WATERWAYS EXPERIMENT STATION

Testing and Analysis of C-17 Live Flight Operations on Semi-Prepared Airfields

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Airfields and Pavements Division

CEWES

Field Structural Analysis

WATERWAYS EXPERIMENT STATION

FIELD STRUCTURAL ANALYSIS

WATERWAYS EXPERIMENT STATION

- Introduction
- Description of the Aircraft and Test Sites
- Tests and Results
- Analysis of Test Results
- Conclusions
- Recommendations

Introduction

- **Background:**
  - Requirement to Evaluate the Capabilities of the C-17 Aircraft
  - Requirement to Validate Current Structural Design and Evaluation Criteria for the C-17 Aircraft

- **Purpose:**
  - Observe the General Behavior of the Test Facilities
  - Conduct Structural Testing to Characterize Each Test Site
  - Conduct Measurements to Evaluate Pavement Performance
  - Analyze Test Results and Evaluate Current C-17 Structural Criteria

- **Scope:**
  - Characterization of the Structural Capabilities of the Six Sites
  - Evaluation of the Current Structural Criteria for the C-17

Description of the Aircraft

- Description of the Aircraft
  - Gross Weight
    - Max. (Semi-Prepared Surfaces) = 447 Kips
    - Field Tests = 361 to 448 Kips
  - Tire Pressure
    - Manufacturer Recommended Values:

      Main Gear: Normal = 138 psi Contingency = 110 psi

      Nose Gear: Normal = 155 psi Contingency = 100 psi
    - Field Values:

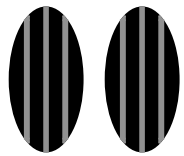
      Main Gear: 132 - 165 psi

      Nose Gear: 123 - 160 psi

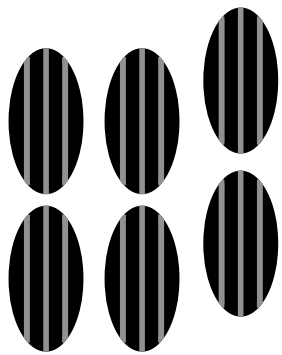
Description of the Aircraft

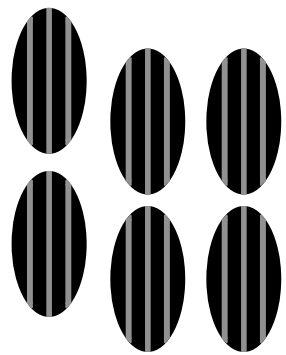
- **Gear Configuration:**
  - **Layout and Dimensions**

Plan View



- **Aircraft Operations:**
  - **Sequence of Events**





Test Sites

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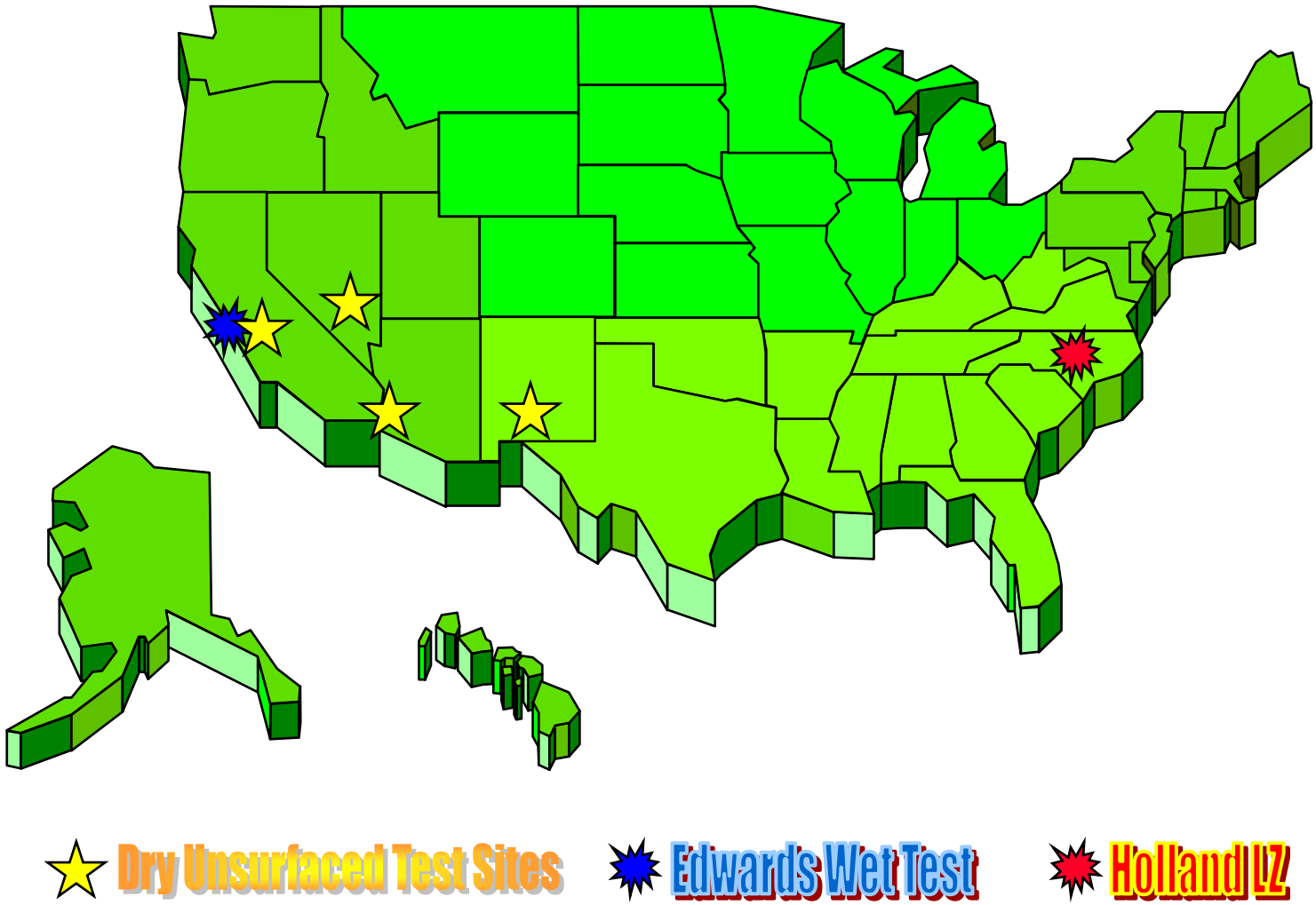

