Examples of Use of Climatic Model on the Design of Flexible Pavements

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Agenda

- Study 1
  Estimation of moisture profile for the Port of Long Beach
- Study 2
  Estimation of moisture content under airfields
- Study 3
  Impact of site location and groundwater table depth on the thickness of airfield pavements

Overview

In the past, the majority of structural designs for highway and airfield pavements have been developed considering saturated conditions for unbound material layers

Variety of environmental locations and groundwater table (GWT) conditions

Overview

Unsaturated soil mechanics coupled with site environmental conditions has not been implemented in airfield pavement analysis by the practicing community

The variations of environmental locations, GWT depth and site soil properties have a significant impact on structural design of highway and airfield pavements

study 1

Estimation of moisture profile for the Port of Long Beach

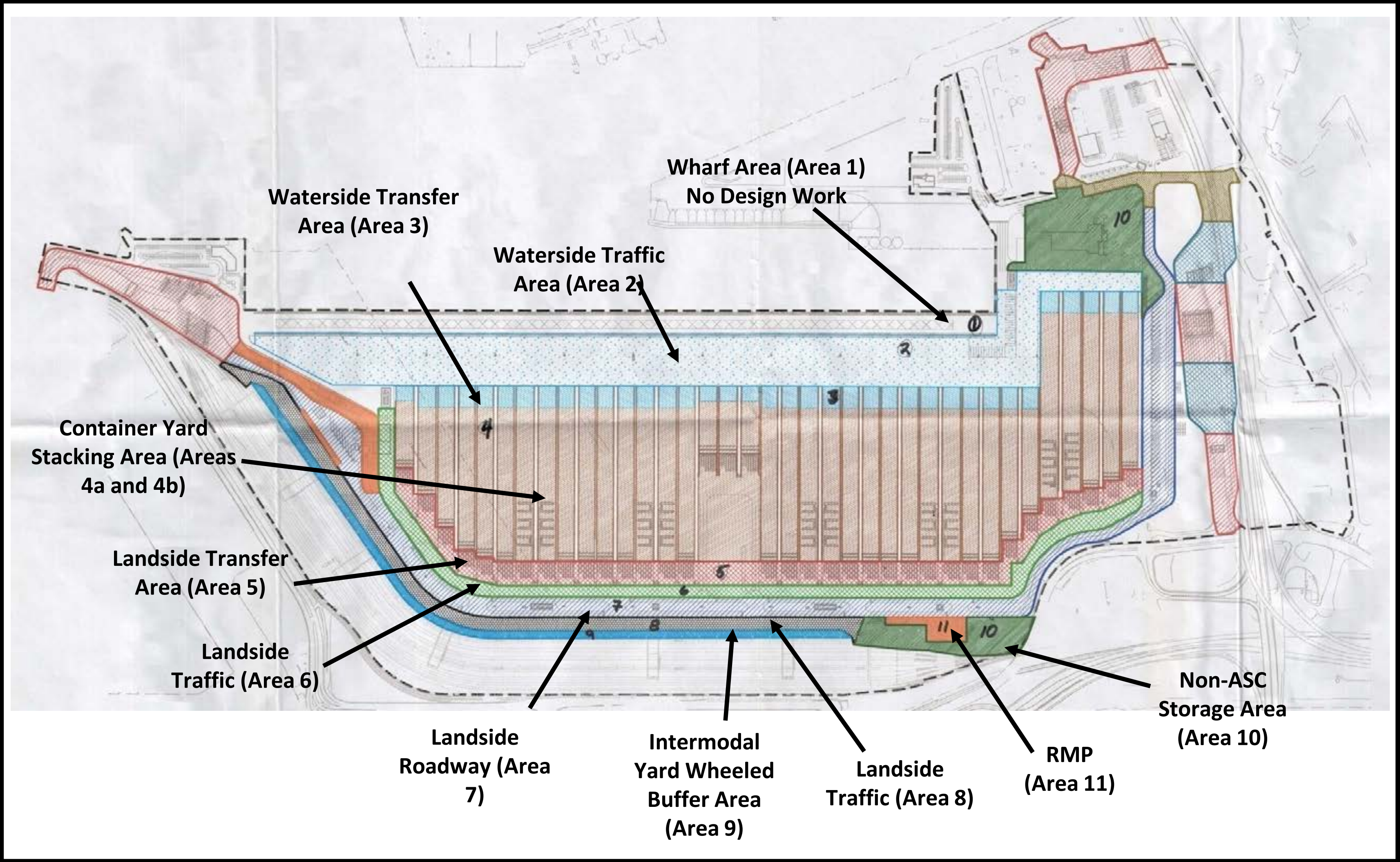
Overview

Independent assessment of the Main Harbor Terminal pavement designs for the port of Long Beach (California)

Project objectives

- Assess economic predictions of alternative designs
- Maintain performance with lowest possible costs in life cycle
- Reduce pavement construction costs

Proposed MHT layout and design area locations



Estimation of the Thornthwaite Moisture Index

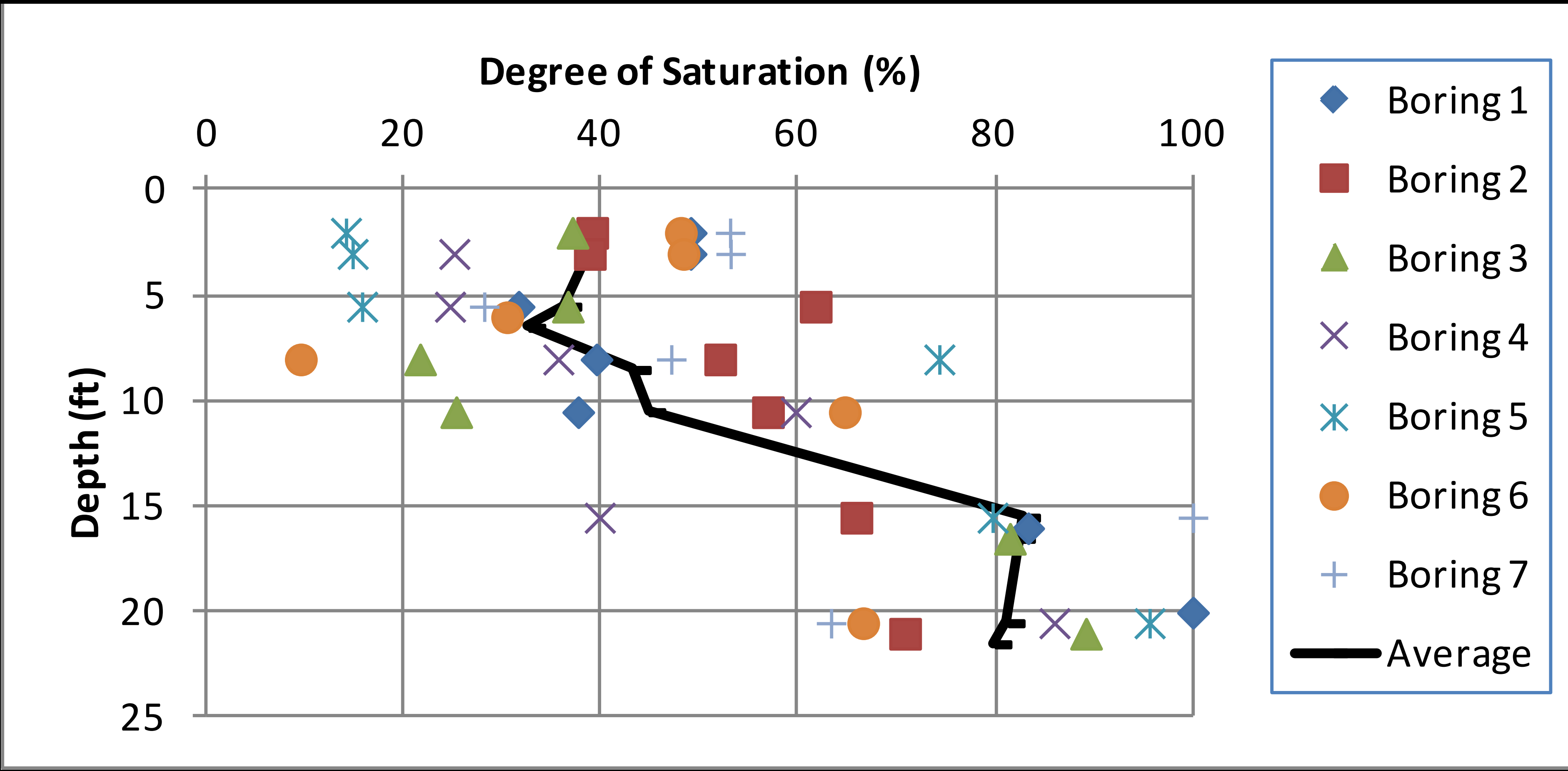
Variable	Mean	Variance	Standard Deviation
Precipitation (in.)	30.2	185.8	13.6
Annual Heat Index	80.7	5.9	2.4
Potential Evapotranspiration	77.8	9.8	3.1
Thornthwaite Moisture Index	-35.7	178.1	13.3

Estimation of the Thornthwaite Moisture Index

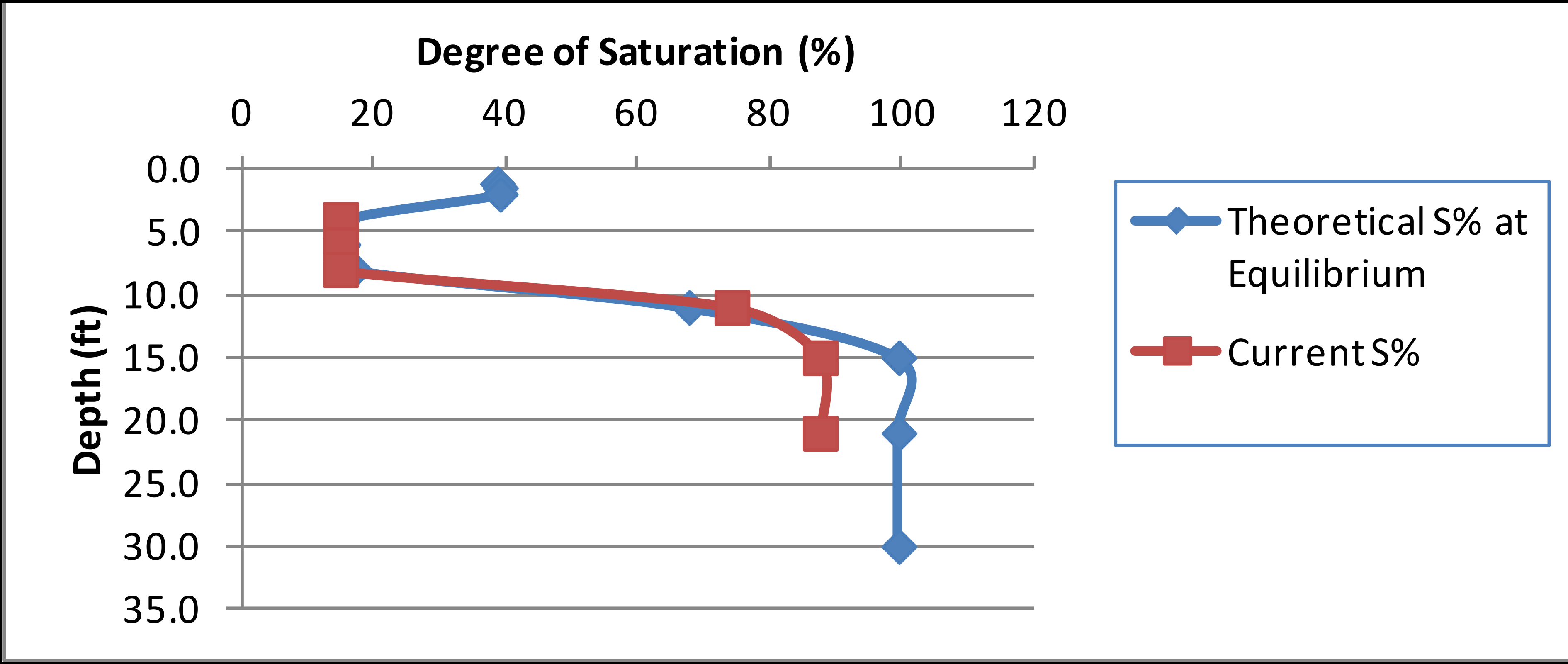
Monte Carlo Simulation Condition

- Number of Simulations: 25,000
- Location: Long Beach, CA
- Weather Station: Long Beach Daugherty Field Airport
- Latitude: 33.5˚
- Longitude: -118.1˚
- Elevation: 37 ft = 11 m

Current degree of saturation



Theoretical degree of saturation at equilibirum vs. current degree of saturation



Final design CBR and Mr

Depth	Mr	Design CBR
Surface to -5’	E = 18,000 psi	20%
-5’ to -7’	E = 15,000 psi	15%
-7’ to -16’	E = 11,000 psi	9.5%
> -16’	E = 8,000 psi	6%

Final design subgrade stiffness

- Equivalent Foundation Reaction Modulus (for Rigid Pavement)

  k_{sg} = 141 pci

- Equivalent Foundation Resilient Modulus (for Flexible Pavement)

  E_{sg} = 15,000 psi

- California Bearing Ratio

  CBR_{sg} = 15

Major findings / benefits to the POLB

- The use of the state-of-the-art technology of unsaturated soil mechanics clearly demonstrated and was verified by field results that Design Equilibrium Strength of Subgrade foundation should not be based upon saturated (soaked) soil strength tests.

