INTERNATIONAL SOCIETY FOR MICROPILES

May 31- June 2, 2023
Vail, Colorado

15TH International Workshop On Micropiles

WHEN HEAT TREATMENT GIVES YOU LEMONS…

Quality Control for Galvanized Washers

presented by Justin Toney, P.E. | Crux Subsurface

CRUX
A QUANTA SERVICES COMPANY

Project Introduction

- Crux's largest EPC contract to date on electrical powerline project
- More than a dozen segments
- 1,700+ poles and 50+ contracting companies
- Drilled shaft, direct embedded, and micropile foundations
- Access concerns
  - Environmental
  - Biological
  - Cultural
  - Fire risk

INTERNATIONAL SOCIETY FOR MICROPILES

Widespread Micropile Use

- 10 unique segments
  - Pole design packages rolled out over multiple years
  - Multiple pole suppliers
  - Different loading and geometry demands
- 624 foundations (3,762 individual piles)
- 4 yr – 3 mo construction duration
  - September 2016 thru December 2020

INTERNATIONAL SOCIETY FOR MICROPILES

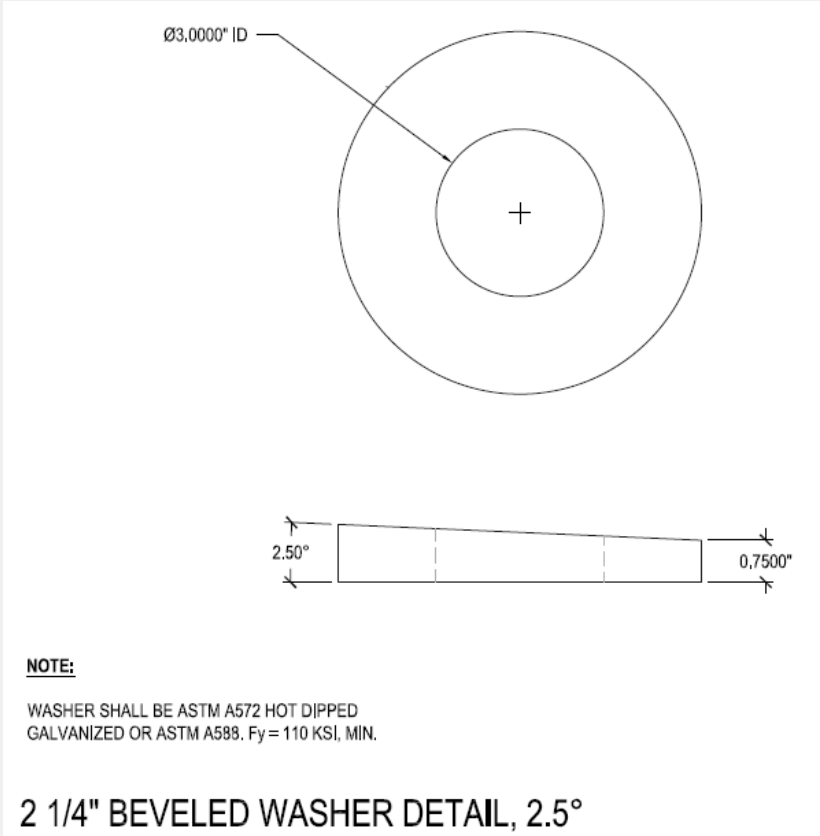
Micropile Connections

- Steel pile caps with bolted connections
- 3 different bar sizes, 2 pile batters
- 7,524 individual washers
  - 192 – 1.75”
  - 3,564 – 2.25”
  - 3,768 2.5”
- 278-354 kip pile axial demand

INTERNATIONAL SOCIETY FOR MICROPILES

Washer Requirements

- Attempted to keep parts as light as possible
- Specified geometry similar to vendor catalogued parts
- No requirement for additional flat hardened washer
- Designed for flexural and bearing demands
- Specified yield strengths up to 110 ksi
- ASTM A572 or A588



INTERNATIONAL SOCIETY FOR MICROPILES

Washer Fabrication

- High yield strengths required heat treating
- Not possible with A572 or A588 material
- Parts fabricated from tubing with SAE 1026 carbon and SAE 1045 or SAE 4140 low carbon steel alloy
- Galvanizing post heat-treatment