Bicycle Lake Test Site

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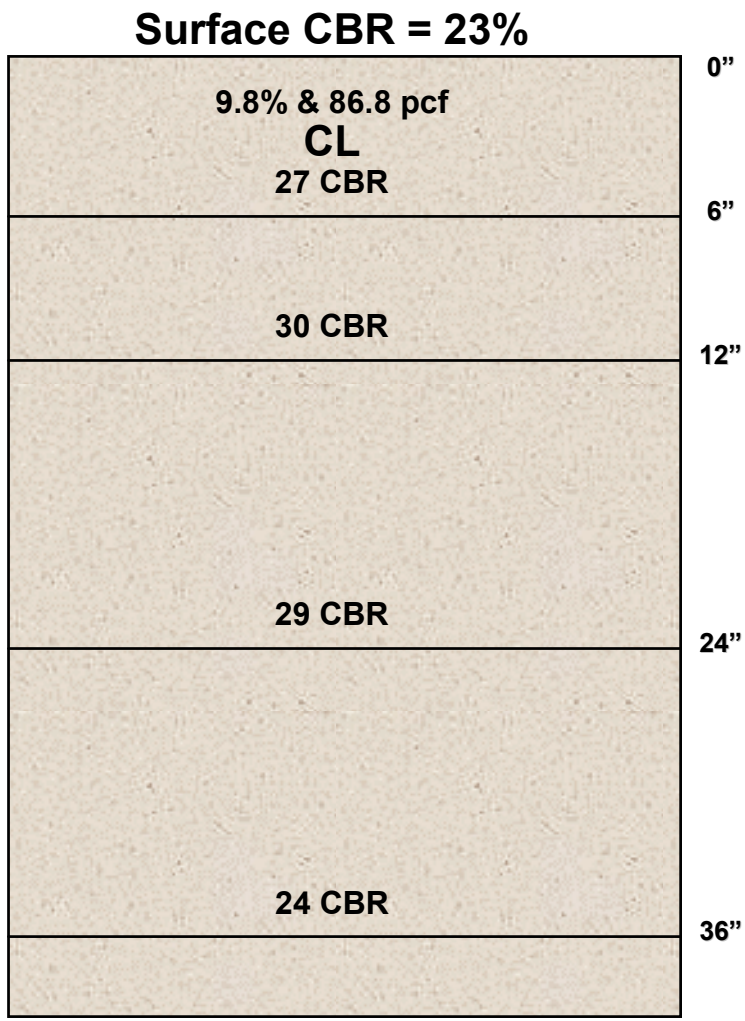
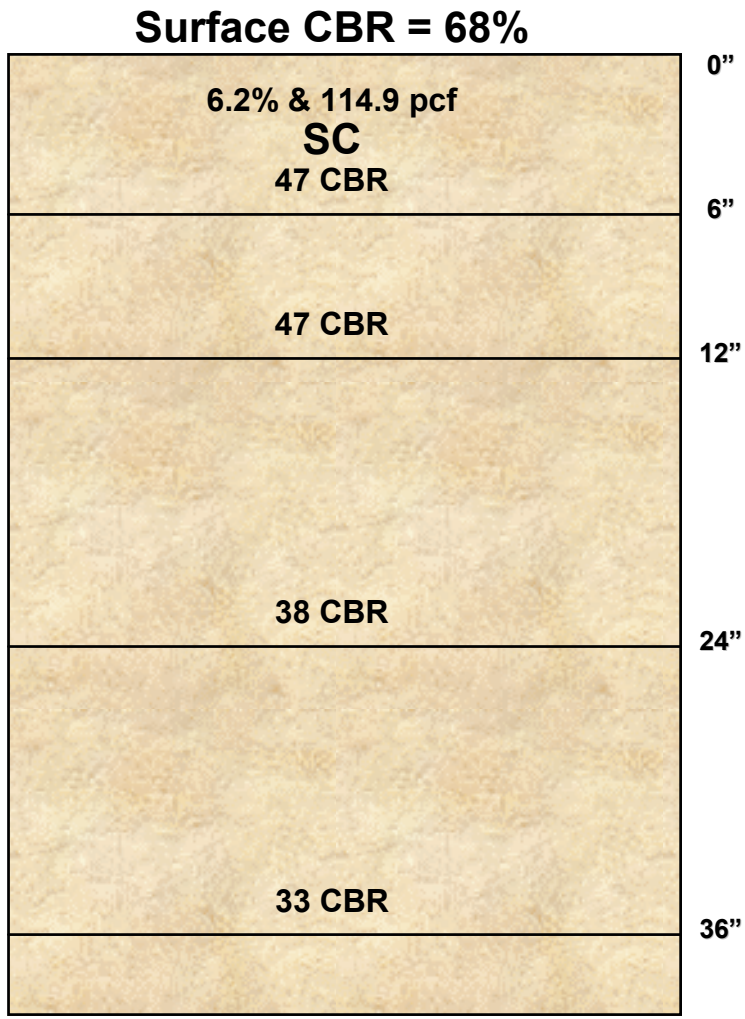
- Climate: Arid
- Airfield Layout
- Soil Type: CL
- Site Characterization Data:
  - Moisture Content & Density
    - In Situ: 9.8% & 86.8 pcf
    - Optimum: 20.5% & 104.6 pcf
  - Avg. Surface CBR = 23%
  - CBRs from DCPs:
    6” = 27% 12” = 30%
    24” = 29% 36” = 24%



Alamo LZ Test Site

WATERWAYS EXPERIMENT STATION

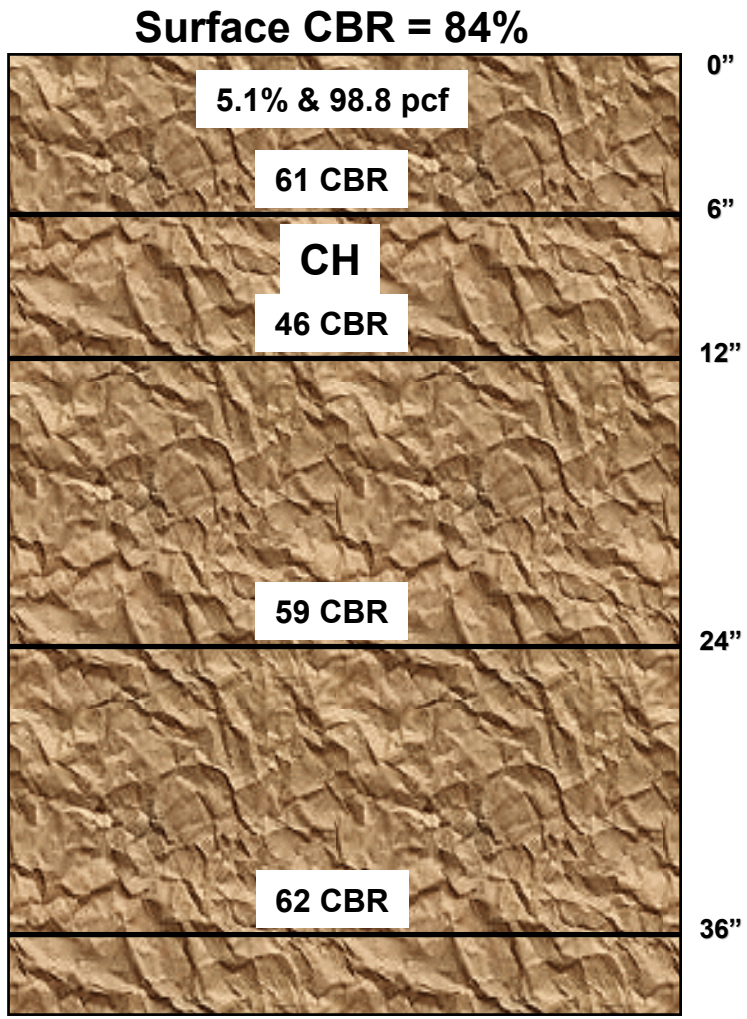
- Climate: Semi-Arid
- Airfield Layout
- Soil Type: SC
- Site Characterization Data:
  - Moisture Content & Density
    - In Situ: 6.2% & 114.9 pcf
    - Optimum: 10.3% & 126.5 pcf
  - Avg. Surface CBR = 68%
  - CBRs from DCPs:
    6" = 47% 12" = 47%
    24" = 38% 36" = 33%