Major findings / benefits to the POLB

- Use of “Soaked Samples” are quite conservative in the Los Angeles basin area, where negative Thornthwaite Moisture Indices show overall tendencies of soils to be in a “suction behavior mode”
- This will lead to the design of much thinner (and cheaper) pavement cross sections that would be actually needed for the performance period

- **Historic strength data used at the port was based on a soaked CBR design value of 8.**

- **The use of unsaturated soil properties allowed for the final design CBR to be increased to a value of 15.**

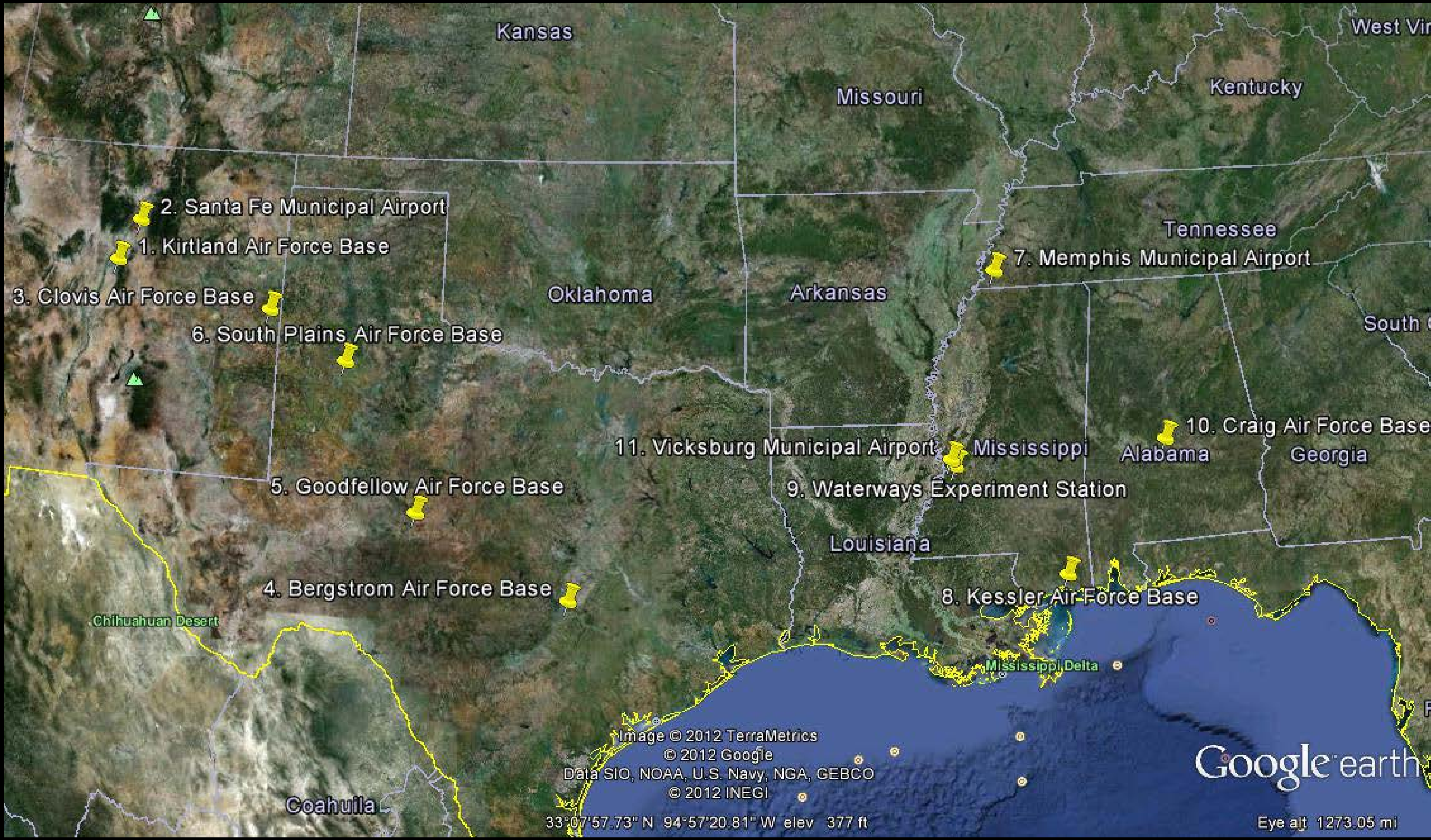
- **Early computations indicated that cost savings of $5-$10 million could be achieved for the approximate 1 million square feet of pavement to be required**

study 2

Comparison of actual field measured moisture contents to theoretically predicted moisture

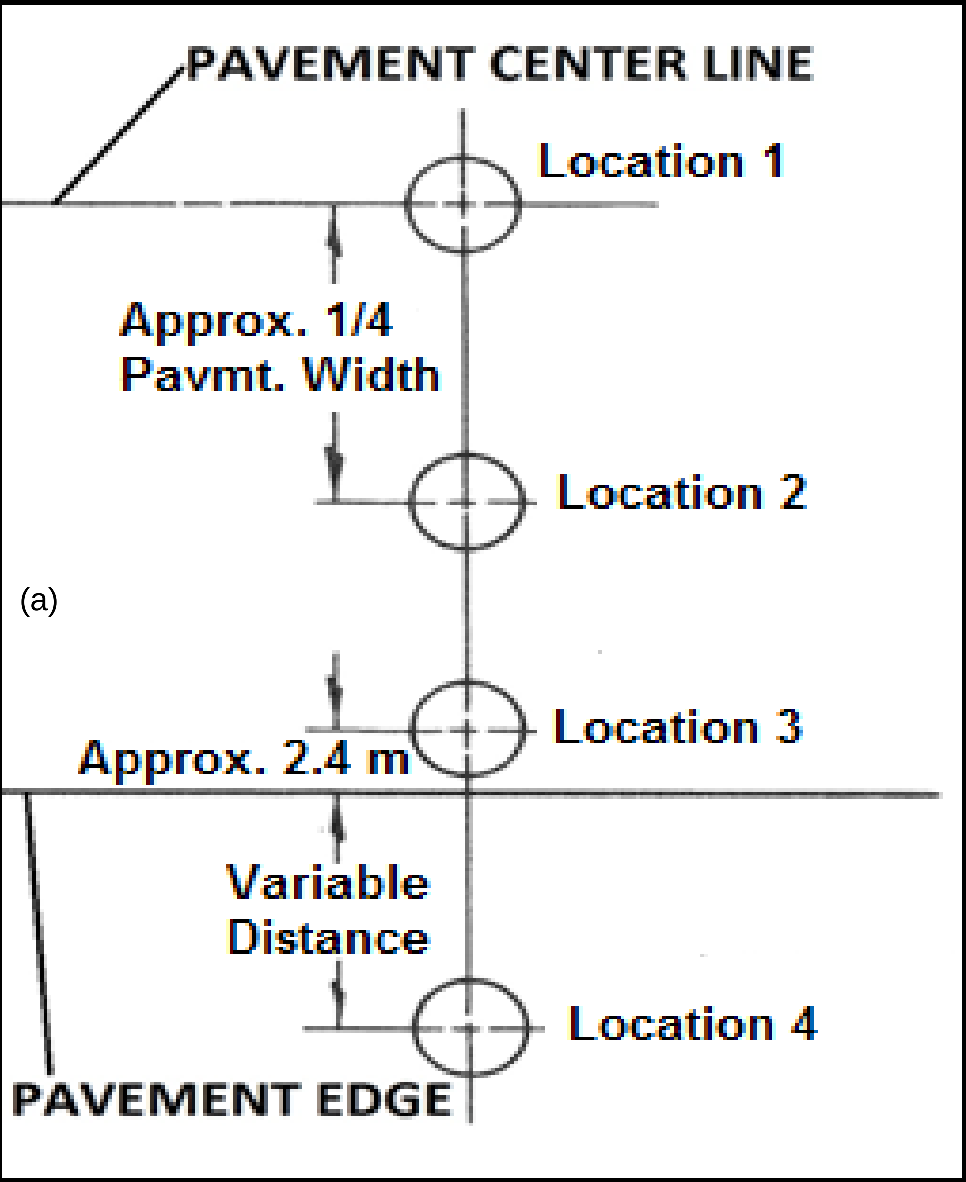
- **To study the feasibility of using the environmental models to estimate moisture content distribution under airfields**

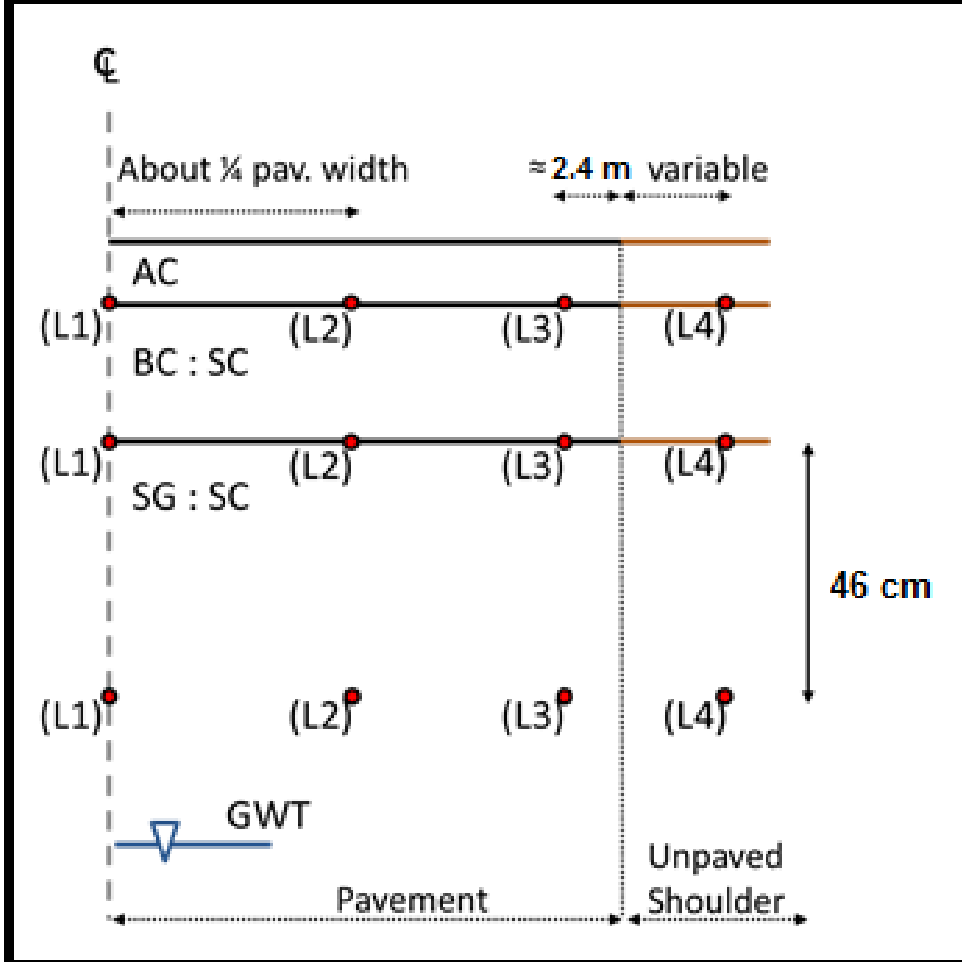
- **Study done for the USAF by Zapata and Cary (2012)**



11 airfields

- **734 water content measurements**
- **October 1945-November 1952**
- **Structure and materials properties obtained from reports**
- **Climatic data files (HCD) generated from NCDC historic records**
- **Results from about 140 M-EPDG runs**





Data from 4 different locations and different depths below runway and taxiway pavements

Site properties

No	Airfield Name	Airfield Location	Zone Class	Sampling Site		Structure															GWT Depth (ft)	Avg.Ann. Rainfall (in)	Temp. Range (F)	Airfield Elevation (ft)
						AC	Base Course				Sub-base				Subgrade-Comp.			Subgrade-Nat.						
						(in)	(in)	Type	PI	P200	(in)	Type	PI	P200	Type	PI	P200	Type	PI	P200				
1	Kirtland AFB	Albuquerque, NM	Arid	Taxiway	L1	2	8.5	SC	4	10					SC	7	29	SC	4	31	>100	7	104 to -10	5000
					L2			SC	4	10					SM	5	-	SM	4	-				
					L3			SC	4	3					SM	NP	30	SC	5	32				
					L4			SC	3	35					SC	4	34	SC	6	36				
2	Santa Fe MA	Santa Fe, NM	Semi-arid	Runway	L1	3	8.5	GC	15	25					CL	21	52	SC	24	35	>100	10	97 to -13	6000
					L2			GC	11	14					SC	18	38	SC	27	25				
					L3			GC	13	18					SC	19	36	SC	21	30				
					L4			CL	17	54					CL	10	-	CL	10	-				
3	Clovis AFB	Clovis, NM	Semi-arid	Runway	L1	1.5	12	SC	6	24					CL	9	50	CL	14	45	>100	15	109 to -11	4100
					L2			SC	7	33					CL	17	44	CL	12	44				
					L3			SC	7	27					CL	16	44	CL	10	44				
					L4			SC	8	-					CL	13	-	CL	8	-				
4	Bergstrom AFB	Austin, TX	Dry Sub-humid	Runway	L1	2	9	GM	1	14	2 to 4	CL	7	41	CH	31	58	CH	33	47	20	33	109 to -1	600
					L2			GM	1	12		CL	8	48	CH	53	55	CH	45	67				
					L3			GM	NP	14		CL	4	46	CH	38	63	CH	40	50				
					L4			CH	29	60		CH	29	60	CH	29	60	CH	29	60				
5	Goodfellow AFB	San Angelo, TX	Semi-arid	Runway	L1	2	14	SC	10	36					CH	30	88	CL	28	87	>50	16	111 to 1	2000
					L2			SC	11	38					CH	33	91	CH	30	91				
					L3			SC	9	37					CH	30	88	CL	28	90				
					L4			CH	32	84					CL	22	78	CL	22	78				
6	South Plains AFB	Lubbock, TX	Dry Sub-humid	Runway	L1	1.5	8	GM	7	11					CL	14	55	CL	18	55	80	17	108 to -17	3200
					L2			GM	3	15					CL	11	54	CL	17	54				
					L3			GM	NP	10					CL	14	54	CL	18	56				
					L4			CL	16	62					CL	16	62	CL	16	62				
7	Memphis MA	Memphis, TN	Humid	Runway	L1	3	9	GC	16	16					CL	14	83	CL	17	80	Near Sf	51	106 to -9	275
					L2			GC	9	6					ML	7	82	CL	20	66				
					L3			GC	13	7					ML	5	89	CL	12	84				
					L4			CL	9	92					CL	9	92	CL	9	92				
8	Keesler AFB	Biloxi, MS	Humid	Runway	L1	2	9	GW	NP	10					SW	NP	5	SW	NP	5	3 to 6	76	104 to 1	10
					L2			GW	NP	8					SW	NP	5	SW	NP	2				
					L3			SW	NP	12					SW	NP	2	SW	NP	0				
					L4			SW	NP	-					SW	NP	-	SW	NP	-				
9	WES Test Strip	Vicksburg, MS	Humid	Turnabout	L1	2	9	SC	4	12					CL	20	100	CL	20	100	>100	52	104 to -1	200
					L2			SC	4	12					CL	19	100	CL	20	100				
					L3			SC	4	12					CL	20	100	CL	20	100				
					L4			CL	20	98					CL	21	100	CL	20	100				
10	Craig AFB	Selma, AL	Humid	Runway	L1	1.5	9	SC	14	17					SM	3	37	SM	4	45	7	50	106 to -5	150
					L2			SC	14	17					SM	3	37	SM	4	45				
					L3			SC	14	17					SC	10	37	SM	4	45				
					L4			SM	3	45					SM	3	45	SM	4	45				
11	Vicksburg MA	Vicksburg, MS	Humid	Taxiway	L1	1.5	9	GC	11	12					ML	3	98	ML	5	-	5.5	52	104 to -1	99
					L3			GC	11	12					ML	3	98	ML	5	-				
					L4			ML	-	-					ML	-	-	ML	-	-				

