TIMOTHY D. STARK *University of Illinois at Urbana-Champaign – tstark@Illinois.edu*

Perry J. Ricciardi *Ohio DOT, District 3 – DCE - perry.ricciardi@dot.state.oh.us*

Ryan D. Sisk *USACE Omaha District-Civil Engineer - Ryan.Sisk@usace.army.mil*

Presented to: Geo-Omaha 2020

Geo-Institute Omaha, Nebraska

February 21, 2020

- Ramp ES

Design & Construction

- Subsurface Conditions
- PVD Evaluation
- Undrained Stability Analyses
- Summary
- Unsaturated Stability Analysis

Timothy D. Stark-Geo-Omaha-2020-©

➢ >115,000 CY embankment, N of US 224 ➢ 3,700 lineal ft. on new alignment

Ramp ES Failure ~ 300 ft.

Timothy D. Stark-Geo-Omaha-2020-©

CR 97

- 35 to 60 ft deep

- 6 ft c/c spacing

- 325,000 lineal ft. installed

- Rate of fill < 1 ft/day to 5 ft/wk.
  - Piezometers to monitor pore water pressure: ➢Read after every 1 ft of new embankment
- $\Delta u < 7$ psi above baseline pore water pressure of 8 psi
- Settlement monuments and platforms read weekly
- Expected 5 ft settlement in places

6/16/07 filling starts

7/13/07-8ft,
cracks, <7 psf

$\Delta u \sim$ 8 to 14 psi $\Delta u \sim$

75%*$\Delta\sigma$; 25%

Consolidation

- July 13, 2007 – Tension cracks; work stopped for geotechnical study
- Fill = 8 ft (2.4 m) of 30 ft (9.2 m) or 32 ft (9.8 m) – 25%=8'/32'
- July 24, 2007 – Filling continues with added monitoring

8/1/07: Work Stopped (1.5 months).

Timothy D.
Stark-Geo-Omaha-2020-©

Timothy D.
Stark-Geo-Omaha-2020-©

- ODOT performs geotechnical evaluation
- July 24, 2007 – Filling continues with added monitoring - Survey pins installed

- July 30, 2007 – more cracking after fill reaches 13 ft
- August 1st, 2007 (1.5 months) – pore-water pressure > 7 psi above baseline - **work stopped**

  - survey pins show uplift and toe rotation
- August 2nd, 2007 – cracking from STA 202 to 205
- August 6th, 2007 – 1.5 ft high scarp at ramp centerline and displacement near R/W fence along STA 202 to 205

Timothy D.
Stark-Geo-Omaha-2020-©

Timothy D.
Stark-Geo-Omaha-2020-©

Timothy D.
Stark-Geo-Omaha-2020-©

Timothy D.
Stark-Geo-Omaha-2020-©

- Potential contract delays were $250,000/month
- Possible remedial measures:
- Lightweight fills,
- Deep soil/concrete columns,
- Geogrid reinforced granular embankment, and.........
- Pile supported bridge

Timothy D.
Stark-Geo-Omaha-2020-©

•Three Causes of Failure – Stratigraphy - Ch - Embankment

Timothy D. Stark-Geo-Omaha-2020-©

Strength

Timothy D. Stark-Geo-Omaha-2020-©

- Ramp ES Design & Construction
- Subsurface Conditions
- Undrained Stability Analyses
- PVD Evaluation
- Summary
-

Unsaturated Stability Analysis

Timothy D.

$c = 1,500$ psf & $\varphi = 0^0$

S_u = 375 psf

S_u = 250 psf

S_u = 500 psf

S_u = 500 psf

Boring ES-8A

Boring ES-8C

Fence 1

2

c = 1,500 psf & $\varphi = 0^0$

Scarp

S_u = 250 psf

- Thicker weak soil layer

-

S_u = 750 psf

S_u = 250 psf

S_u = 200 psf S_u = 1,000 psf

Weakest Station Weakest 201+61 soil soil is at deeper (SStation $_u$ > 250 (El. 203+58 psf/12 964 ft kPa);
to (S_u 954 of ft)
200-250 psf/9.6-12 kPa) at

Evaluation

- Ramp ES Design & Construction
- Subsurface Conditions
- PVD
- Undrained Stability Analyses
- Summary
- Unsaturated

Stability Analysis

Timothy D. Stark-Geo-Omaha-2020-©

Stratigraphy -

Ch -

Embankment

Strength

- **Three Causes of Failure** _

Timothy D.