Edwards AFB Test Site

WATERWAYS EXPERIMENT STATION

- Climate: Semi-Arid
- Airfield Layout
- Soil Type: CH
- Site Characterization Data:
  - Moisture Content & Density
    - In Situ: 5.1% & 98.8 pcf
    - Optimum: 15.6% & 113.8 pcf
  - Avg. Surface CBR = 84%
  - CBRs from DCPs:
    6" = 61% 12" = 46%
    24" = 59% 36" = 62%



Holland LZ Test Site

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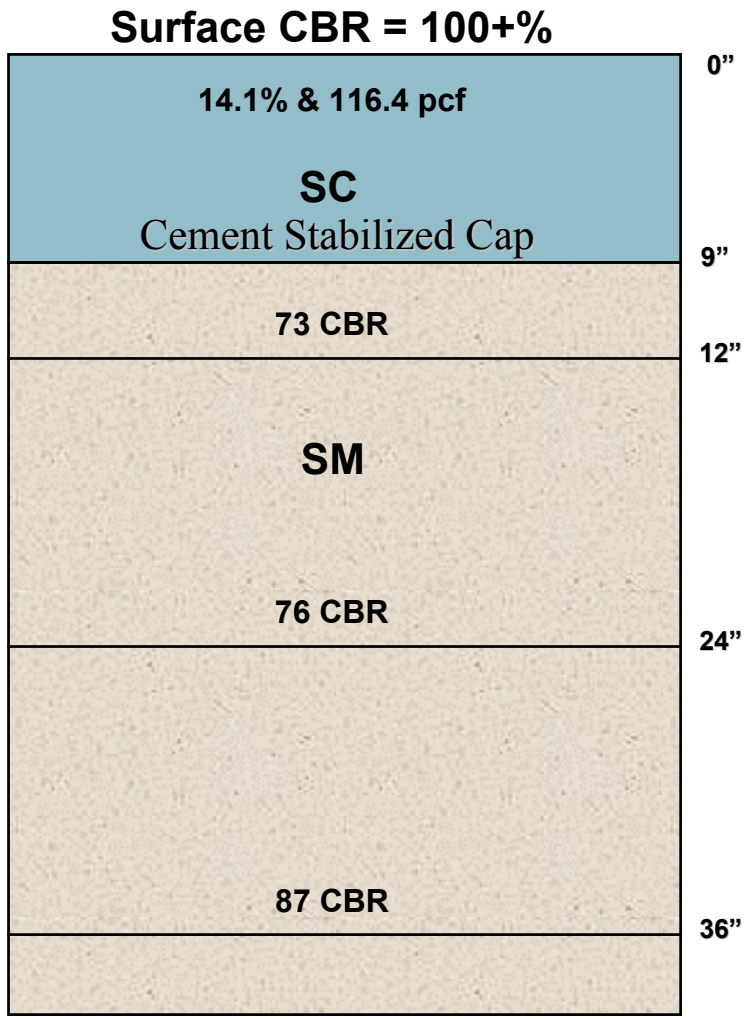
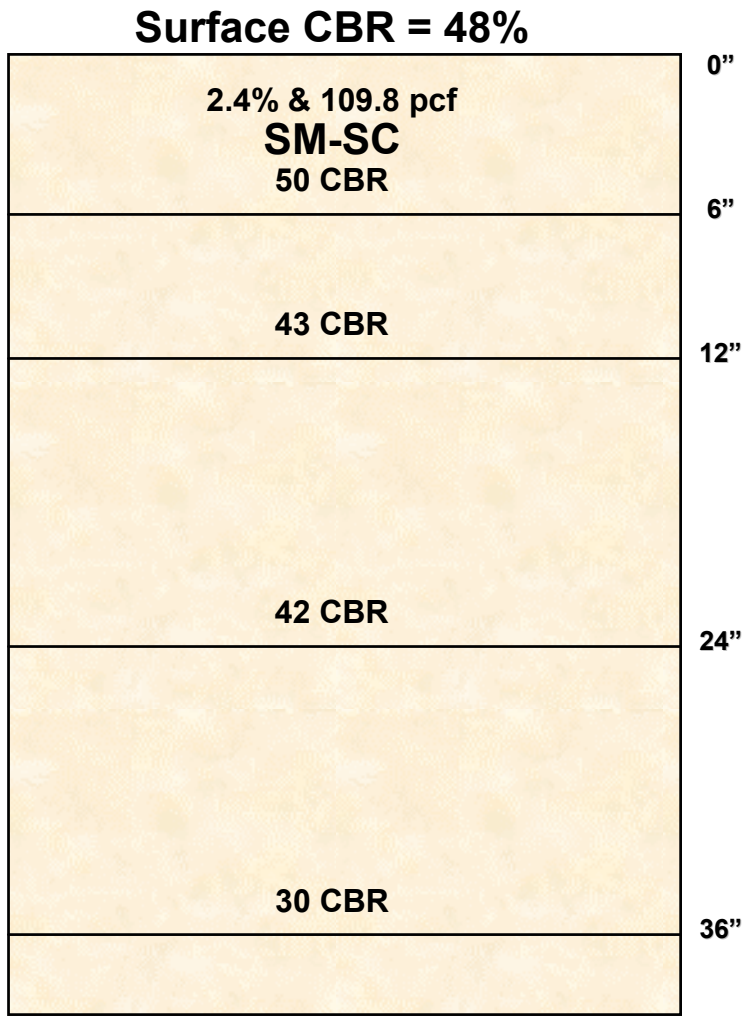
- **Climate:** Humid
- **Airfield Layout**
- **Soil Type:** SC (Cap) SM (Subgrade)
- **Site Characterization Data:**
  - **Moisture Content & Density**
    - **In Situ:** 14.1% & 116.4 pcf
  - **Avg. Surface CBR = 100+%**
  - **CBRs from DCPs:**
    - 12” = 73%
    - 24” = 76%
    - 36” = 87%