Thornthwaite Moisture Index

Zone Class	No	TMI	Material
Arid and Semi-arid (TMI < -20)	1	-49 (Kirtland)	Base Material Compacted Subgrade Natural Subgrade
	2	-35 (Goodfellow)	Base Material Compacted Subgrade Natural Subgrade
	3	-32 (Santa Fe)	Base Material Compacted Subgrade Natural Subgrade
	4	-24 (Clovis)	Base Material Compacted Subgrade Natural Subgrade
Dry Sub-humid (0 > TMI > -20)	5	-19 (South Plains)	Base Material Compacted Subgrade Natural Subgrade
	6	-8 (Bergstrom)	Base Material Subbase Material Compacted Subgrade Natural Subgrade
Humid (TMI > 20)	7	35 (Vicksburg)	Base Material Compacted Subgrade Natural Subgrade
	8	38 (Memphis)	Base Material Compacted Subgrade Natural Subgrade
	9	41 (Craig)	Base Material Compacted Subgrade Natural Subgrade
	10	47 (WES)	Base Material Compacted Subgrade Natural Subgrade
	11	54 (Keesler)	Base Material Compacted Subgrade Natural Subgrade

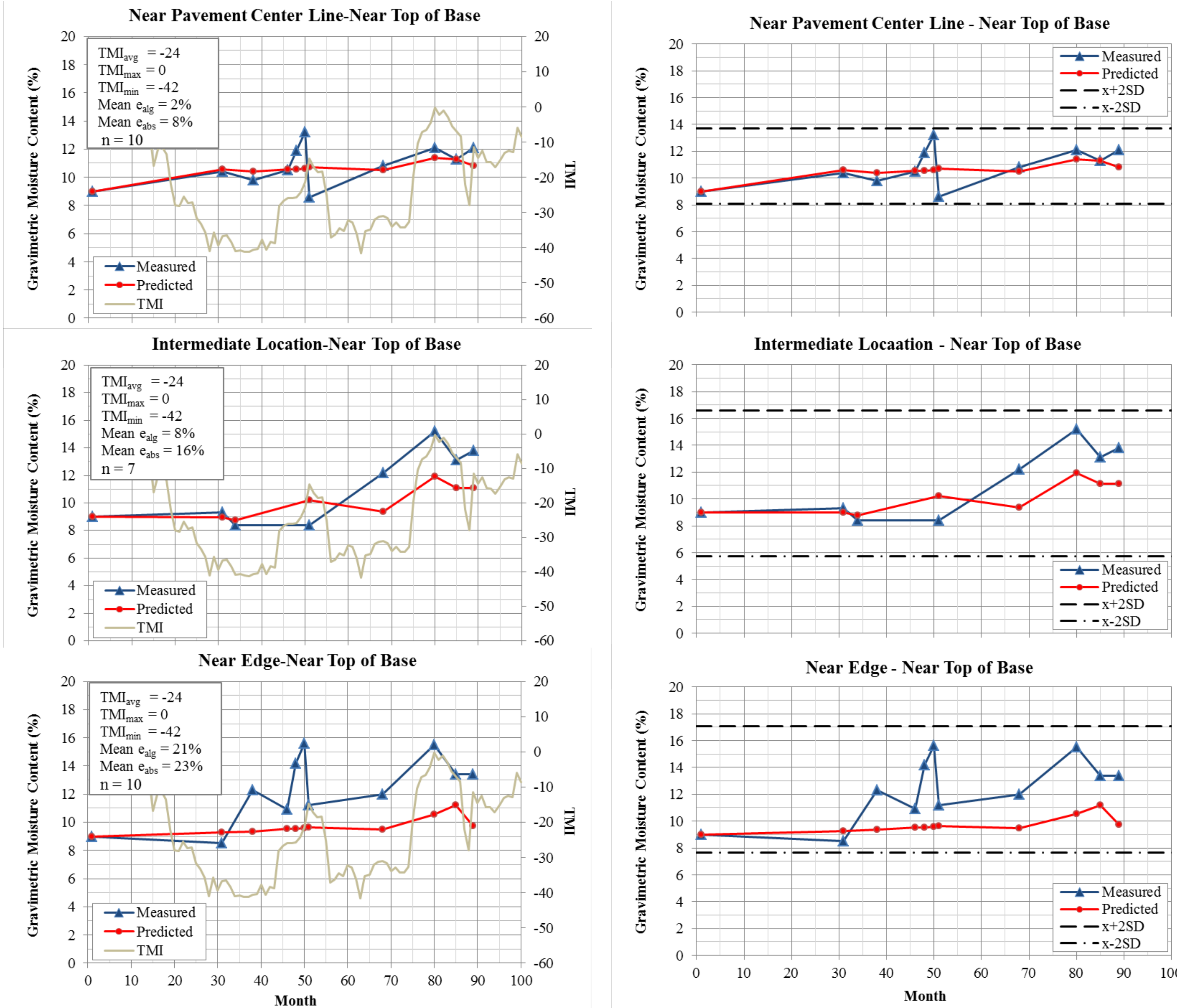
Climatic data collected from NCDC

Kirtland Air Force Base / Albuquerque WB AP Station

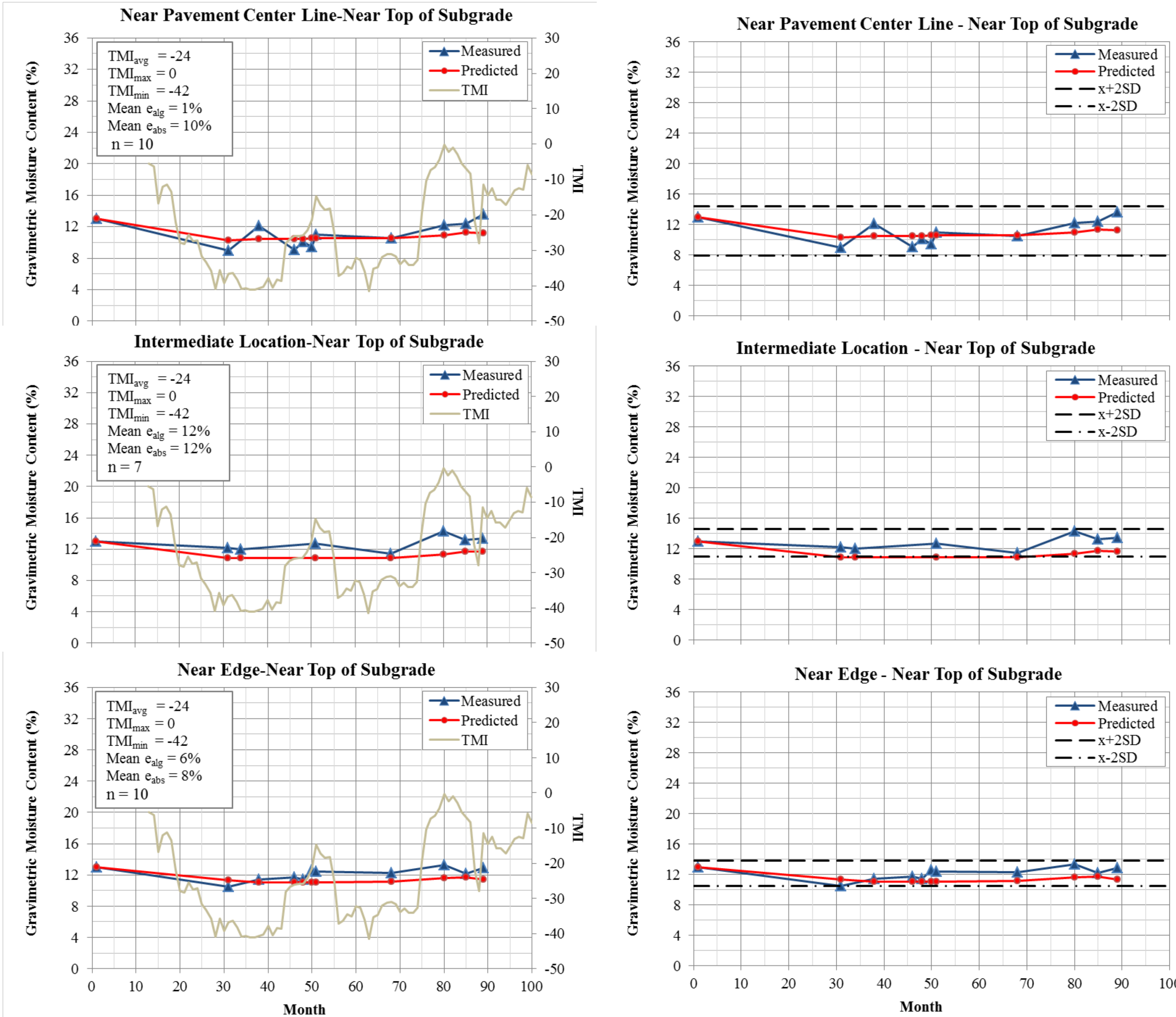
Elevation (ft) 5,314 Latitude 35°02'60" Longitude 106°36'60"

Mo./Yr.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
	Mean Monthly Temperature (F)												
1944	29.2	40.0	44.4	52.2	63.9	73.3	76.4	76.3	68.6	58.7	43.0	36.3	55.2
1945	36.8	43.0	45.0	52.3	66.2	72.6	78.4	78.2	70.6	58.6	45.2	33.4	56.7
:													
1957	39.9	48.1	47.3	54.2	61.9	74.8	79.1	76.0	70.3	56.6	40.3	38.5	57.3
1958	35.3	43.5	42.8	53.0	68.6	78.5	79.6	78.9	69.2	56.9	46.0	41.5	57.8
	Monthly Precipitation (in)												**Total**
1944	0.46	0.42	0.49	0.91	0.57	0.85	1.58	1.44	0.65	0.86	0.56	0.76	9.55
1945	0.34	0.32	0.50	0.77	0.01	0.01	1.09	2.27	0.26	0.43	0.01	0.35	6.36
:													
1957	0.78	0.59	0.52	0.38	0.35	0.04	2.48	1.32	0.00	2.59	1.24	0.32	10.61
1958	0.21	0.27	1.71	0.62	0.43	0.22	0.14	1.74	1.34	1.72	0.37	1.35	10.12