- Sta. 203+58
- Design FS: $FS_{undrained} > 1.3$ and $FS_{drained} > 1.5$
- Predicted strength increase due to consolidation

Fill Height (ft)		Design Value	EOC[1] 15 ft	EOP[2] 15 ft	EOC 30 ft	EOP 30 ft
Depth	Soil Type	Undrained Shear Strength, s_u (psf)				
0-8	A-6b	750	750	2592	2592	4435
8-13	Peat	250	250	824	824	1398
13-18	A-5	250	250	732	732	1213
18-28	A-7-6	200	200	477	477	755
28-32	A-6b	1,000	1000	2099	2099	3197
Factor of Safety		>1.3	0.88	1.8	1.04	1.48

[1] EOC = End of construction [2] EOP = End of primary consolidation

6/16/07 filling starts

7/13/07-8ft, cracks, <7 psf

- Not dissipating

$\Delta u \sim 8$ to 14 psi $\Delta u \sim 75\% * \Delta\sigma$; 25% Consolidation

8/1/07: Work Stopped (1.5 months).

- **Inverse analysis easier than design!!**
- Design analysis:
- - Use C_h field = 200 settlements ft^2/year

to

- estimate Asaoka (1978) C_h • - Low -

Csmearing, $_h$ = C68 $_h$ due to clogging, 91

to: ft^2/year

or drain discharge capacity

5

4) tf(S1+jEOP Settlement ~ 4 ft 3**β = 0.9**

21 00 1 2 3 4 5

S_j (ft) Observed settlements at STA 204+00 with 6-ft drain spacing.

- **Design Analysis:** - C_h = 200 ft^2/year - Design C_h/C_v = 7.5 to 10.4

- **Typical Design Ratio:** - C_h/C_v = 1.5 to 4.0

- **Inverse analysis:** - Asaoka C_h = 68 ft^2/year - Asaoka C_h/C_v = 2.6 to 3.6 - Typical C_h/C_v =

1.5 to 4.0 months - 8/1/07 – work stopped

- **Lesson:** C_h = (1.5 to 4.0)* C_v

Timothy D. Stark-Geo-Omaha-2020-©

- **Inverse analysis:** - Asaoka C_h = 68 ft^2/year - 90% at ~5 months - 55% at ~1.5

- Ramp ES Design &

Construction

- Subsurface Conditions
- PVD Evaluation
- Undrained Stability Analyses
- Summary
-

Unsaturated Stability Analysis

Timothy D. Stark-Geo-Omaha-2020-©

- **Three Causes of**

Failure _

Stratigraphy -

Ch -

Embankment

Strength

Timothy D. Stark-Geo-Omaha-2020-©

- **Easier than design!!**
- STA 202+00 to 205+00

Timothy D.

Fence 2

$c = 1{,}500$ psf & $\varphi = 0^0$

1

Scarp

$S_u = 250$ psf

- **Boring ES-8C at STA 203+58**
- • • **Design Failed Design at FSH=13**

undrained H=32 ft ~ 1.6 ft so FS(30 ft + at
H=15 ft = ok

undrained 2 ft)
~ 1.0

S_u = 750 psf

S_u = 250 psf

S_u = 200 psf S_u = 1,000 psf

- **Check design $FS_{undrained}$ ~ 1.6 at H=15 ft**

$FS_c^{*} \; u_{,avg}$

$Fill^{*}$

$Fill$

c

$$5.14 N\; S_H\; N$$

$=$

$\gamma =$

c' = 300 psf & φ' = 33^0

Fence **Scarp**

$, \; 750 \quad {}_{u\,avg} \; (8\;)\; 250\; (10\;)\; 200 \quad (8\; 10\; 60\;) \quad (60$