INTERNATIONAL SOCIETY FOR MICROPILES

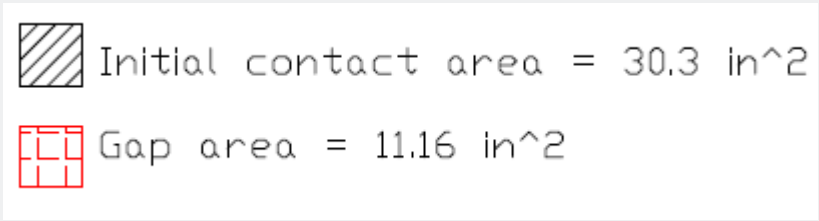
Discovered “Warped” Washers

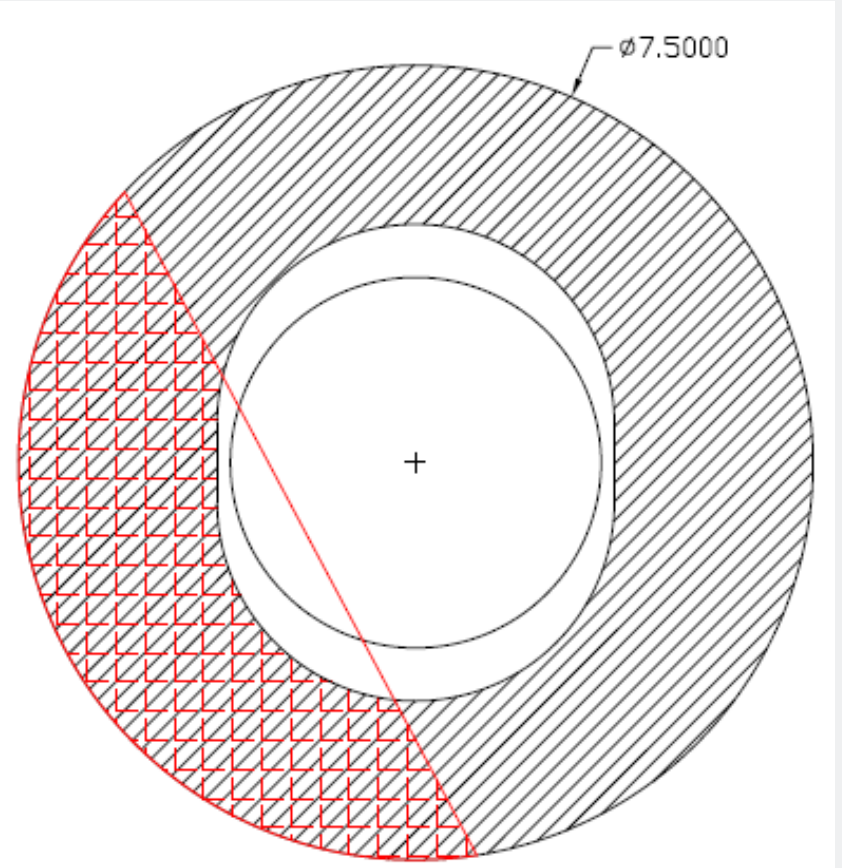
- **October 2018** gaps observed between washer and pile cap surface
- Probable cause attributed to band saw cutting high yield strength (high hardness) parts
- Measured gaps up to 1 mm (0.04”) thick
- No defined allowable fabrication tolerance
- Client concern over reduced contact area and potential increase in bearing stress

INTERNATIONAL SOCIETY FOR MICROPILES

“Warped” Washers - Analysis

- Gaps identified at nearly 50 individual washers over 12 structure locations
- Feeler gauges used to determine extent and depth of gaps
- Measurements mapped
- Bearing analysis performed to analyze bearing stress under theoretical reduced area





INTERNATIONAL SOCIETY FOR MICROPILES

“Warped” Washers - Fix

- Flatness tolerance established for fabrication
  - 0.032” ASTM F438 washers greater than 3” nominal size
- Out of tolerance washers removed and re-worked to within tolerance where possible
- Solutions for future fabrication
  - Slower feed rate when cutting
  - Manually checking every washer
  - Additional machining prior to galvanizing

Discovered Fractured Washers

- **December 2018** single broken washer observed on segment “A”
  - 2.25” x 2.5 degree washer
  - Located on top of pile cap
  - Pole set but line not installed
- **May 2019** multiple broken washers observed on segment “B”
  - 2.25” x 5.0 degree washer
  - Located on both top and bottom of pile cap
  - Poles set and line energized

ISM INTERNATIONAL SOCIETY FOR MICROPILES

Questions...

- Is there a life/safety risk with potential washer failure?
- What is the cause/plausibility of washer failure(s)?
- How do we fix the issue?
- How do we prevent the issue from reoccurring?

INTERNATIONAL SOCIETY FOR MICROPILES

Life/Safety Risk

- No (**December 2018**)
  - Only one broken washer indicating isolated issue
  - No wire strung
- Possibly (**May 2019**)
  - Additional broken washers in different size indicate potential widespread issue
  - Energized line
- Mitigation measures
  - Broken and suspected top washers replaced
  - Bottom washers “banded” with temporary replacement washers

ISM INTERNATIONAL SOCIETY FOR MICROPILES

What's the Cause/Plausibility?