Tyson LZ Test Site

WATERWAYS EXPERIMENT STATION

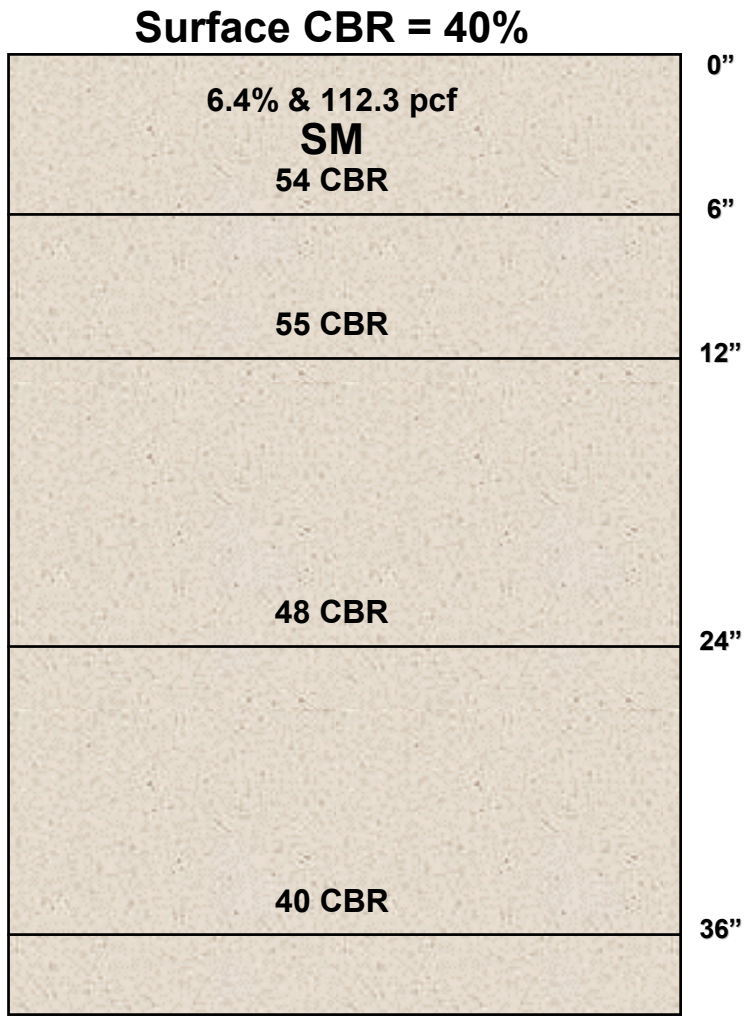
- Climate: Semi-Arid
- Airfield Layout
- Soil Type: SM-SC
- Site Characterization Data:
  - Moisture Content & Density
    - In Situ: 2.4% & 109.8 pcf
    - Optimum: 11.6% & 120.5 pcf
  - Avg. Surface CBR = 48%
  - CBRs from DCPs:
    6" = 50% 12" = 43%
    24" = 42% 36" = 30%



Wilde-Benton LZ Test Site

WATERWAYS EXPERIMENT STATION

- Climate: Semi-Arid
- Airfield Layout
- Soil Type: SM
- Site Characterization Data:
  - Moisture Content & Density
    - In Situ: 6.4% & 112.3 pcf
    - Optimum: 11.4% & 123.7 pcf
  - Avg. Surface CBR = 40%
  - CBRs from DCPs:
    6" = 54% 12" = 55%
    24" = 48% 36" = 40%

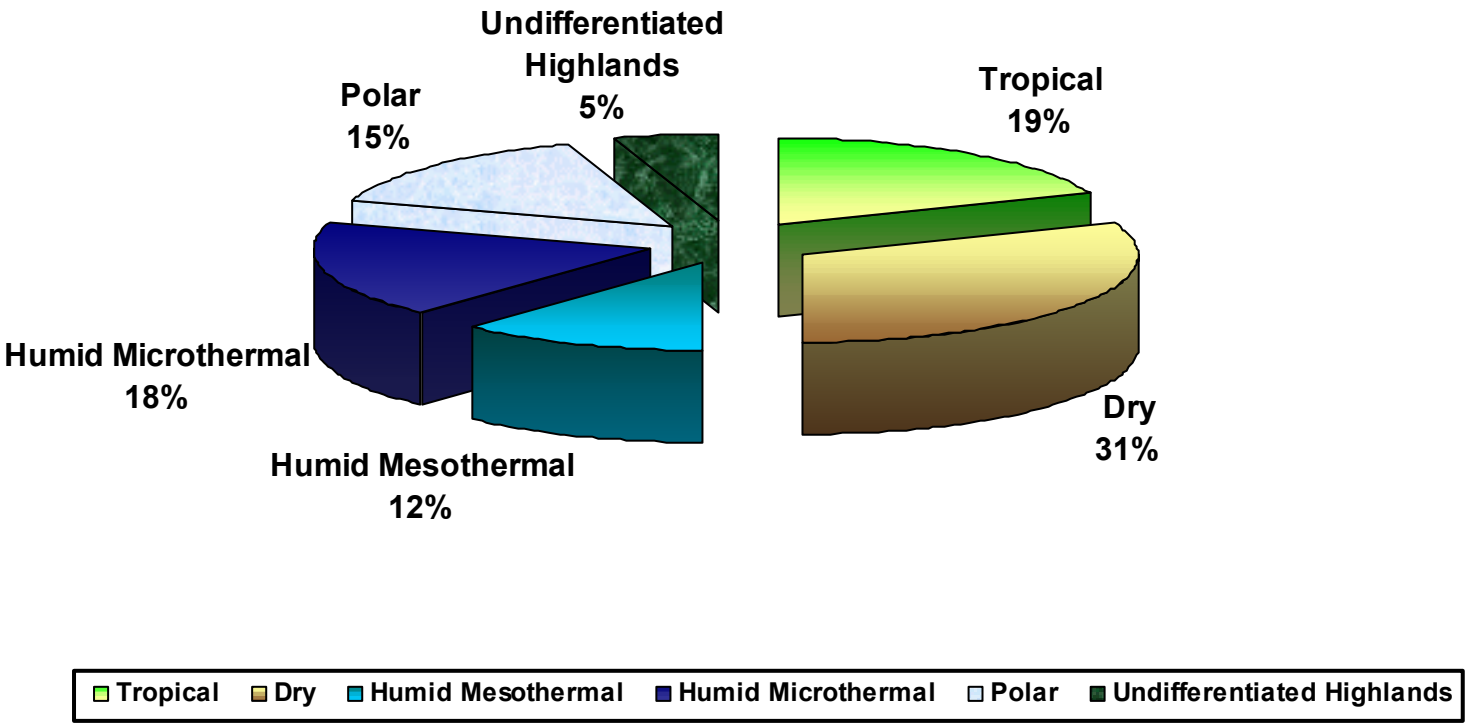


General Site Characterization

- **Two Categories:**
  - **Dry Unsurfaced Test Sites**
  - **Edwards AFB & Holland LZ**
- **Climate: Arid or Semi-Arid**
- **Soils Data:**
  - **Combined Average Surface CBR = 45%**
  - **Relatively High CBR(45%) Compared to Capabilities (9%)**
  - **In Situ Moisture Contents Averaged 7.3% less than Optimum**
  - **In Situ Dry Densities Averaged 12.9 pcf less than Optimum (83-91% of Optimum)**