$) \; 230.8\; S = psf\; ft + psf\; ft + psf \quad ft + ft +$

$$\frac{ft}{ft} = psf$$ Timothy D. Stark-Geo-Omaha-2020-©

2 1

S_u = 750 psf

S_u = 250 psf S_u = 250 psf

S_u = 200 psf S_u = 1,000 psf

- **Check design $FS_{undrained}$ ~ 1.6 at**

H=15 ft $$FS = N_c * S_{u,avg}$$

$\gamma_{Fill} *$

H

$_{Fill}FS = 5.14*230.8$

$130\,pcf * 15$

$$0.61\,\frac{psf}{ft}=$$

- **Check design $FS_{undrained}$ ~ 1.6 at H=15 ft**

$$FS = \frac{N_c * S_{u,avg}}{}$$

$\gamma_{Fill} *$

H

$FS_{Fill} = 5.14*230.8$

$130\,pcf * 8$

$1.14\,psf\,ft$

$=$

Bearing Capacity Factor of Safety

7/7/07 – tension cracks first observed

2.4m/8 ft 1.14

8/1/07 – tension cracks restart 4.0m/13 ft 0.71

Stage 1 Fill Height 4.6 m/15 ft 0.61 Full

Embankment Height 9.2 m/30 ft 0.31

$H = c\,\gamma * 375\;130$

$N = psf\;pcf * 5.14 = 14.8\,ft$

Fill c critial

Fill

Embankment Fill Condition
Fill Height (H_{Fill}) (m/ft)

- Why failure at 13 ft?!?! -

Staged and controlled construction
- Compacted -

$FS_{undrained}$ ~ 1.6 > 1.3 fill strength - c = 1,500 psf & φ =

0^{0}

0 $FS = \sum (c \sum + (\sigma$

$W^{*} \tan \sin$

$\alpha \; \varphi))$

$* \, \Delta \, l$ Moment Equilibrium

- GB-6 – inactive
- $c = 1{,}500$ psf & $\varphi = 0^0$
- PI = 10; $\varphi' = 33^0$ and $c'=0$
- $c = 1{,}500$ psf & $\varphi = 0^0$

- Compacted fill strength - $c = 1{,}500$ psf & $\varphi = 0^0$

H

Crack

$= \gamma$

Fill

$*\tan 2* \Big(\,\Big|\, \Big(45\ c$

Fill

0

$- \varphi\ _{Fill}\ 2$

Timothy D. Stark-Geo-Omaha-2020-©

$$2 * \frac{2 * 1{,}500}{130} = 23.0 \; H$$

Fill crack

$$c_{Fill} \; psf \; ft \; pcf \; \gamma = = =$$

- Failed at 13 ft....................
- No embankment strength!
- Bearing Capacity Analysis ~

field condition

- Chirapuntu and Duncan (1976) -

strain incompatibility - strength

mobilized in stiff

embankment<foundation

H_{Crack}

$= 5.1 * c_{Foundation\ Fill} * \left(\right| \left(^{0.75}\ _{0.25}$

$0.75\ 0.25\ K_{Foundation}$

K_{Fill}

$)^{*}$

$\left(\frac{W}{D} \right) H_{Crack} = 5.1 *$

$348.5 \; 130 \; pcf \; psf * (\; 120$

$150 \;) * (\; 90.5 \; 27.9$

$ft \; ft$

$) \; H_{Crack}$

$=$

15.5

ft

Timothy D. Stark-Geo-Omaha-2020-©

γ

$$S_u/\sigma'_p = 0.22$$

TC: $S_u/\sigma'_p \sim 0.32$ DSS: $S_u/\sigma'_p \sim 0.00061*(PI) + 0.22$ TE: $S_u/\sigma'_p \sim 0.00117*(PI) + 0.13$