- Washers sourced for individual segments as designs were completed, so follow the material tracking trail, right?
- Review of installation records revealed lack of transparency in material tracking
  - No marking of individual parts
  - No tracking of installed washers
- It was assumed that segment specific material was installed in the respective segments
- At this point 2,028 (60%) 2.25" washers installed across 365 structure locations

What's the Broken Washer Tell Us?

- 2.25" x 2.5 degree broken washer from segment "A" and control washer known to be fabricated for segment "A" sent to lab
- Chemical and physical testing identified the following for the broken washer
  - Rockwell C hardness 46.9 (30-35 specified)
  - Hydrogen embrittlement ruled out
  - Zinc deposits on fractured faces
  - Machining marks on washer surface

Table 2: Rockwell hardness in Interior, HRC

Sample:	Intact	Fracture 2	Fracture 5
Impression #1	34.2	47.2	45.4
Impression #2	34.7	46.3	45.4
Impression #3	34.7	47.3	45.0
Average	34.5	**46.9**	**45.3**
Print specification	30 to 35 HRC		

SAE 4140 Material

- Control washer close match with MTR for segment “A” fabricated washers (*Heat ABCD*)
- Nearly identical chemical composition between two washers except for Nickel (same material different heats)
- SAE 4140 identified as material for both washers
- Field hardness testing on segment “A” in **January 2019** revealed HRC>41.5 on 14 washers of 172 tested

Element	Symbol	Intact	Fracture 2	Specification for 4140 Steel Per ASTM A519-17
Carbon	C	0.40	0.42	0.38-0.43
Sulfur	S	<0.005	<0.005	0.040 max.
Phosphorus	P	0.007	0.006	0.040 max.
Silicon	Si	0.28	0.31	0.15-0.35
Manganese	Mn	0.96	0.94	0.75-1.00
Chromium	Cr	1.04	1.04	0.80-1.10
Nickel	Ni	0.19	0.12	
Molybdenum	Mo	0.21	0.19	0.15-0.25
Vanadium	V	0.024	0.024	

INTERNATIONAL SOCIETY FOR MICROPILES

Heat WXYZ Heat Treatment and Identification

- 4140 material only supplied on three fabrication orders prior to segment “A”, all using an identical material heat (*Heat WXYZ*)
- *Heat WXYZ* MTR closely matched Nickel content of broken washer from segment “A”
- Fabrication records for previous *Heat WXYZ* revealed a single batch improperly listed as SAE 1026 material for heat treatment
  - Tempering temperature SAE 1026<SAE 4140 which could lead to a higher hardness
- Improperly listed batch was for 96 individual 2.25” x 5.0 degree washers for 4 foundations in segment “B”
- Installation records revealed five segment “A” foundations installed prior to shipment of *Heat ABCD* washers to segment “A”

Cause/Plausibility Summary

- 96-2.25” x 5.0 degree washers fabricated for segment “B” *Heat WXYZ*
  - 15 broken 2.25” x 5.0 degree washers found on 3 of 4 identified foundations on segment “B”
- 1-2.25” x 2.5 degree washer broken on segment “A”
  - Fabricated from *Heat WXYZ*
  - Previously machined down from “warped” 2.25” x 5.0 degree washer
  - 14 additional high hardness 2.25” x 2.5 degree washers located on segment “A” through field hardness testing

All 96 washers were located and removed from stock to eliminate the potential for future broken washers

ISM INTERNATIONAL SOCIETY FOR MICROPILES

How Do We Fix It? Containment Apparatus

- Top washers were easily replaced; however, bottom washers with energized line and helicopter access were difficult
- **February-March 2019** Containment apparatus considered to confine washers in the event of a break
- Oversized casing “sleeve” filled with grout
- Tests performed with segmented washers and tested to 25 cycles at maximum design load
- Client rejected approach given mitigative nature and observed subsidence of grout