General Site Characterization

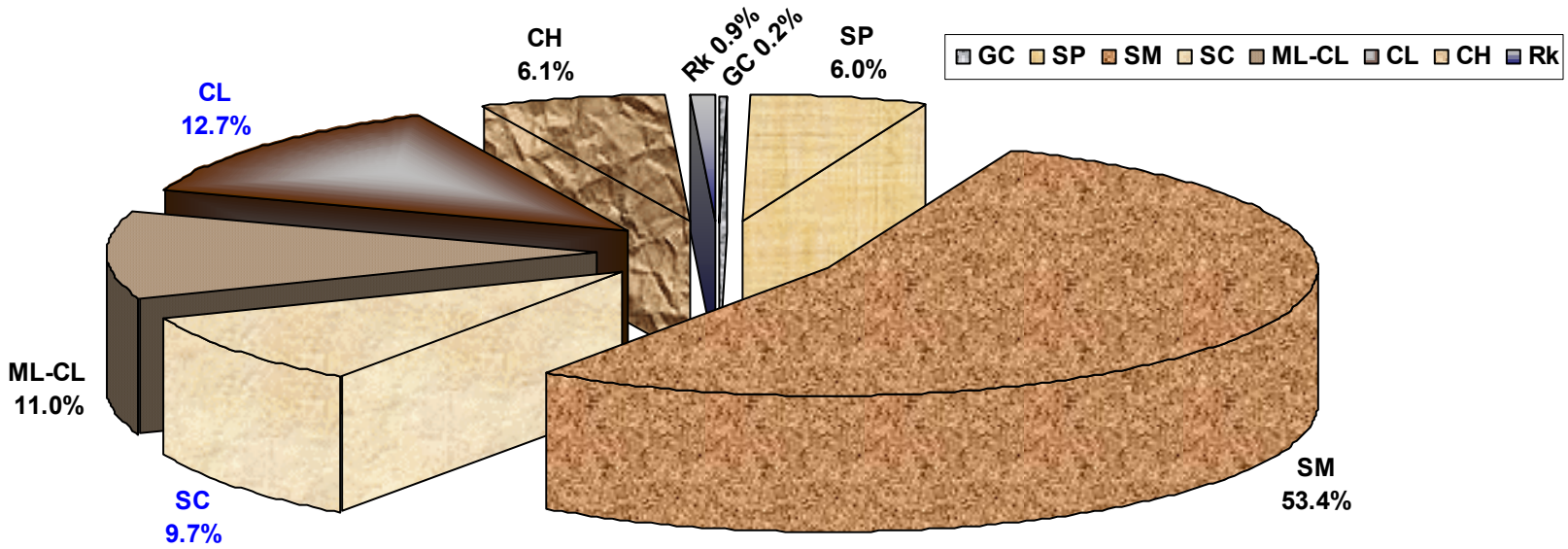
World Climate Distribution (% Area)



General Site Characterization

WATERWAYS EXPERIMENT STATION

Percentage of Soil Types Within the Dry Climate Zone (% Area)



22.4% of Dry Climatic Zones are Composed of the CL and SC Soil Types

C-17 Field Flight Testing has been accomplished in 7% of the Worlds Soils (31% is Dry Climate and 22.4% of Soils in Dry Climates were Tested)

Tests and Results

- **Dynamic Cone Penetrometer (DCP)**
- **California Bearing Ratio (CBR): Surface & Subsurface**
- **Cross Sections and Longitudinal Profiles**
- **Rut Depth Measurements**
- **Loose Till Depth Measurements (CRREL)**
- **Nuclear Density and Moisture Measurements**
- **Soil Classification**

Tests and Results

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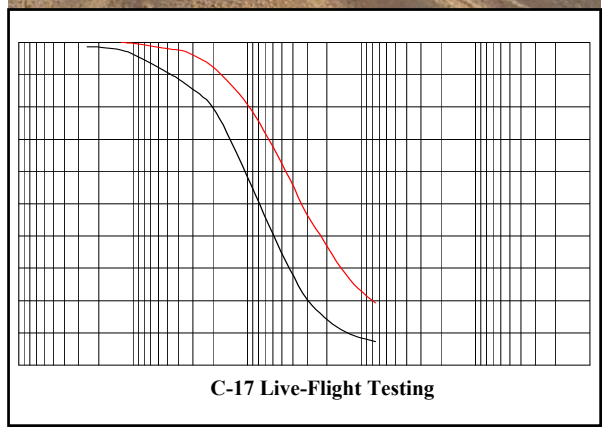
FY97 Field Structural Testing



C-17 Live-Flight Testing

Analysis of Test Results

- **General Analysis**
  - Failure Criteria
  - Rutting
  - Aircraft Operations
  - Dust
  - Foreign Object Damage (FOD) Potential
- **Specific Site Observations**
  - Dry Unsurfaced Test Sites
  - Edwards AFB Test Site
  - Holland LZ Test Site
- **Failure Mechanism**
  - Remolded Soil Layer
  - Quantifying Surface Soil Properties
  - Shear Criteria Model
  - HMMWV Testing
- **Site Characterization Techniques**
- **Examination of Existing Criteria**

General Analysis

- **Failure Criteria:**
  - **Initially - 6” Rut Depth**
  - **Actual - Maintenance was Performed when Ruts > 9”**

- **Rutting:**
  - **Rutting was NOT Traditional Rutting (Plastic Deformation)**
  - **Total Rut = Loose Till + Transition Zone (“Hard” Rut)**

- **Aircraft Operations:**
  - **Star Turns are not Recommended**
  - **High Loads and Tire Pressures Resulted in Increased Damage**
  - **Maximum Braking Resulted in Increased Damage**
  - **Reduce Damage by:**
    - **Using Thrust Reversers on Landings**
    - **Using the Whole Length of the Runway on Landings**
    - **Using the Widest Possible Turning Angle**
    - **Operate at Manufacturer Recommended Tire Pressures**

General Analysis

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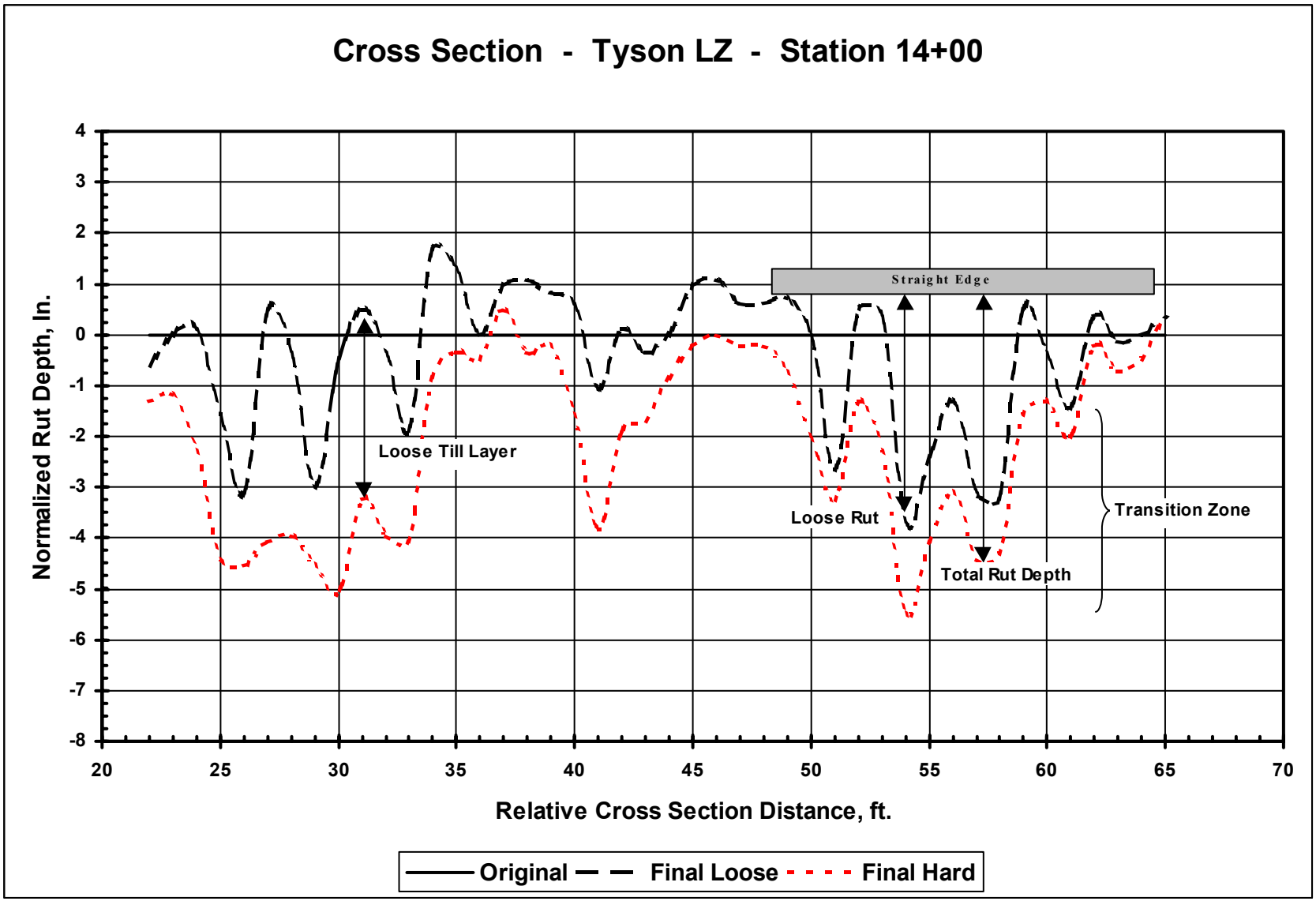