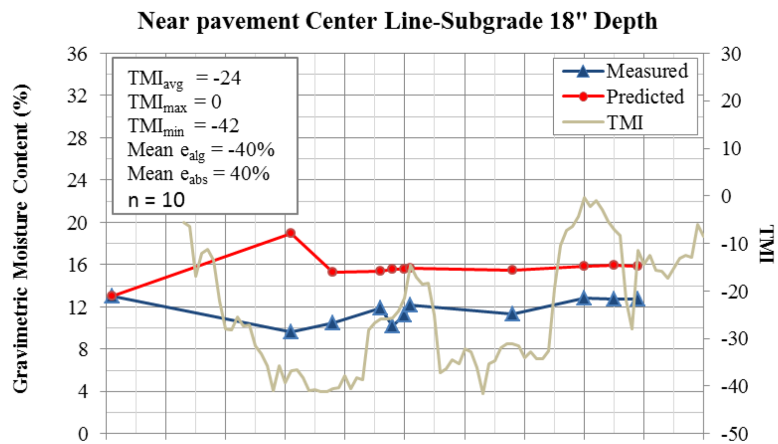
CLOVIS AFB - BASE COURSE

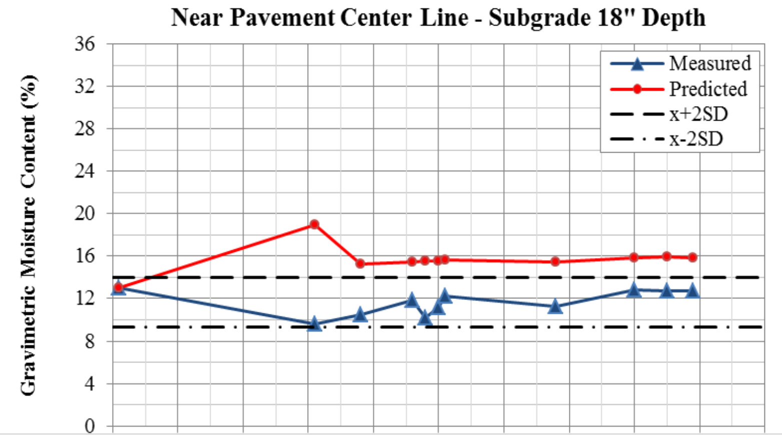


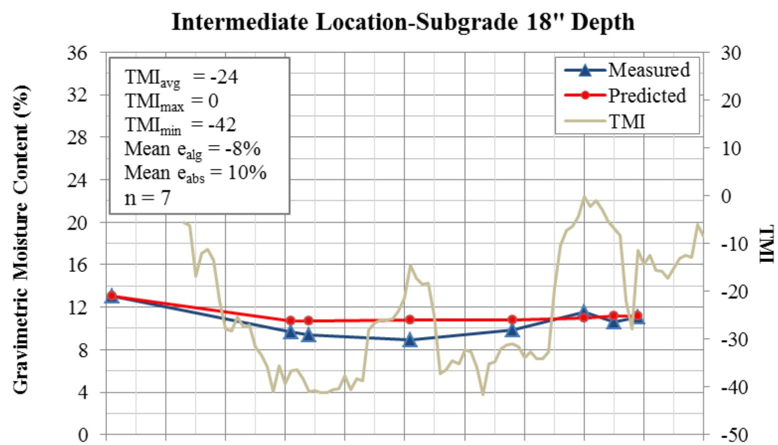
CLOVIS AFB – COMPACTED SUBGRADE

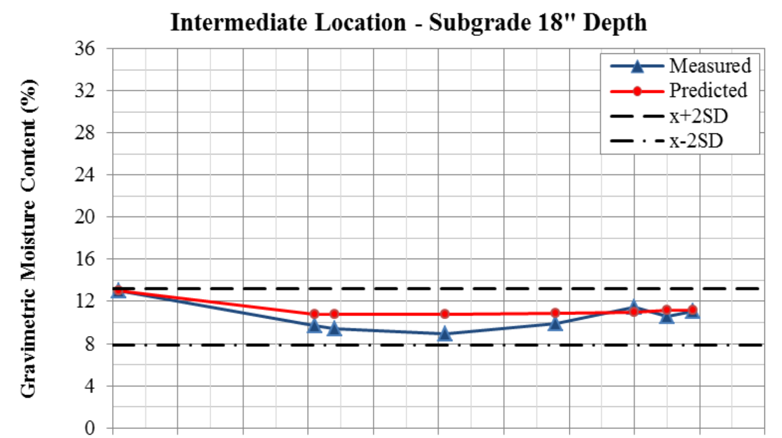


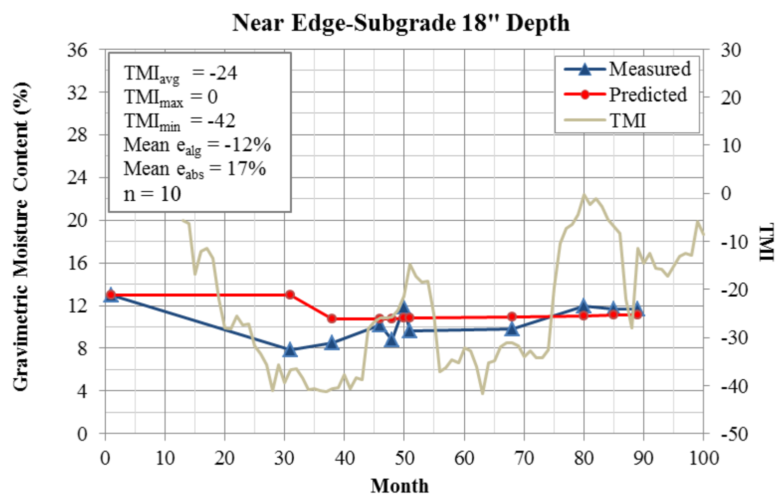
CLOVIS AFB – NATURAL SUBGRADE

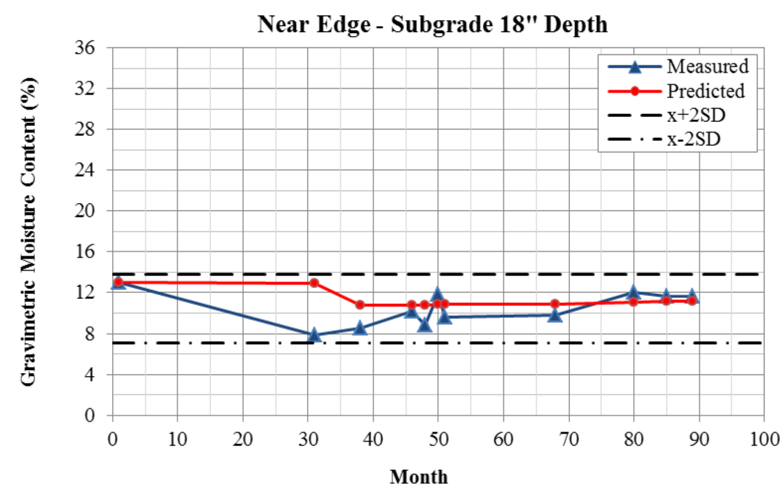


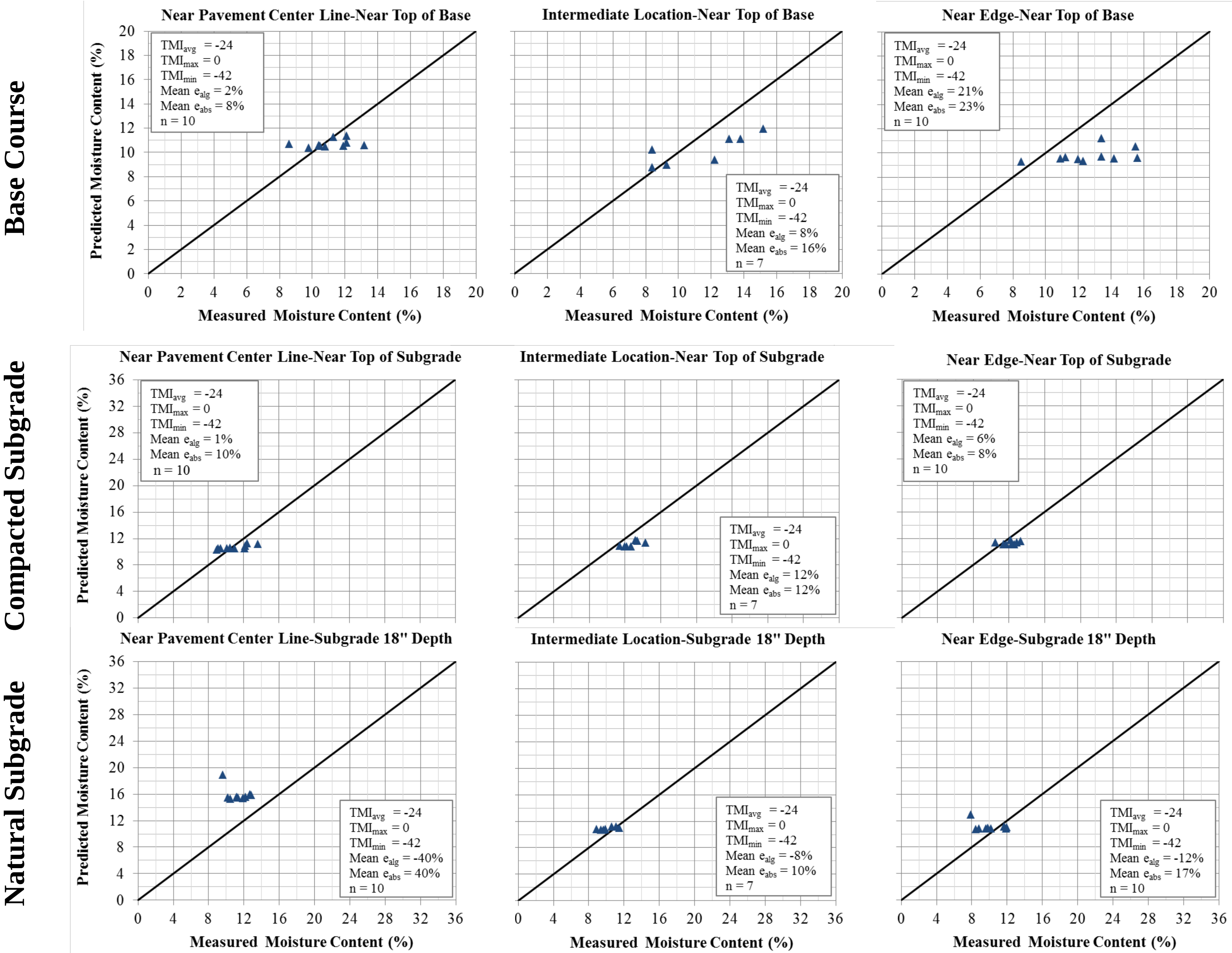




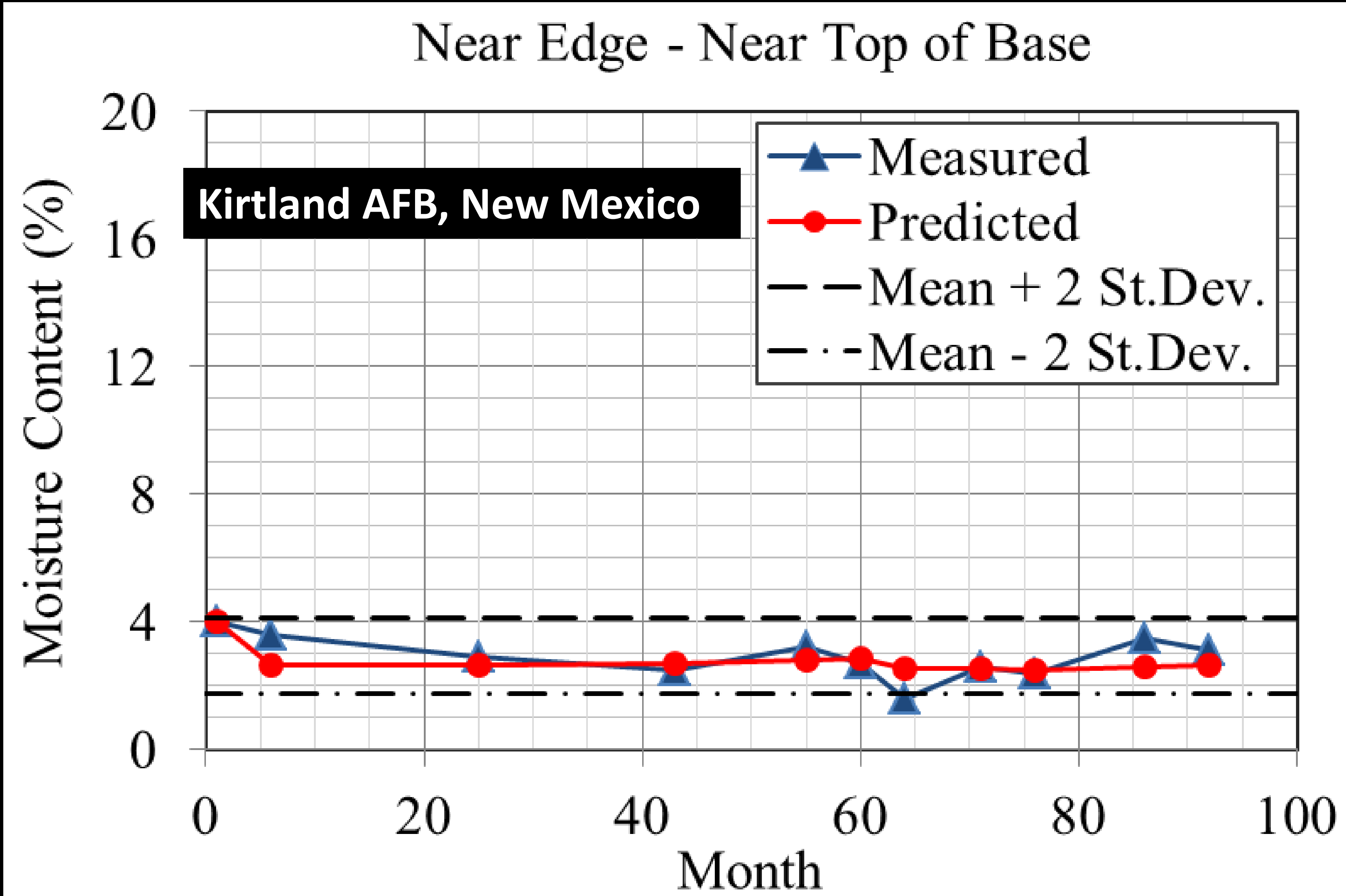




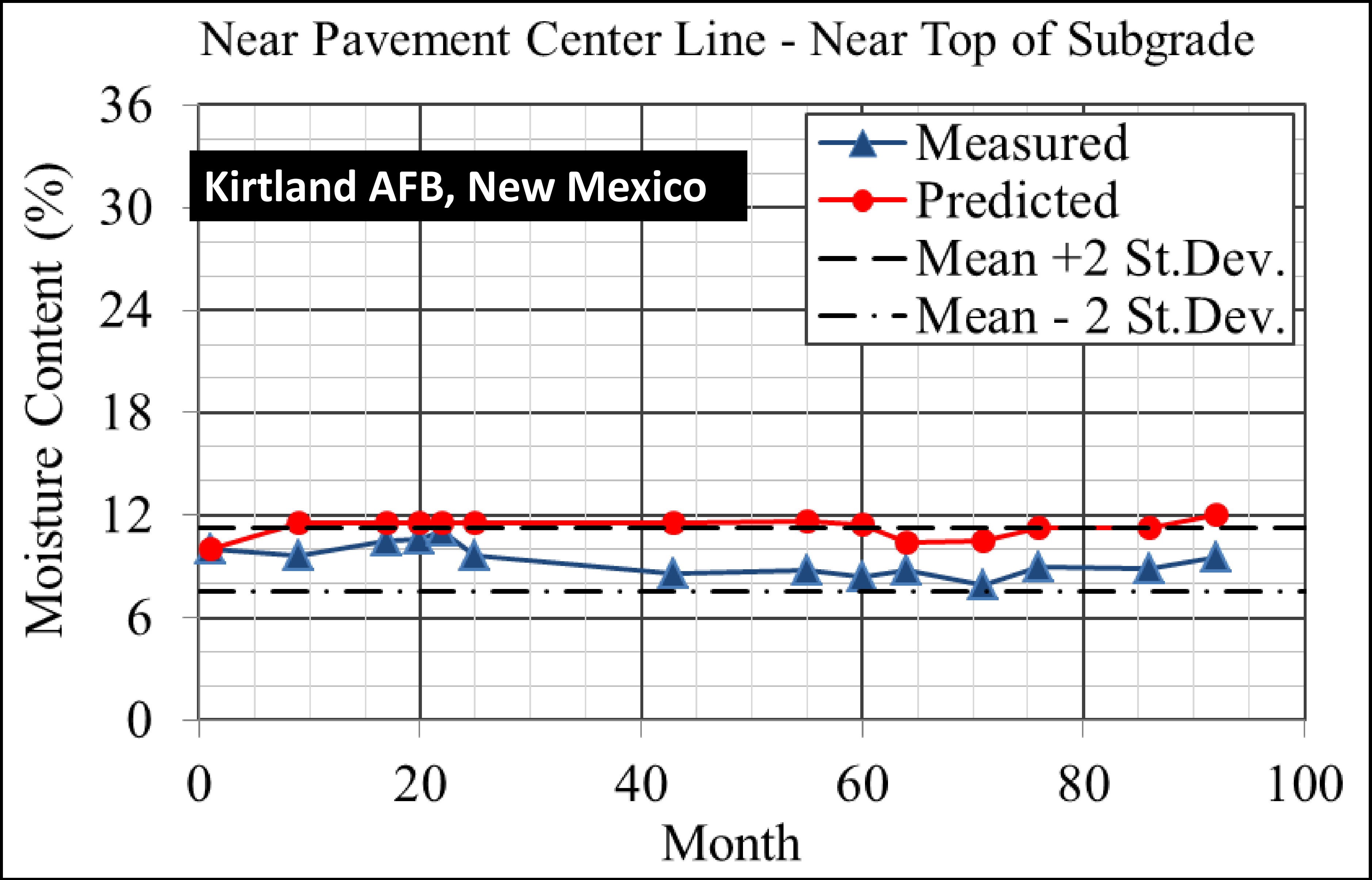




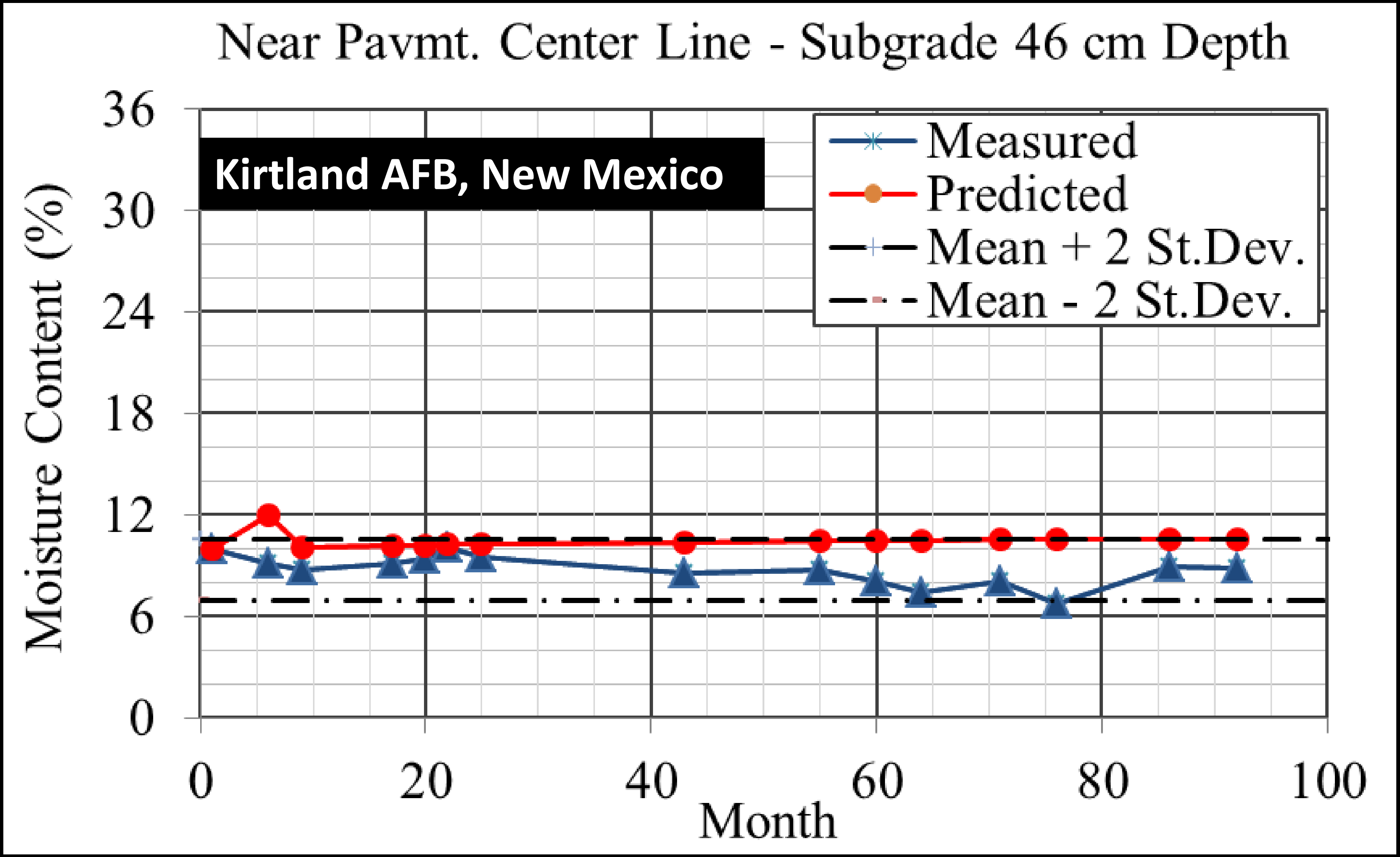
Base Course
Compacted Subgrade
Natural Subgrade
Near Pavement Center Line-Near Top of Base
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = 2%
Mean eabs = 8%
n = 10
Intermediate Location-Near Top of Base
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = 8%
Mean eabs = 16%
n = 7
Near Edge-Near Top of Base
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = 21%
Mean eabs = 23%
n = 10
Near Pavement Center Line-Near Top of Subgrade
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = 1%
Mean eabs = 10%
n = 10
Intermediate Location-Near Top of Subgrade
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = 12%
Mean eabs = 12%
n = 7
Near Edge-Near Top of Subgrade
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = 6%
Mean eabs = 8%
n = 10
Near Pavement Center Line-Subgrade 18" Depth
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = -40%
Mean eabs = 40%
n = 10
Intermediate Location-Subgrade 18" Depth
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = -8%
Mean eabs = 10%
n = 7
Near Edge-Subgrade 18" Depth
TMIavg = -24
TMImax = 0
TMImin = -42
Mean ealg = -12%
Mean eabs = 17%
n = 10
Predicted Moisture Content (%)
Measured Moisture Content (%)



