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Geotechnical Engineering at Kennedy Space Center

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Geotechnical Engineering at Kennedy Space Center

- Stability of the Transporter on the Crawlerway
- Crawlerway Surfacing
- Vehicle Assembly Building Foundations
- Slope Protection at Launch Pads
Transporter Stability on Crawlerway
Loads Imposed on Crawlerway

1960s Apollo
18 million lbs

Space Shuttle
18 million lbs

Proposed Ares I
<18 million lbs

Proposed Ares V
25 million lbs
Study Area:
Poor Conditions, Historical Data Available
Study Area:
Loose Zones under Crawlerway B (Peck 1969)
Pore Water Pressure Response in Loose Zone as Partially Loaded Transporter Approaches

Normal speed 0.1 mile/h

aa' : stopped 4 - 4 min.
bb' : stopped 5 - 1/2 min.
cc' : stopped 6 - 1/2 min.
dd' : stopped 5 - 1/2 min.
ee' : stopped 2 min.

EXCESS PORE PRESSURE: lb/sq. in.

HORIZONTAL DISTANCE TO PRESSURE CELL FROM CENTRE OF LEADING TRACK: ft
Pore Water Pressure Response in Loose Zone as Partially Loaded Transporter Approaches

Rate of dissipation during interval cc'

EXCESS PORE PRESSURE: lb/sq. in.

TIME: min.

0 2 4 6

10 5 0
2008 Field Testing at Study Area: SPT, CPT, DMT
2008 Dilatometer Tests
Plan View of Transporter Tracks

Two tracks comprise one truck

Centerline of transporter

45 ft width represented in finite element model

Centerline of a pair of trucks
Symmetry

Transporter Track Loads

Lines of symmetry

= Transporter Track Load
Mesh Geometry

- **River gravel and compacted limerock**
- **Dense sand with silt**
- **Loose sand with silt**
- **Dense sand with silt**

Dimensions:
- Width: 310 ft
- Height: 57 ft
- Depth: 45 ft
Placement of Tracks

Initial position of tracks

- Length: 310 ft
- Width: 45 ft
- Height: 57 ft
Placement of Tracks

Tracks travel in this direction at specified velocity

Initial position of tracks
Placement of Tracks

Tracks travel in this direction at specified velocity

Initial position of tracks

Final position of tracks, then held in this position for 4.5 minutes of consolidation time
Animation of Deformations and Excess Pore Water Pressures
Excess Pore Water Pressures

Excess Pore Pressure (psi)

Horizontal Distance to Pressure Cell from Center of Track (ft)

Peck Data
Numerical Model
Settlement and Lateral Movement

- Calculated settlement = 3.96 inches, versus estimated settlement of 4.1 inches from 1967 Apollo field test
- Calculated maximum lateral movement = 1.04 inches, versus observed maximum lateral movement of \( \frac{3}{4} \) to 1\( \frac{1}{2} \) inches

Overall, the numerical model is in good agreement with the observed response from the 1967 field test for the Apollo program.
2008 Site Investigation Showed Improved Conditions Compared to 1960s

- About a hundred passes of heavily loaded transporter
- 40+ years of aging
Ares V Settlement, Excess Pore Water Pressure, and Lateral Movement versus Transporter Speed

<table>
<thead>
<tr>
<th>Transporter Speed (mph)</th>
<th>Excess Pore Water Pressure (psf)</th>
<th>After 4.5 min.</th>
<th>Settlement (in.)</th>
<th>Lateral Movement (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Maximum 1,680</td>
<td>835</td>
<td>1.73</td>
<td>0.45</td>
</tr>
<tr>
<td>0.9</td>
<td>2,410</td>
<td>1,020</td>
<td>1.69</td>
<td>0.53</td>
</tr>
<tr>
<td>1.3</td>
<td>2,460</td>
<td>1,030</td>
<td>1.68</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Degree of Shear Strength Mobilization at Depth 22 ft at Stopping Point for 1967 Apollo Field Test Load

Final position of tracks
Degree of Shear Strength Mobilization at Depth 22 ft at Stopping Point for Ares V

Final position of tracks
Prediction Analyses, Load vs Settlement

Total Transporter Load (million pounds)

Settlement (in.)