General Analysis - Dust

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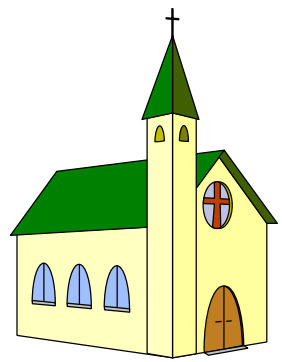
- **Dust Problems:**
  - Aircraft Visibility
  - Personnel Visibility
  - Aircraft Maintenance
  - Signatures for the Enemy
- **Effects of Dust:**
  - Increased Maintenance
  - Increased Time for Consecutive Operations
  - Reduced Aircraft Capabilities

Foreign Object Damage (FOD)

- **Problems:**
  - **Unsurfaced = High FOD Potential**
  - **Poorly Constructed Cement-Stabilized Surfaces = FOD Potential**
  - **FOD Potential is a Function of ?**
  - **FOD = High Aircraft Maintenance**
  - **How Can FOD be Reduced ?**

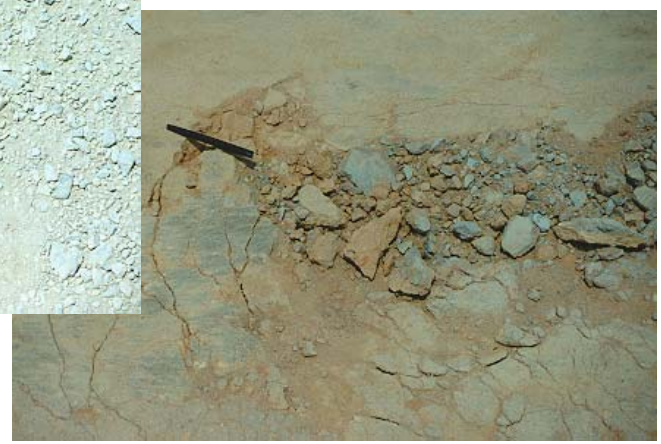
- **Analysis:**
  - **FOD is a Function of the Maximum Aggregate Size**
  - **FOD is also a Function of Unknown Variables (i.e. Specific Gravity)**
  - **Potential Methods for Reducing FOD:**
    - **Stabilization of Critical Areas of the Airfield**
    - **New Surfacings for Semi-Prepared Airfields**
    - **Development of Dust/FOD abatement materials**
    - **Giant Sieve**
    - **Prayer (Current Criteria)**



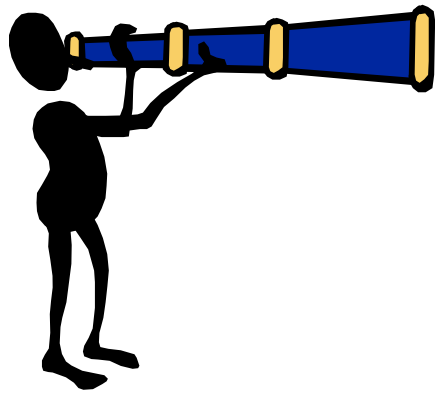
Foreign Object Damage (FOD)

- **Proposed Guidance:**

Maximum Aggregate Size	Operational Code	Operational Code Description
> 1”	Red	Operate Aircraft Only in Emergency Situations.
3/4” - 1”	Amber	Operate Aircraft for a Limited Number of Operations.
< 3/4”	Green	Operate Aircraft for Unlimited Mission Operations.