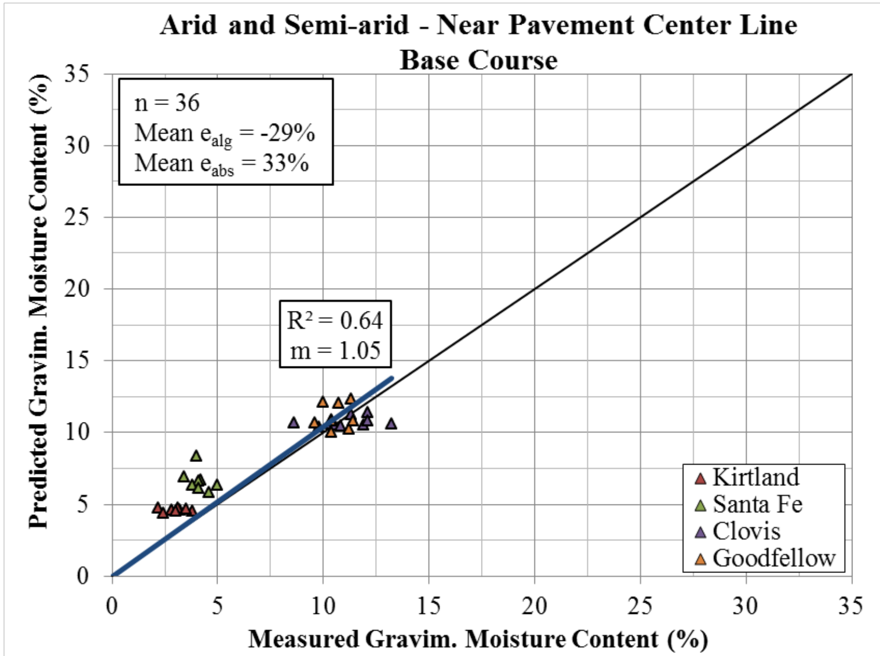
Top of Base Course

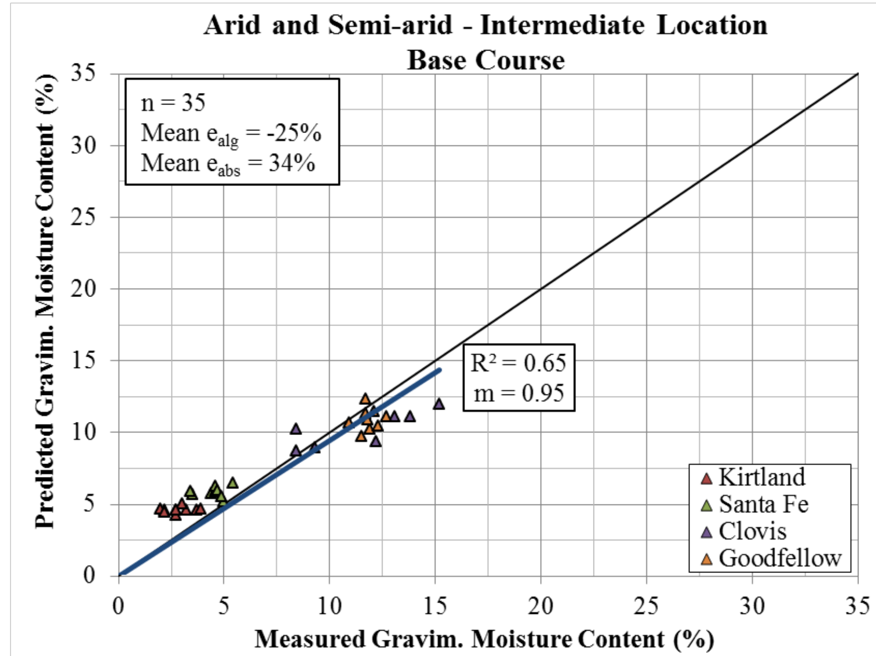


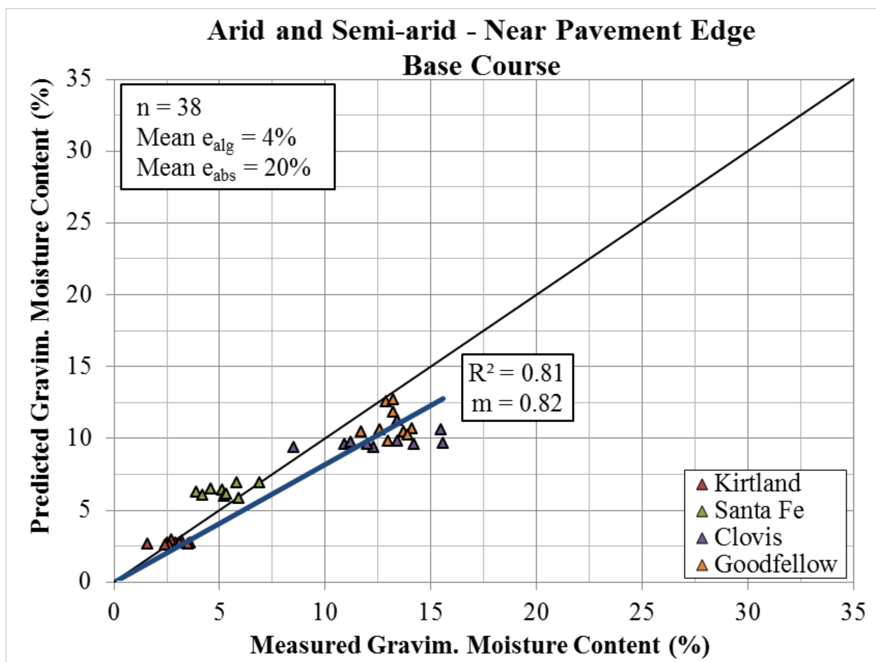
Top of Subgrade

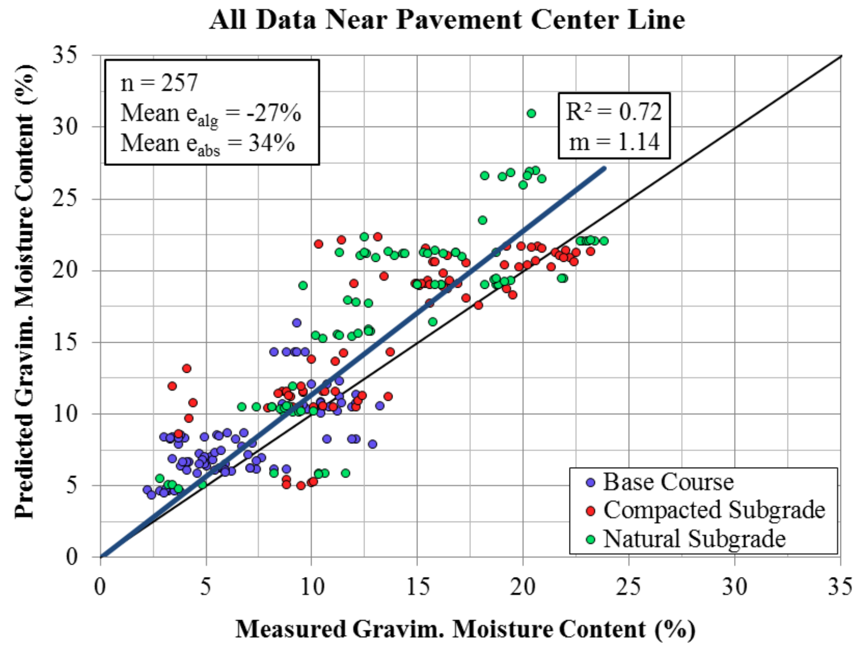


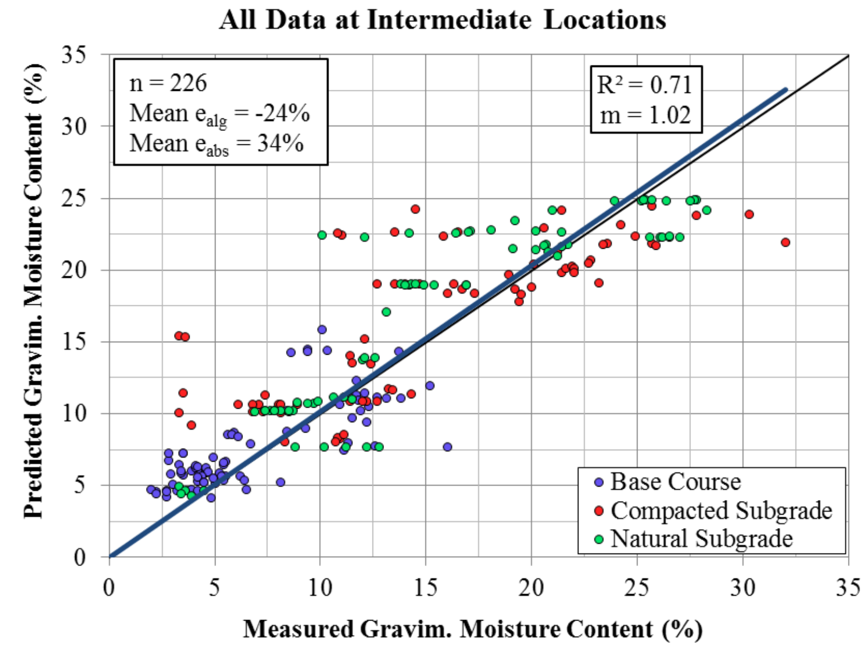
Into the Subgrade

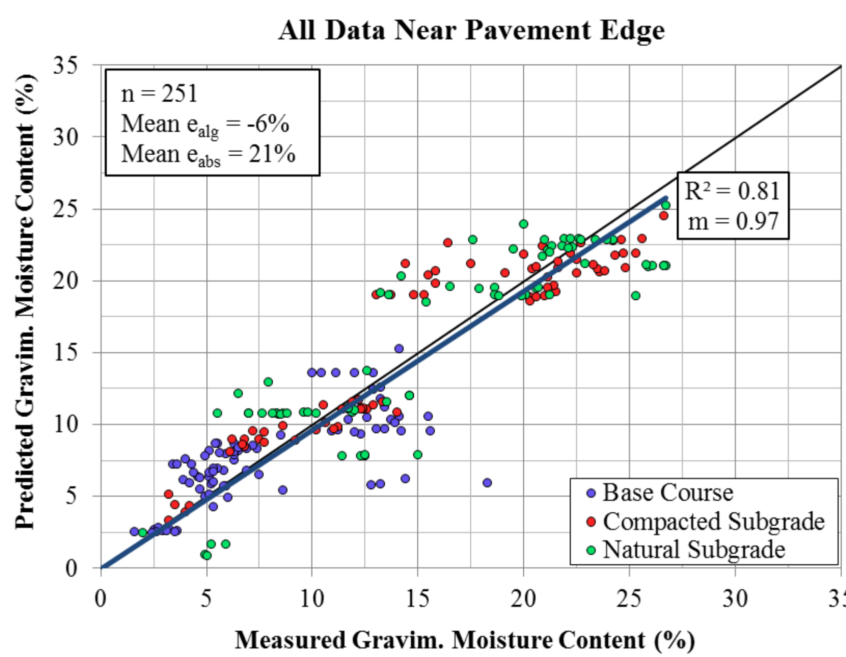

Arid and Semi-arid - Near Pavement Center Line
Base Course
n = 36
Mean e_{alg} = -29%
Mean e_{abs} = 33%
R^2 = 0.64
m = 1.05
Kirtland
Santa Fe
Clovis
Goodfellow
Predicted Gravim. Moisture Content (%)
Measured Gravim. Moisture Content (%)
0
5
10
15
20
25
30
35


Arid and Semi-arid - Intermediate Location
Base Course
n = 35
Mean e_{alg} = -25%
Mean e_{abs} = 34%
R^2 = 0.65
m = 0.95
Kirtland
Santa Fe
Clovis
Goodfellow
Predicted Gravim. Moisture Content (%)
Measured Gravim. Moisture Content (%)
0
5
10
15
20
25
30
35

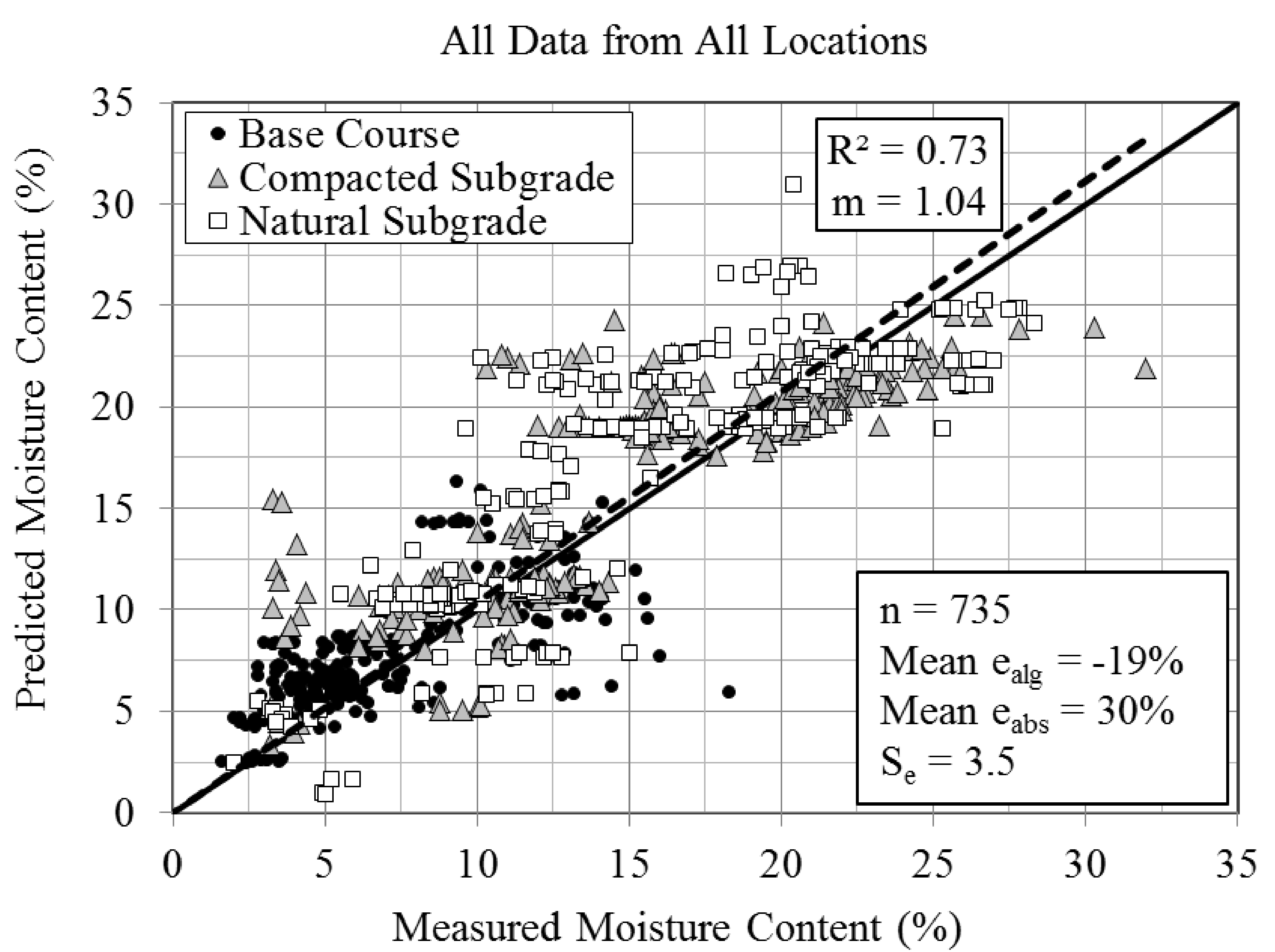

Arid and Semi-arid - Near Pavement Edge
Base Course
n = 38
Mean e_{alg} = 4%
Mean e_{abs} = 20%
R^2 = 0.81
m = 0.82
Kirtland
Santa Fe
Clovis
Goodfellow
Predicted Gravim. Moisture Content (%)
Measured Gravim. Moisture Content (%)
0
5
10
15
20
25
30
35







Parameter	***Near Pavement Center Line***	***Intermediate Location***	***Near Pavement Edge***
n	*257*	*226*	*251*
e_{alg}	*-27%*	*-24%*	*-6%*
e_{abs}	*34%*	*34%*	*21%*
Total Number of Data Points Analyzed			*734*



735 datapoints – 11 airfields

part I: conclusions

- **Less error in predictions were observed near the pavement edge**

- **Better predictions were obtained for subgrade materials**

- **Evaluation, adjustment and calibration of EICM models to accommodate for airfield pavements will be needed**

- **2-D water flow analysis will be necessary to improve predictions**

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Results suggest EICM model has potential to be adapted and incorporated in airfield pavements design

The primary factor driving the selection of in-situ strength must be governed by the site environmental conditions along with the location of the groundwater table at the design site location

The development and eventual implementation of the proposed enhanced methodology, that would lead to a more accurate estimate of the in-situ strength, could provide significant economic benefits and cost savings to airfield pavement design, evaluation and rehabilitation studies all over the world.

study 3

Impact of site location and groundwater table depth on the thickness of flexible airfield pavements

part I: introduction

Environmental effects on pavement design and performance is a fundamental component of any Mechanistic-Empirical Pavement Design procedure.

However, current airfield design procedures do not consider the effects of groundwater table depth and the effect due to environmental conditions.

There is a significant need to incorporate the influence of environmental site factors and the groundwater table depth upon flexible airfield pavement design and performance.

A methodology and computer code was developed at Arizona State University that allows for this analysis, including special considerations for unsaturated regions.

part II: objective of the study

Provide a quantitative assessment of the potential benefits and savings in pavement design thickness that occur due to the inclusion of specific environmental site properties

Environmental site properties analyzed included moisture, temperature and groundwater table depth

The study focuses upon the prediction of pavement thickness to guard against excessive shear deformations or rutting for asphalt pavements.

Analysis was provided for a series of aircraft types, subgrade support values, different geographic locations across the US, and a range of GWT depths.