- Front Track at Stopping Point
- Rear Track after Projected Ultimate Consolidation Settlement
Impact of Boundary Conditions in Numerical Analyses on Potential Failure Modes

- Boundary conditions applied for numerical analyses prevent failure that extends beyond the model domain.
Link between Numerical Analyses and Limit Equilibrium Analyses: Excess Pore Water Pressure
Limit Equilibrium Analyses for Ares V Load
Factor of Safety vs Transporter Load

Recommended Minimum FS = 1.25

1967 Field Load Test

Ares V Load

1967 Properties, 0.1 mph

2008 Properties, 0.1 mph

2008 Properties, 0.9 to 1.3 mph

Total Load (million pounds)
Justification for Minimum $FS = 1.25$

- Temporary loading
- Applied recommendations by Silva et al. (2008):
  - Well characterized site
  - High quality analyses
  - Therefore, this is a “Category I” project, and $FS = 1.25$ corresponds to probability of failure $= 0.1$ to $0.01\%$
Numerical Analysis of Stability: One of Several Critical Areas Analyzed along Crawlerway A

Critical SRF: 1.60

12,115 psf

12,115 psf
Vehicle Assembly Building (VAB) Foundations
HIGH BAY 4
EXTERNAL TANK PROCESSING AND STORAGE

TOWER C

HIGH BAY 4
TRANSFER AISLE

TOWER D

HIGH BAY 2
EXTERNAL TANK PROCESSING AND STORAGE
3RD ORBITER SAFE HAVEN

TOWER A

HIGH BAY 1

TOWER F

HIGH BAY 3

TOWER E

HIGH BAYS 1 & 3
STACK SOLID ROCKET BOOSTERS
MATE EXTERNAL TANK TO SOLID ROCKET BOOSTERS
MATE ORBITER TO EXTERNAL TANK SHUTTLE INTERFACE TEST
CLOSEOUT SHUTTLE VEHICLE FOR ROLLOUT TO PAD

TRANSFER AISLE
SUPPORT AREA FOR SHUTTLE PROCESSING
SOLID ROCKET BOOSTER STAGING
EXTERNAL TANK TRANSFER TO PROCESSING CELLS
ORBITER PRE-MATE

YOU ARE HERE

VEHICLE ASSEMBLY BUILDING (VAB)
Perspective View of Mesh, Showing Plane of Symmetry between High Bays 1 and 3
View of Plane of Symmetry at Centerline of High Bay 1 Showing Pile Caps and Piles
Findings and Recommendations from Analyses of VAB Foundations

- Main VAB foundations will be OK under Ares V loads
- Pile-supported threshold will be overloaded
- Remediation options at threshold:
  - Reconfigure threshold to avoid direct loading of transporter on threshold pile cap
  - Install additional pile supports at threshold
Crawlerway Surface Treatment
Point Load Testing to Estimate Crushing Strength of Surface Gravel
Distribution of Point Load Strength Data

- Test results
- Normal distribution

Size-corrected Point Load Strength (MPa) vs. Frequency
Used Principals of Statistical Inference to Establish Acceptance Criteria

Check that the mean strength is high enough:

$$\bar{x}_n \geq \bar{x}_e - 1.65s_e \sqrt{\frac{1}{n_n} + \frac{1}{n_e}} = 6.8 \text{ MPa}$$

Check that the mean minus one std. dev. is high enough:

$$\bar{x}_n - s_n \geq \bar{x}_e - s_e - 1.65s_e \sqrt{\frac{1}{n_n} + \frac{1}{n_e}} = 4.7 \text{ MPa}$$
Slope Protection at Launch Pads
Analysis and Remediation

- Newmark displacement analysis to determine necessary stabilizing force
- Inclined helical anchors to provide the force
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