Specific Site Observations

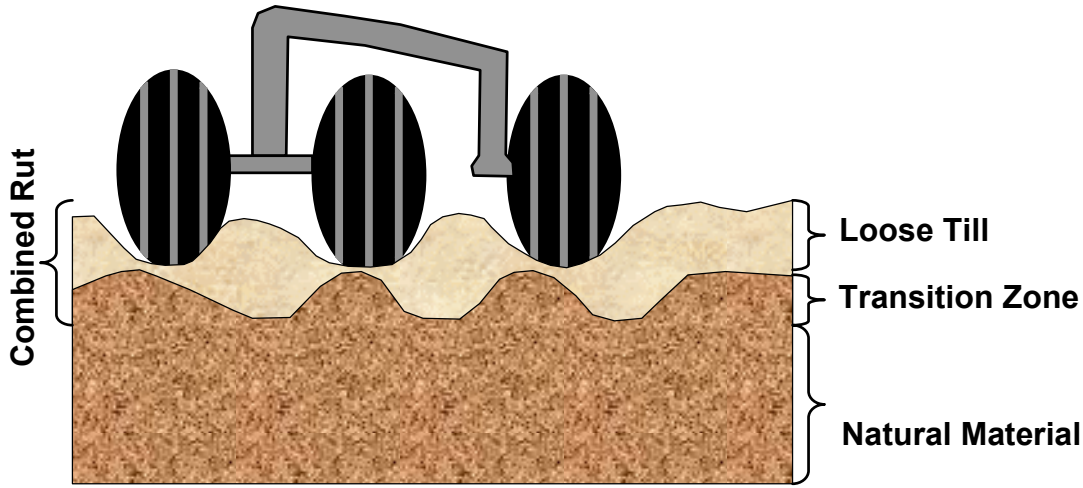


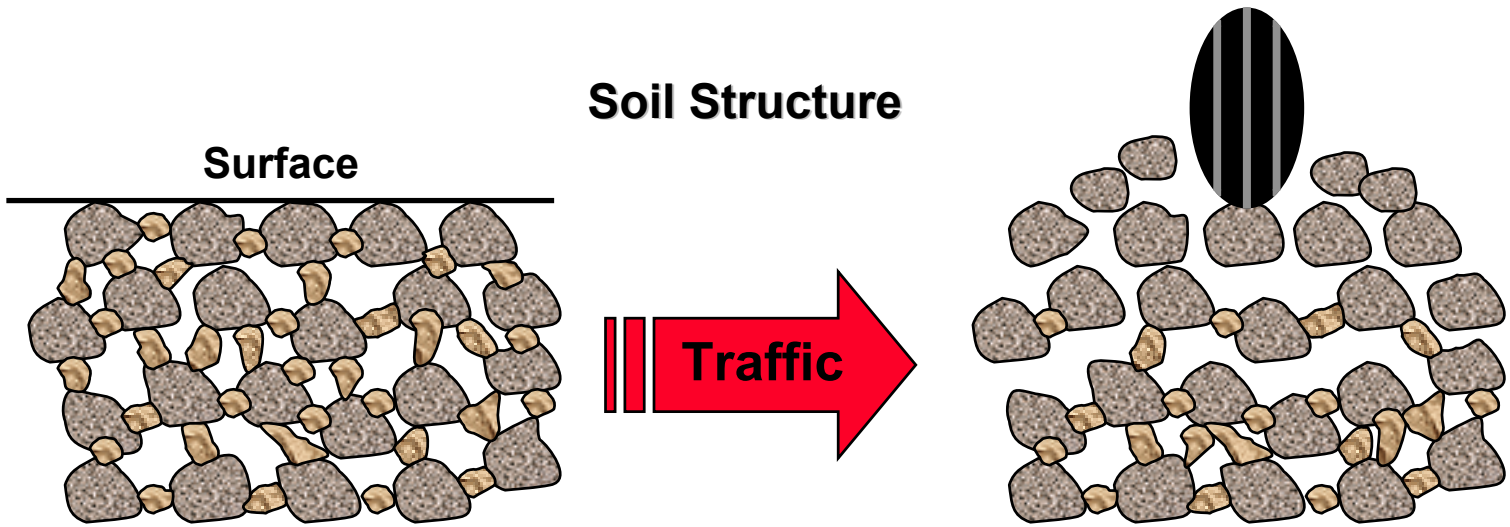
- **Dry Unsurfaced Test Sites**
  - Limited Soil Types in Arid and Semi-Arid Climates
  - Performed in a Noncohesive Manner
- **Edwards AFB**
  - Similar Dry, Hard Surfaces May Support Significant Operations
  - Wet Runway Surfaces Significantly Increase Aircraft Stopping Distance
- **Holland LZ**
  - Poor Construction Resulted In FOD and Roughness
  - Cement Stabilized Surface Defects Deteriorated Under Wet Conditions

Failure Mechanism

- **Remolded Soil Layer:**
  - **Remolding is the Lowering of Material Strength Under Traffic**
  - **Unsurfaced Airfields Lack a Wearing Surface to Resist Shear**
  - **Failure was Due to Shearing of the Surface Rather than Rutting**
  - **Shearing of the Surface Resulted in the Development of a Two Layer System**
  - **Surface Material is Gradually Remolded into a Loose Soil Layer**
  - **Material Below the Loose Soil Layer Retained its Original Strength**
  - **The Thickness of the Loose Soil Layer Increases with Traffic Until an Unknown Constant Depth Is Attained**

Failure Mechanism - Remolded Soil Layer





Quantifying Surface Soil Properties

- **Problem: Soil Characteristics Need to Be Quantified**
- **Potential Solution: Development of the X-value**
  - **CBR_S**
  - **CBR_L**
  - **$X = CBR_L/CBR_S$**
- **The X-value Can Be Used To Estimate the Shear Potential of a Soil**
- **The X-value is a Function of a Wide Variety of Soil Properties: Moisture Content, Density, Resistance to Shear, Gradation, Soil Structure, Mineralogy, etc.**

Shear Criteria Model

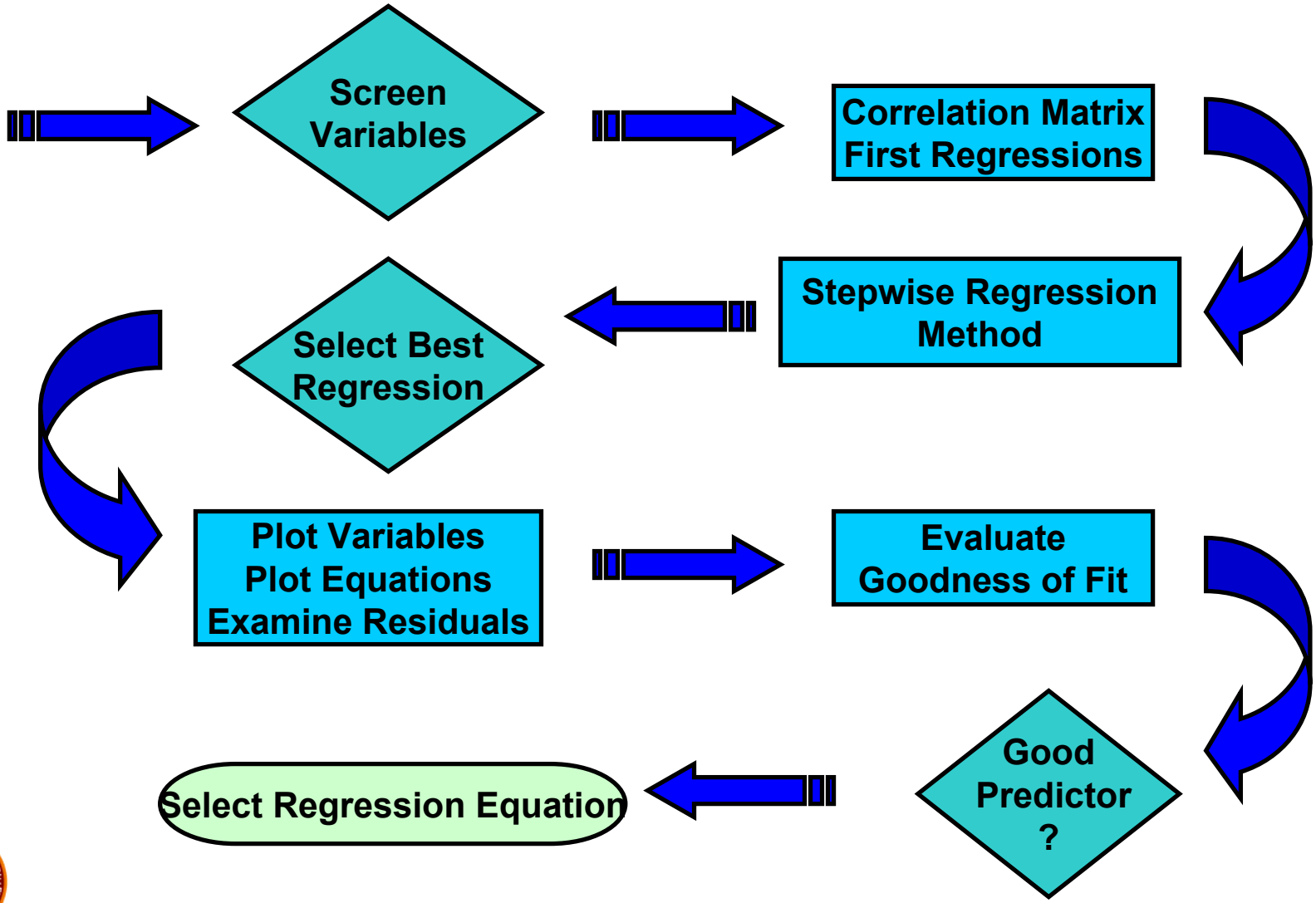
- **Problem: No Method for Predicting the Behavior of Unsurfaced Airfields in Arid and Semi-Arid Regions**
- **Solution: Development of a Numerical Model that can be used to Predict the Loose Till Depth**
- **The Amount of Loose Till Will Dictate Maintenance Requirements**