part III: the analysis

5 different climatic conditions

6 groundwater table depths

3 subgrade soils

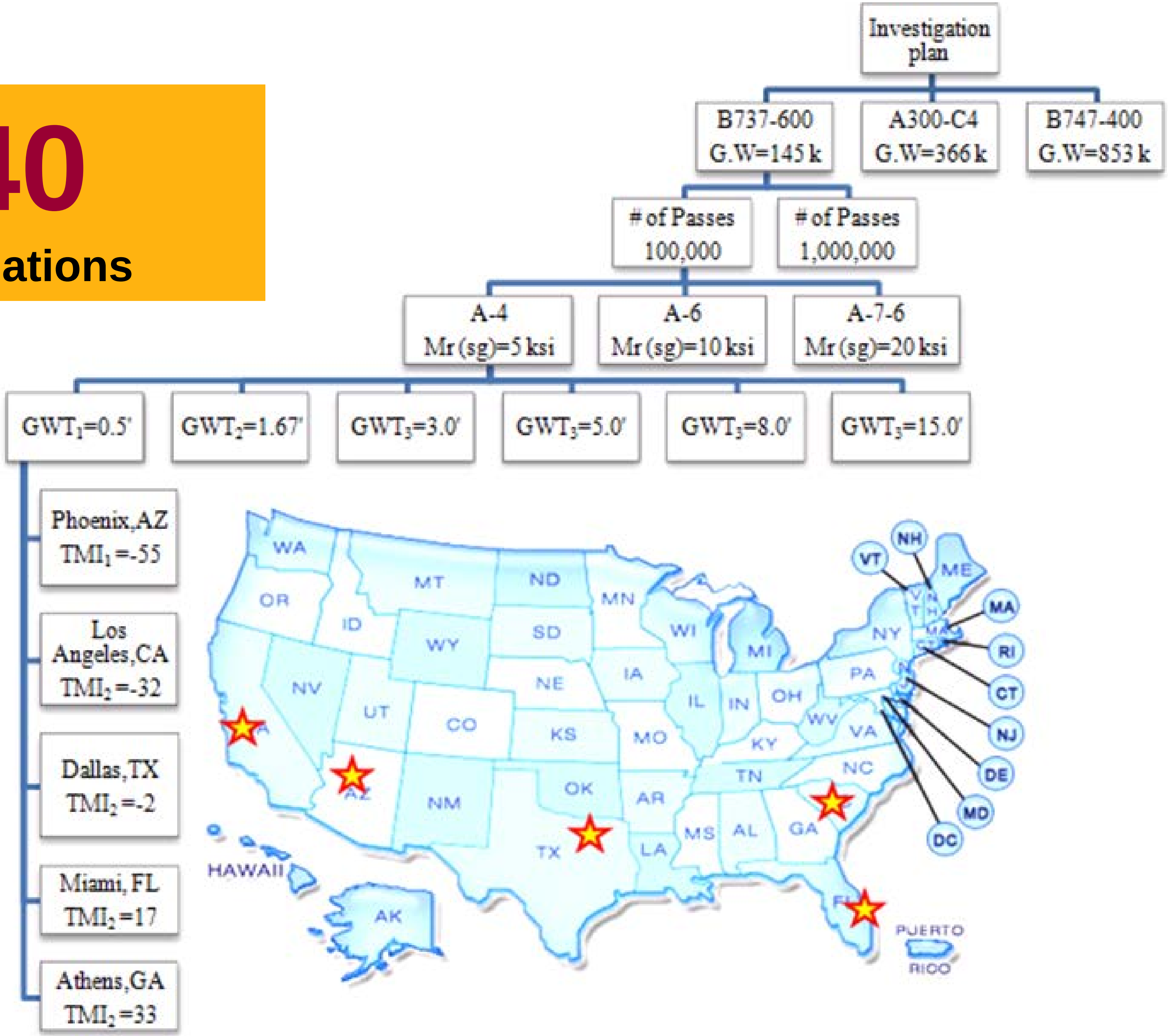
Experimental Matrix

2 levels of design traffic

3 aircraft types

540

simulations



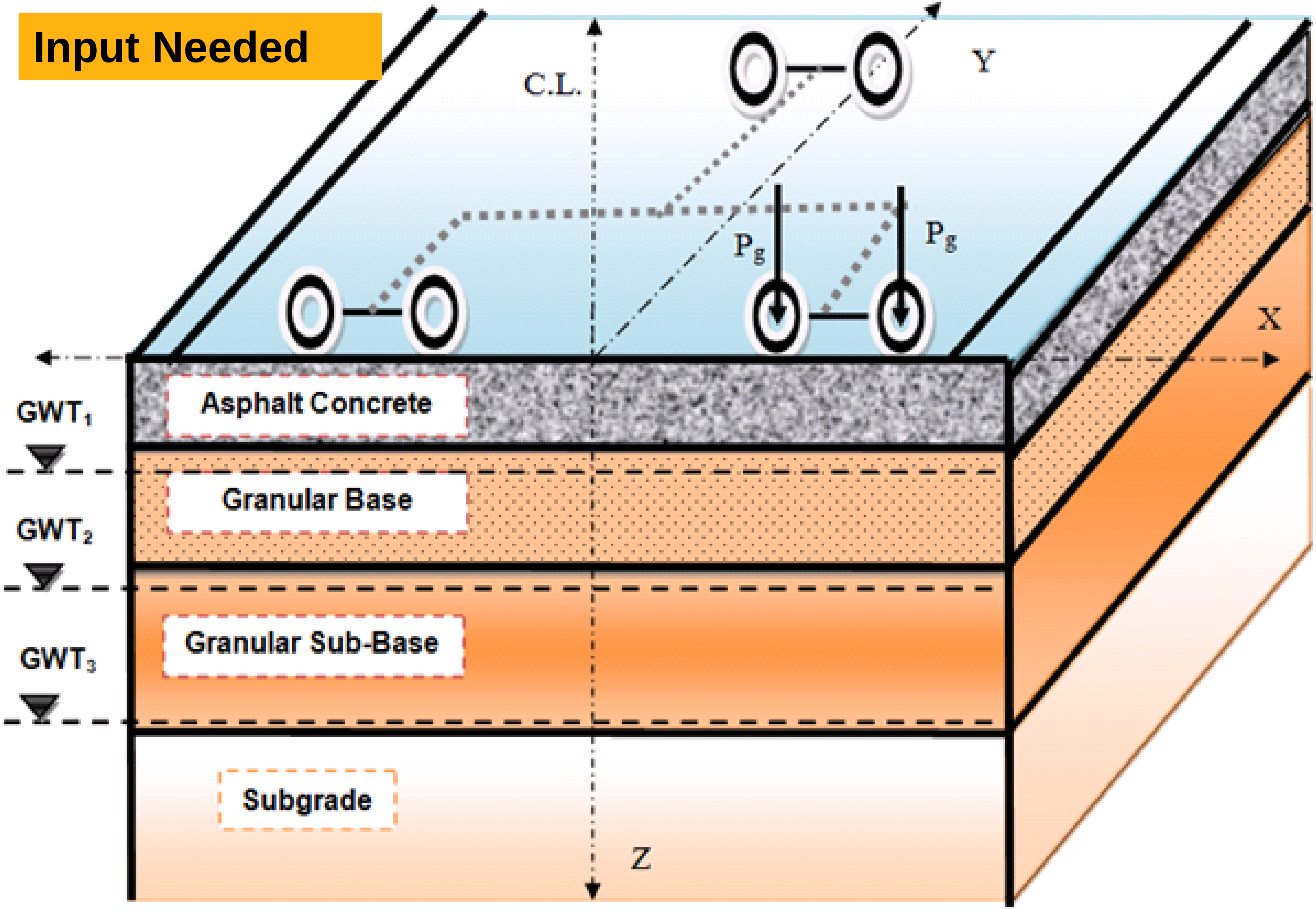
This study used the Limiting Subgrade Strain criteria developed for the newly revised USACE-β approach.

The Limiting Subgrade Strain criteria is a performance criteria applicable to design for excessive shear deformations (rutting) of the pavement.

The USACE limiting strain criteria is expressed as follows:

$$\log\left(\varepsilon_{v_{sg}}\right)=\frac{-2.1582-1.3723\log\left(N_f\right)}{1+0.4115\log\left(N_f\right)}$$

Input Needed



Material Properties and Structure

Layer Number	1	2	3	4		
Material Type	Asphalt	Base	Subbase	Subgrade		
Thickness (in)	6.0	14.0	Variable	Semi-Infinite		
Poisson Ratio	0.35	0.40	0.45	0.45		
Elastic Modulus (ksi)	300	38	32	20	10	5
AASHTO Classification	--	A-1-b	A-2-4	A-4	A-6	A-7-6
Passing #200 (%)	--	17	22	60	70	80
Plasticity Index , PI	--	1.5	4	6	14	28
Specific Gravity, G_s	--	2.65	2.68	2.68	2.69	2.68
w_{opt} %	--	8	14	12	15	20
$\gamma_{d\ max}$ (pcf)	--	130	115	119	114	102

part IV: the software

Claudia E. Zapata

Matthew Witczak

Carlos Cary

ZAPMEDACA

Ramadan Salim

Mena Souliman

Daniel Rosenbalm

ZAPMEDACA

- This program is an educational software program for the analysis of asphalt highway and airfield pavement structures
- The program computes stress, strains, and displacements within the pavement structure from an enhanced application of Odemark's transformation theory of layered systems
- Pavement responses are computed by numerical integration of the Boussinesq solution

ZAPMEDACA

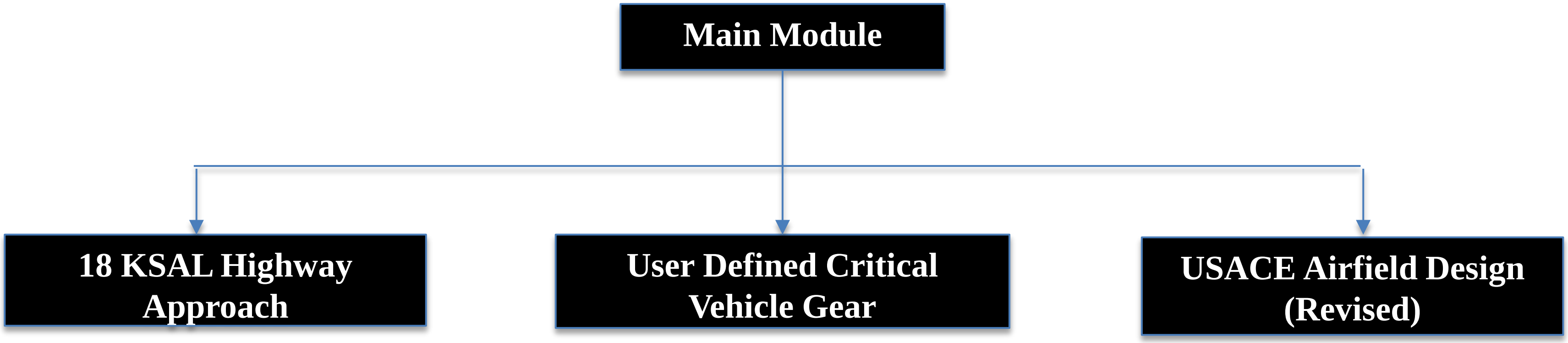
- Program evaluates any multi-tire configuration of wheel loads

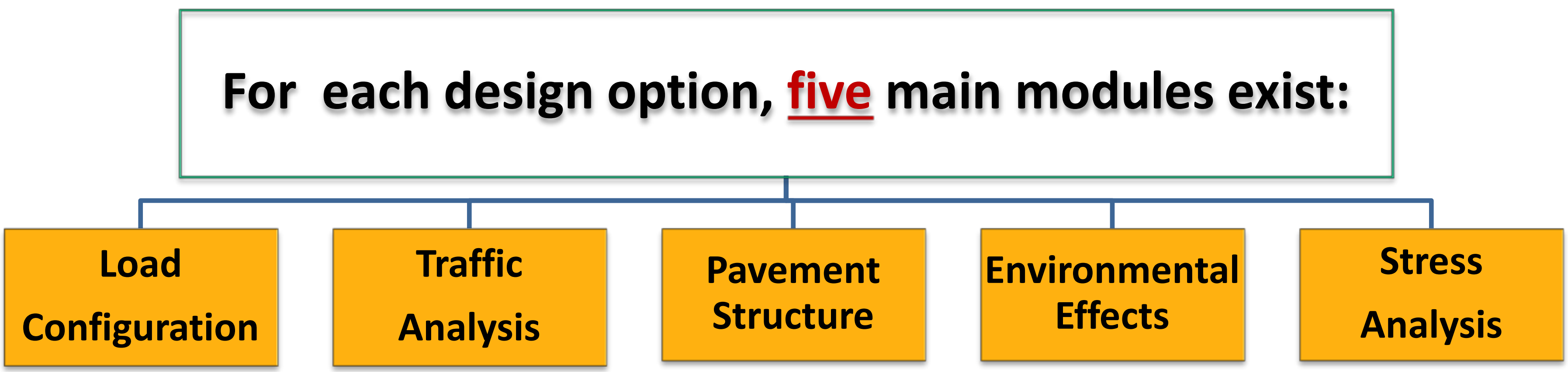
- Each tire can be modeled by a circular, rectangular or elliptical wheel load and can be treated with either a uniform or non-uniform contact pressure

ZAPMEDACA

- The most significant capability of the program is its ability to incorporate actual site environmental factors and GWT depth to characterize real time effect of partially saturated to saturated conditions/response of all unbound layers

Main module

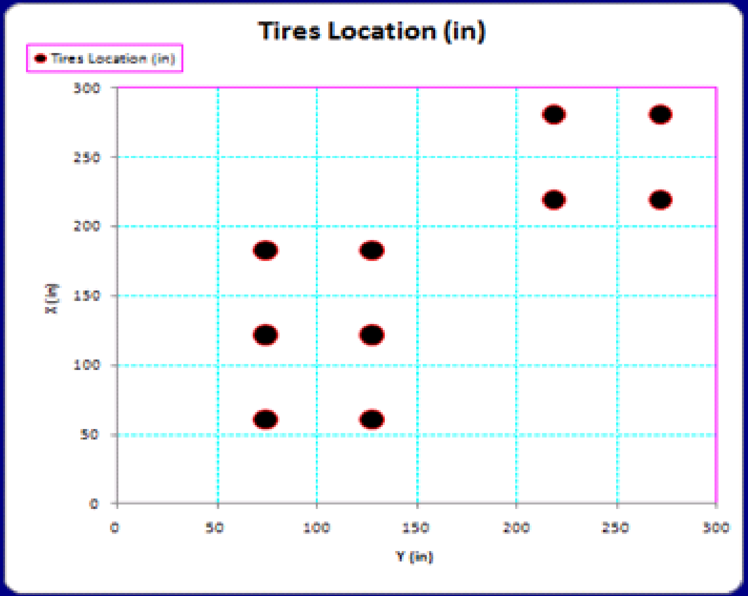

Main Module
18 KSAL Highway Approach
User Defined Critical Vehicle Gear
USACE Airfield Design (Revised)


For each design option, five main modules exist:
Load Configuration
Traffic Analysis
Pavement Structure
Environmental Effects
Stress Analysis

Load Configuration

Airbus A-380

Number of Tires	10
Distance Between Loading Points, S_d (in)	
Load per Tire (lb)	59400
Tire Pressure (psi)	218
Pressure Distribution	Uniform
Tire Imprint Shape	Elliptical
Number of the Main Gear for Each Side	2
Pavement Width Analyzed, (ft)	150
Number of Longitudinal Segments (dy) in Tire Imprint	10
Number of Transversal Segments (dx) in Tire Imprint	10
Number of Radial Segments (dr) in Tire Imprint	10
Size of Angular Segments (dθ) in Tire Imprint	10
Distance to Mean Location of Load for main Gear1 , xj1 (ft)	20.40
Distance to Mean Location of Load for main Gear2 , xj2 (ft)	8.40
Distance from y Axis to Centerline of Main Gear1 , yj1 (ft)	20.87
Distance from y Axis to Centerline of Main Gear2 , yj2 (ft)	10.17
Horizontal Tire Spacing , Sd1 , Sd2 (in)	53.10
Vertical Tire Spacing , St1 , St2 (in)	61.00



Loading Points Cartesian Coordinates (in)

	1	2	3	4	5	6	7	8	9	10
X	74.25	127.35	74.25	127.35	74.25	127.35	218.25	271.35	218.25	271.35
Y	61.00	61.00	122.00	122.00	183.00	183.00	219.90	219.90	280.90	280.90