Timothy D. Stark-Geo-Omaha-2020-©

TC TE DSS

- **Terzaghi, Peck, and Mesri (1996)**

- Compacted fill strength - drained

strength - GB-6 - PI = 10; $\varphi' = 33^0$ - c'

from inverse analysis - c' = 300 psf

- GB-6 - Clays c' = 300-550 psf

Timothy D. Stark-Geo-Omaha-2020-©

(Phone App)

- New cross-section at changes in soil stratigraphy - review borings carefully
- Big impact of c or S_u on FS
- If S_u, use tension crack
- Undrained Bearing Capacity Analysis
- Shear strength correlations – - Planning level?? - Use Atterberg Limits not SPT - CPT, Vane Shear, etc.

Design & Construction

- Ramp ES

- Subsurface Conditions
- PVD Evaluation
- Undrained Stability Analyses
- Summary
- Unsaturated Stability Analysis

- • **3** Stiff **Reasons:** embankment

stratigraphy, over soft foundation **C_h,**
with **and** Su, **fill** include **strength**

tension crack

- Depth of tension crack Chirapantu and Duncan (1976) or :

$$H_0 = \frac{2 * c * \tan\left(45 - \frac{\varphi}{2}\right)}{\gamma}$$

- Don't use N to estimate Su, use PI and undrained strength ratio
- Undrained bearing capacity analysis to guide short-term design
- Reasonable range of C_h/C_v =1.5 to 4.0

- Asaoka consolidation (1978) occurring method to as estimate predicted. mobilized If not, modify C_h to verify fill placement

Fill Crack

Fill *Fill*

- Ramp ES Design & Construction
- Subsurface Conditions
- PVD Evaluation
- Undrained Stability

Analyses

- Summary
- Unsaturated Stability Analysis

- Fredlund et al. (1978)

= 14.4 kPa

= 33^0

= pore water pressure = suction pressure = strength due to suction

- Desiccation Crack Depth - Lu and Likos (2004) - Steady-state ¯ □

□ - 6.6 ft (2.0 m) □◌|□ □ ગ.□ષભગ/□ _

Field ~ 0.3 to 0.6 m

- Strain Incompatability Crack Depth - Lu and Likos (2004) - Steady-state

¯ □□

ଗ□ 0Δ ◌| ஐ ஷஐ□

- 0.9 to 3.4 m - Sand Blanket not Cracked

- Total Crack Depth ~ 1.2 to 4.0 m
- Fill = 8 ft (2.4 m)
- Final Fill = 32 ft (9.8 m)
- No Embankment Strength

Timothy D.
Stark-Geo-Omaha-2020-©

• • **3** Stiff **Reasons:** embankment

stratigraphy, over soft foundation **C_h,**

with **and** Su, **fill** include **strength**

tension crack

• Depth of tension crack Chirapantu and Duncan (1976) or :

H

$= \gamma$

$_0 2^* c^* \tan \left(45 - \varphi \; 2 \right)$

- Don’t use N to estimate Su, use PI and undrained strength ratio
- Undrained bearing capacity analysis to guide short-term design
- Reasonable range of C_h/C_v =1.5 to 4.0
- Asaoka consolidation (1978) occurring method to as estimate predicted. mobilized If not, modify C_h to verify fill placement

Fill Crack

Fill *Fill*

- ODOT for supplying data and project information
- Luke Wysocki – ODOT Project

Engineer

- Mike Currier - ODOT/Shelly & Sands
- Beth Wilson – ODOT District 3 Construction

Timothy D. Stark-Geo-Omaha-2020-©

TIMOTHY D. STARK *University of Illinois at Urbana-Champaign – tstark@Illinois.edu*
Perry J. Ricciardi *Ohio DOT, District 3 – DCE - perry.ricciardi@dot.state.oh.us*
Ryan D. Sisk *USACE Omaha District-Civil Engineer - Ryan.Sisk@usace.army.mil*

Presented to: Geo-Omaha 2020

Geo-Institute Omaha, Nebraska

February 21, 2020