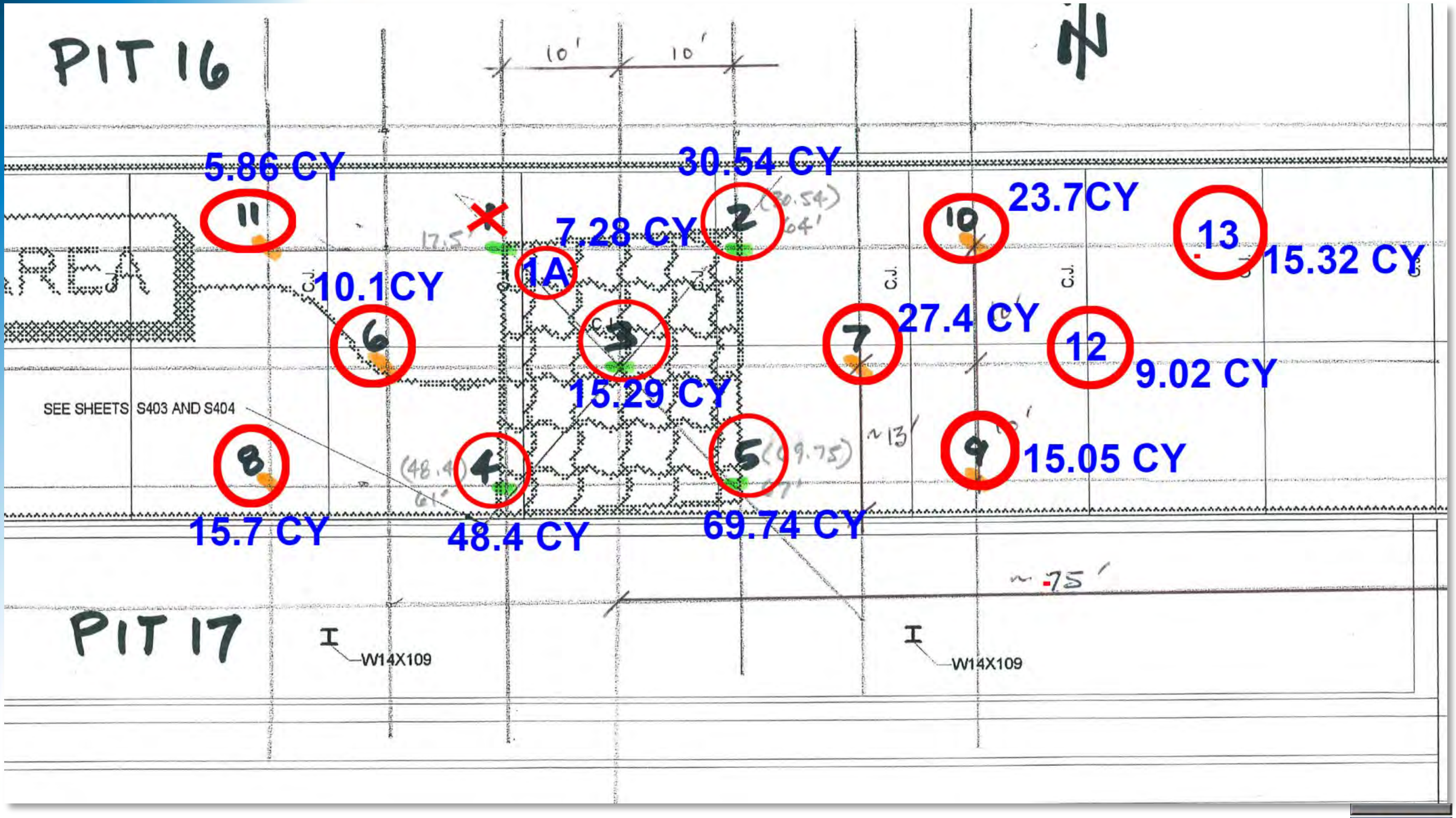


Ph 5 Equip. Pits – Typical ACIP Info

Pile Number		Drilled Date	Ground Surface Elev.	Drill Depth (Ft.)	Theoretical Pile Volume (CU. Ft.)	Total Number of Pump Strokes	Actual Grout Volume (CU. Ft.)	Grout Factor (%)	Grout Return Depth/Head (FT.)	Grout Subsided After/During Placement
357		5/4/2018	921.00	53.00	93.81	164	146	156	8	No
358		5/3/2018	921.00	61.00	107.97	180	160	148	5	No
359		5/3/2018	921.00	62.00	109.74	194	173	157	5	No
360		4/30/2018	921.00	44.00	77.88	131	117	150	12	No
360	R1	5/3/2018	921.00	60.00	106.20	174	155	146	8	No
361		5/3/2018	921.00	70.00	123.90	205	182	147	15	No
361	R1	5/4/2018	921.00	72.00	127.44	240	214	168	15	No
362		5/2/2018	921.00	65.00	115.05	176	157	136	15	No
362	R1	5/3/2018	921.00	57.00	100.89	160	142	141	10	No
363		5/4/2018	921.00	65.00	115.05	225	200	174	5	No
364		5/4/2018	921.00	80.00	141.60	240	214	151	5	No
365		4/28/2018	921.00	49.00	86.73	197	175	202	5	No
366		4/28/2018	921.00	51.00	90.27	154	137	152	8	No
367		5/2/2018	921.00	52.00	92.04	150	134	145	5	No
368		5/2/2018	921.00	57.00	100.89	156	139	138	10	No
369		5/5/2018	921.00	52.00	92.04	171	152	165	10	No
370		5/4/2018	921.00	62.00	109.74	180	160	146	14	No
371		4/28/2018	921.00	35.00	61.95	102	91	147	10	No
372		5/4/2018	921.00	42.00	74.34	158	141	189	5	No
373		5/2/2018	921.00	63.00	111.51	215	191	172	0	Yes
373	R1	5/3/2018	921.00	63.00	111.51	178	158	142	5	No

Phase 5 Equip. Pits – Sinkhole

Grouting Plan – Pits 16 & 17



Grouting Results – Pits 16 & 17

Grout Injection No.	Initial Casing Depth (ft)	Total Grout Take (cy)	Ave. Grout Take (cf/LF)	Remarks
1	17.5	NA	NA	Refusal at 17.5', Point not grouted.
1A	52	7.28	3.8	
2	64	30.54	12.9	
3	72	15.29	5.7	
4	61	48.40	21.4	
5	67	69.74	28.1	
6	57	10.10	4.8	
7	72	27.40	10.3	
8	59	15.70	7.2	
9	71	15.05	5.7	
10	70	23.70	9.1	
11	52	5.86	3.0	
12	55	9.02	4.4	
13	71	15.32	5.8	
Totals	**823.0**	**293.4**		
Average	**63**	**22.6**	**9.4**	

Lessons Learned from Phase 5

- Even when you try & mitigate risk of ground relaxations & damage, surprises can happen.
- After ACIP piles went in w/no issues a sinkhole formed less than 5 feet from a pile.
- Moderate to high grout takes were experienced after ACIP installation.
- Sinkholes can appear when least expected…

Overall Lessons Learned from NS2

- Construction over Karst is challenging. Expect the unexpected - highly variable conditions.
- Use of ACIP piles can be messy in Karst but save money overall.
- Japanese clients want you to prove your opinions & that quality is built into the project.
- Prepare to grout in areas that show ground relaxations, voids or sinkhole formation.
- A trusting client allows us to push the envelope & truly become a consultant.

Questions?