Shear Criteria Model

- **Model Development:**
  - **Define the Problem: Premature Functional Failure**
  - **Establish the Dependent Variable: Till Depth**
  - **Identify Potential Independent Variables:**
    - **Aircraft Operations**
    - **CBRL**
    - **CBRS**
    - **X-value**
    - **Percent Fines**
    - **Critical Depth**
    - **Surface CBR**
    - **Soil Type**
    - **Density**
    - **Moisture Content**
    - **Soil Structure**
    - **Internal Angle of Friction**
    - **Cohesion**
    - **Plasticity Index**
    - **Aircraft Load**
    - **Tire Pressure**
    - **Climate**

Shear Criteria Model

- **Model Development:**



Shear Criteria Model

- **Equation:**

  Till Depth = 2.554log(Operations) +1.708(X-value) - 5.074

- **Goodness of Fit:**
  - **R^2 = 0.775** **(22.5% Unexplained Variation)**
  - **Standard Error = 0.806**
  - **For CL, SC, and SM-SC Soils**
  - **Relatively Good Fit**

Shear Criteria Model

Predicted Till Depth For a Contingency Operation Level

(For Unsurfaced Airfields Evaluated During FY97 SPAM Testing)

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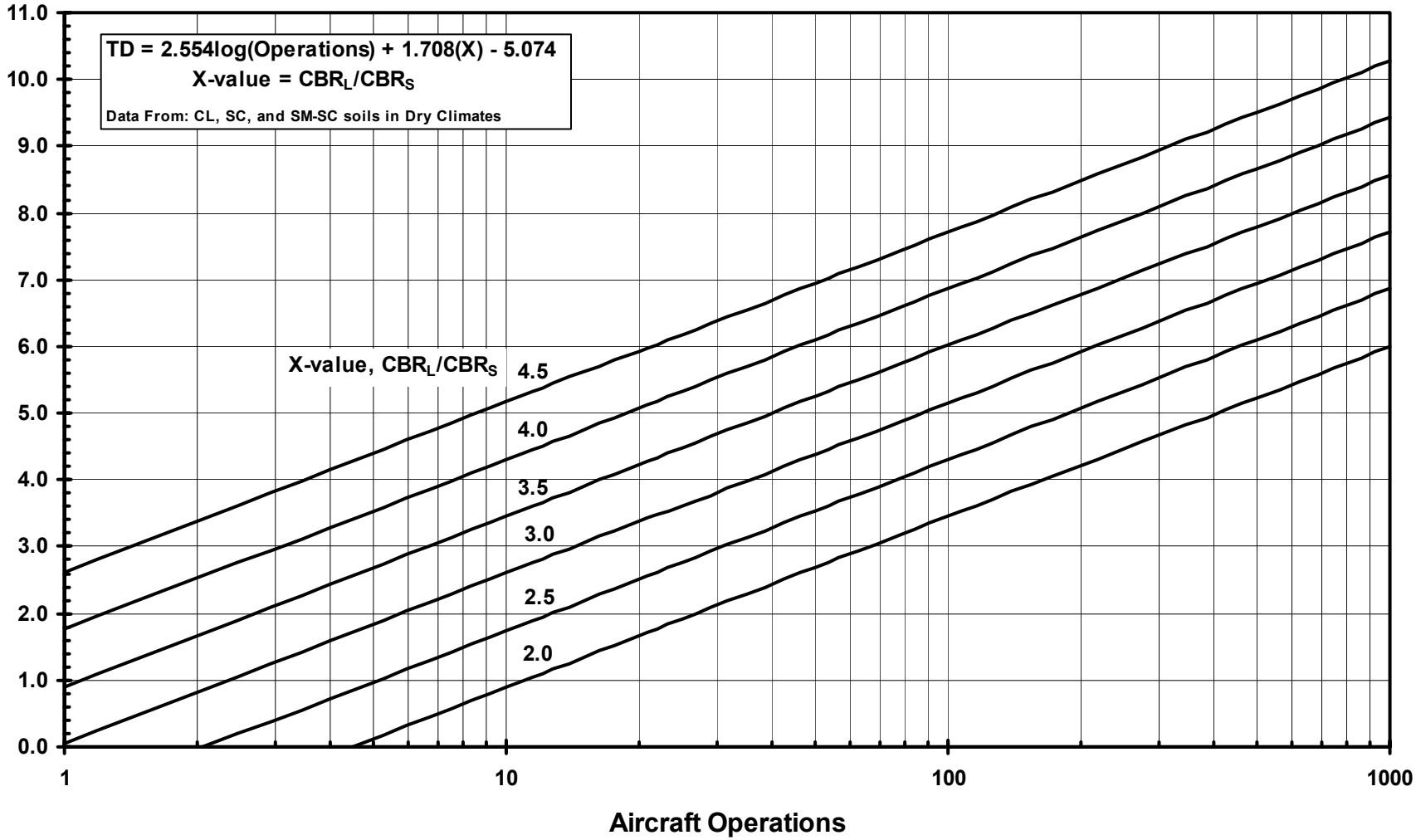

Examination of Existing Criteria

- **Existing Criteria Assumptions:**
  - **Load Cart (No Shear)**
  - **Humid Climate (Normal Range of Moisture Contents)**
  - **CH Subgrade**

- **Examination of the Unsurfaced Airfield Nomograph:**
  - **Predicted Values Do NOT Agree With Observed Field Values**
  - **Observed Values were Much Lower**

- **Conclusion:**

  The Unsurfaced Airfield Nomograph Should Not Be Used to Predict the number of Aircraft Passes til Failure of an Unsurfaced Airfield in an Arid or Semi-Arid Climate under Dry Conditions

Conclusions

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- All Dry Unsurfaced Airfields were in Arid or Semi-Arid Climates
- Failure of the Unsurfaced Runways Due to Shearing of the Surface Material
- The Shear Criteria Prediction Model Presented can be used to Predict Loose Till
- FOD was a Major Maintenance Problem
- Dust was a Major Visibility and Maintenance Problem
- Existing Unsurfaced Criteria is NOT Valid for Dry Unsurfaced Airfields in Arid and Semi-Arid Climates
- The Structural Integrity of Holland LZ was NOT Tested
- Aircraft Operations Under Wet Conditions Require Greater Landing Distances
- The Aircraft Exhibited Difficulty Taxiing Out of Ruts > 9”

Recommendations

- Flight Tests Should Be Conducted on an SM Soil in an Arid or Semi-Arid Climate
- Flight Tests Should Be Conducted on Various Soil Types in Humid and/or Tropical Climates
- Flight Tests Should Be Conducted on Soft Soils (CBR~9)
- The Current Prediction Model Should Be Used (Until Refined) to Predict the Amount of Loose Till
- An Investigation Should Be Conducted To Determine the Soil Properties Affecting the Soil's Shear Potential
- Aircraft Operating Procedures Should Be Modified to Reduce the Damage to the Airfield
- The FOD Potential Guidance Presented Should Be Used Until an Investigation Is Conducted to Determine FOD Potential

Recommendations - Concluded

- An Investigation Should Be Conducted to Evaluate Various Palliatives to Reduce Dust Signatures
- Current Cement Stabilization Criteria Should Be Evaluated
- Additional Expedient Airfield Surfacings Should Be Investigated
- An Investigation Should Be Initiated To Determine the Feasibility of Using HMMWV Skids to Predict Shear Potential