ISM INTERNATIONAL SOCIETY FOR MICROPILES

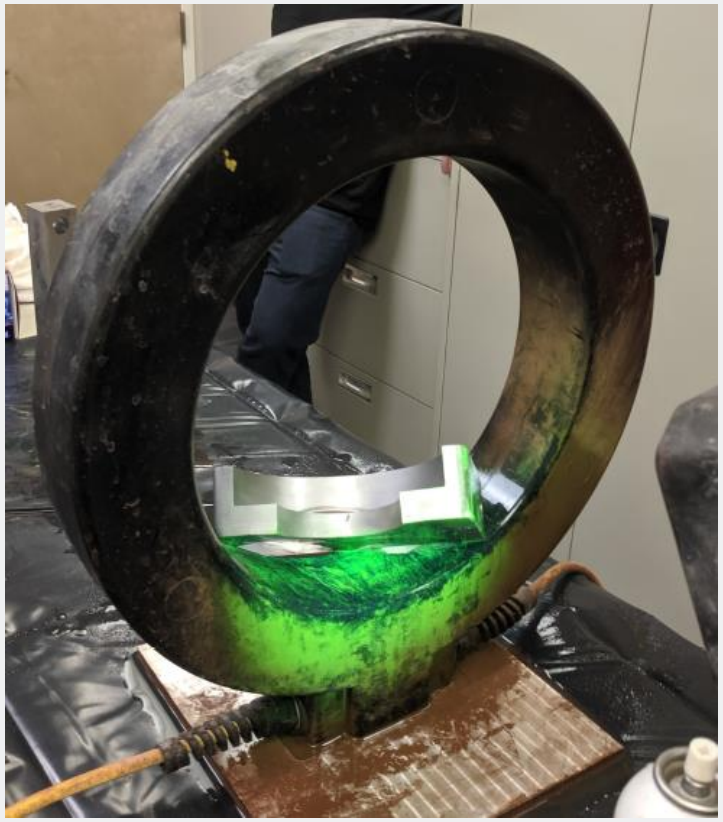
How Do We Fix It? Prototype Replacement Washer

- **May-July 2019** development and testing of prototype two-piece washer to be installed with energized lines
- Testing program
  - Applied 205 kip (1.0 DL) and 308 kip (1.5 DL) load at 2.5 minute hold
  - Three unique placements wrt slotted hole
  - Deformation measurements taken at 4 locations
- Testing results
  - No apparent flexure at 1.0 DL but visual flexural deformation at 1.5 DL
  - Client receptive but provided comments for future testing

ISM INTERNATIONAL SOCIETY FOR MICROPILES

How Do We Fix It? Revised Replacement Washer

- **August 2019** changes to test program
  - Scale up test loads 1.16 factor for Fy fabricated steel (58/50 ksi)
  - Extended hold times
    - 15 minute hold at 1.0 DL and 1.5 DL
  - 25 cycles at 1.0 DL
  - Additional measurement locations, closer to center of washer
  - Magnetic particle testing
    - Prior to loading
    - Post 1.0 DL static and 1.0 DL cyclic



How Do We Fix It? Revised Replacement Washer

- Testing results
  - Good performance at 1.0 DL static test
  - Apparent bending and increased deflection at thin side during 1.0 DL cyclic test
  - Ductile behavior at 1.5 DL showed no sudden catastrophic failure
- Replacement washers fabricated to provide immediate temporary replacement to banded bottom washers

INTERNATIONAL SOCIETY FOR MICROPILES

How Do We Fix It? Final Replacement Washer

- **September 2019** changes to washer thickness and another round of testing
- Impacts of increased thickness
  - Stiffer section increased performance
  - Slight increase in pile cap elevation
- Testing results
  - Maximum recorded deflection
    - 2.24 mm (0.09 in) 1.0 DL static
    - 2.95 mm (0.12 in) 1.0 DL cyclic
  - Maximum apparent creep
    - 0.03 mm (0.001 in) 1.0 DL static
      - 0.54 mm (0.02 in) 1.0 DL cyclic

How Do We Fix It? Execution

- Loosen top hex nut
- Support and raise pile cap with jacks
- Drill and break intact bottom washers
- Install replacement washer
- Lower pile cap
- Reinstall top hex nut
- Crux is actively inspecting select washers to monitor long term performance

INTERNATIONAL SOCIETY FOR MICROPILES

How Do We Prevent It? Immediate Changes

- Implemented hardness testing of each individual production washer for remainder of project
- Reduced required yield strength
  - Increased bearing area by using flat hardened washers
  - Increased minimum washer thickness
- Performed full scale performance testing for future segments with lower strength washers
- Include heat number tracking on all manufactured washers

How Do We Prevent It? Long Term Changes

- Keep design yield strength to 50 ksi maximum to eliminate requirement for heat treatment
  - Added benefit is flexibility in fabrication
- Reduced washer inner diameter and use flat hardened washers when needed to reduce bearing stress
- Increased minimum washer thickness
  - Added benefit is dimensional stability during galvanizing
- Require heat number tracking on all manufactured washers

Sigh of Relief

INTERNATIONAL SOCIETY FOR MICROPILES

Questions?

INTERNATIONAL SOCIETY FOR MICROPILES