Pavement Structure and Material Properties

Pavement Structure and Material Properties- User Defined Critical Vehicle Gear

NEXT | MAIN MENU

INPUT :

Number of Layers: 4

Ground Water Table Depth, (ft): 3

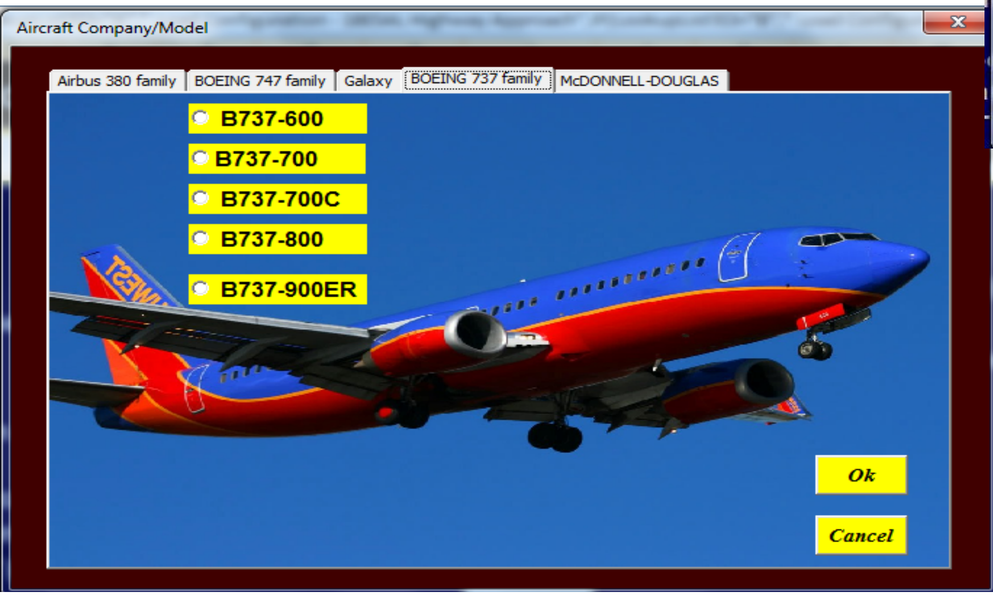
Layer Number	1	2	3	4
Material Type	Asphalt	Gran. Base	Gran. Sub-base	Subgrade
Thickness *(in)*	8.00	12.0	20.0	
Poison Ratio, *u*	0.35	0.40	0.45	0.45
*E** or *E* at Optimum Conditions, *(psi)*	300,000	38,000	24,000	8,877
CBR (%)				7
R value				
AASHTO Layer Coefficient, a_i				
Soil Classification (AASHTO or SUCS)		A-1-b	A-2-7	
Percentage Passing Sieve #200, *P200*		17	28	65
Plasticity Index , *PI*		14	24	30
Specific Gravity of Solids, G_s		2.65	2.75	2.7
Optimum Moisture Content, w_{opt} %		8	12	16
Maximum Dry Density, $\gamma_{d\,max}$ *(pcf)*		130	112	110

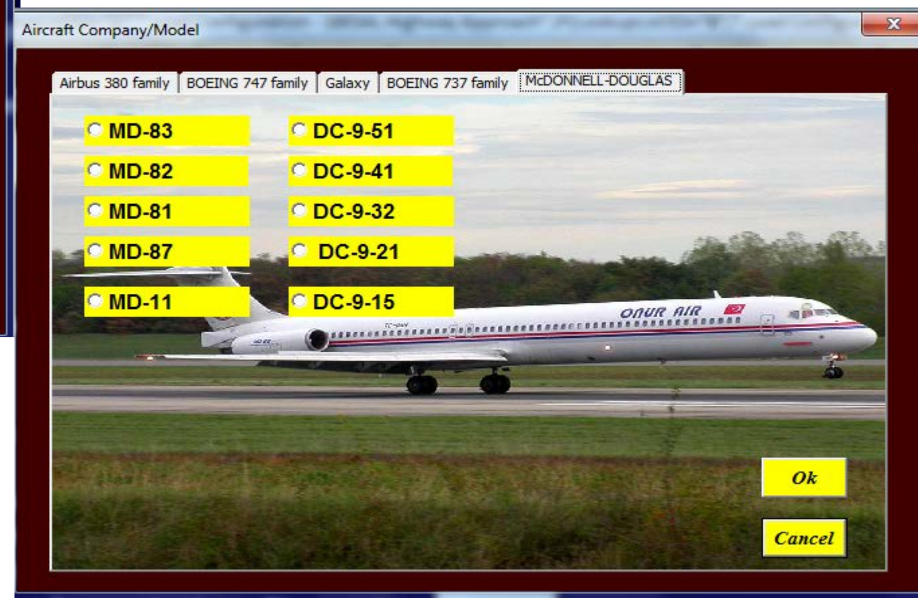
CORRECTION FACTOR FOR TRANSFORMED SYSTEM

	1	2	3
Correction Factor (f)	0.95	0.80	0.80

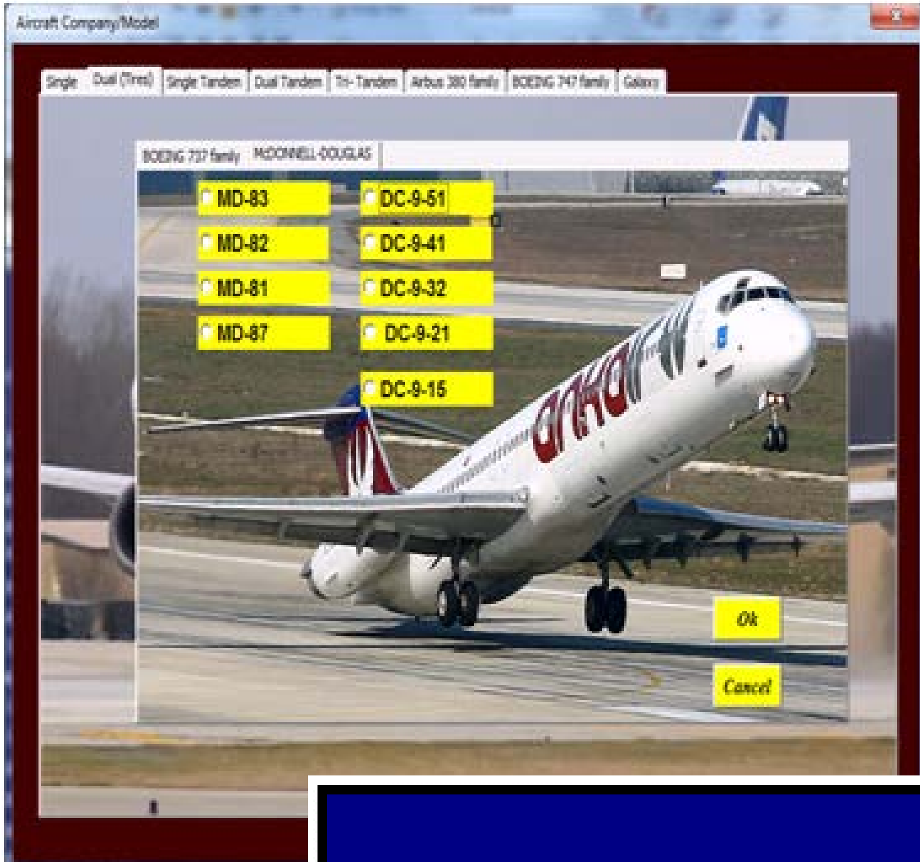
Main Menu | LoadC | PavSt | Traffic-OP1 | Traffic | EnvEff | StressA | Stress | Stress Summary | TFAC | CDATA | Rutting | LookupList | Sheet1 | Sheet2 | Sheet3 | Sheet4

Traffic library



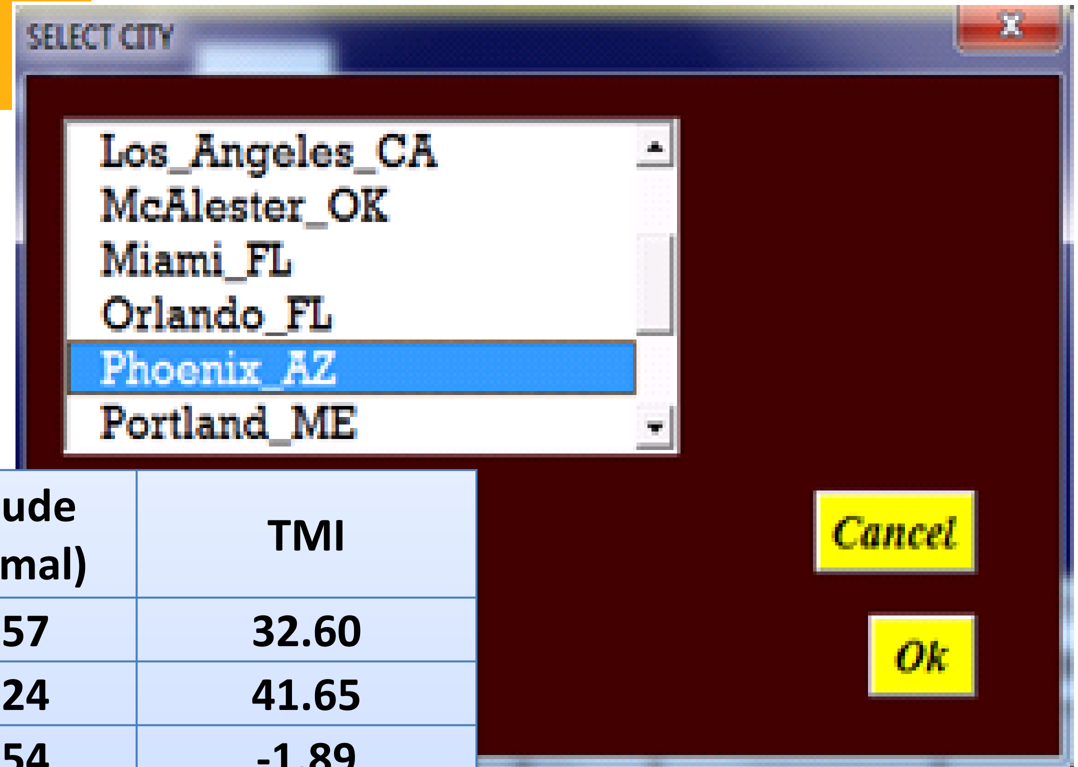


Traffic Input



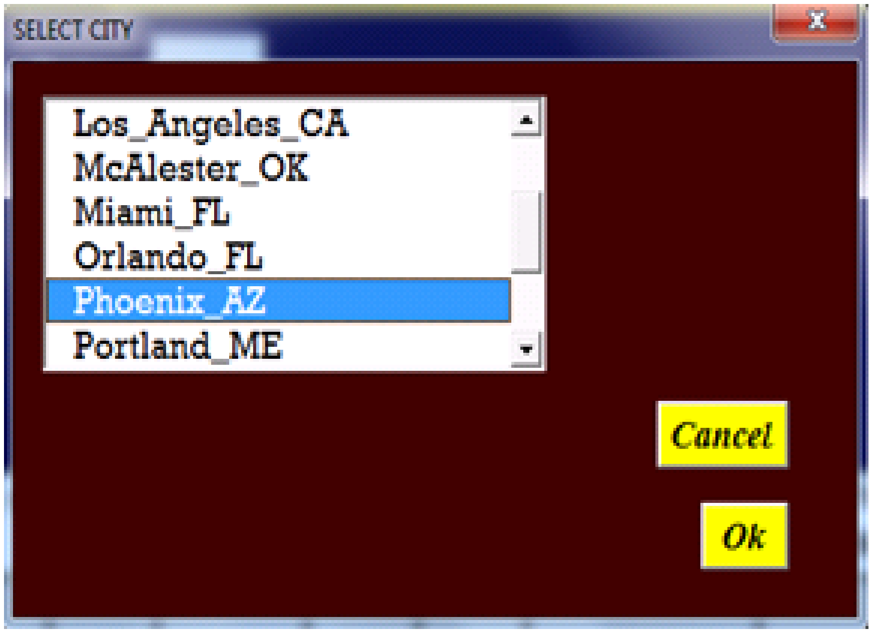
Passes of Vehicle at Base Year, Pjo	4000
Design Life(yr)	20.00
Traffic Growth Rate (%)	2.00
Passes of Vehicle at End of Design Life, Pjt	98158
Gear Wander Standard Deviation, fjx (ft)	12

Environmental effects



Location	Longitude (decimal)	Latitude (decimal)	TMI
Athens-GA	-83.20	33.57	32.60
Cleveland-OH	-81.51	41.24	41.65
Dallas-TX	-97.02	32.54	-1.89
Los Angeles-CA	-118.25	33.56	-31.62
McAlester-OK	-95.54	34.54	2.51
Miami-FL	-80.19	25.49	17.32
Orlando-FL	-81.19	28.26	18.63
Phoenix-AZ	-112.07	33.45	-54.95
Portland-ME	-70.18	43.38	59.31
Raleigh-NC	-78.47	35.52	37.52
Salem-OR	-123.00	44.55	50.84
Seattle-WA	-122.19	47.28	40.57
Shreveport-LA	-93.49	32.27	31.84

Environmental effects



City	Phoenix-AZ
Longitude in decimal	-112.07
Latitude in decimal	33.45
TMI	-54.95

Layer	Suction, ψ (psi)	SWCC Constants				Degree of Saturation, S%	S% at Optimum	Environmental Factor, F_U	Resilient Modulus, M_R (psi)
		a_f	b_f	c_f	h_{rf}				
Above GWT: Asphalt									
Above GWT: Gran. Base	9	5.0	3.28	1.28	500	55.7	93.6	1.512	60,462
Below GWT: Gran. Base	0					100.0	93.6	0.937	37,496
Below GWT: Gran. Sub-base	0					100.0	77.4	0.539	10,789
Below GWT: Subgrade	0					100.0	83.8	0.402	3,214

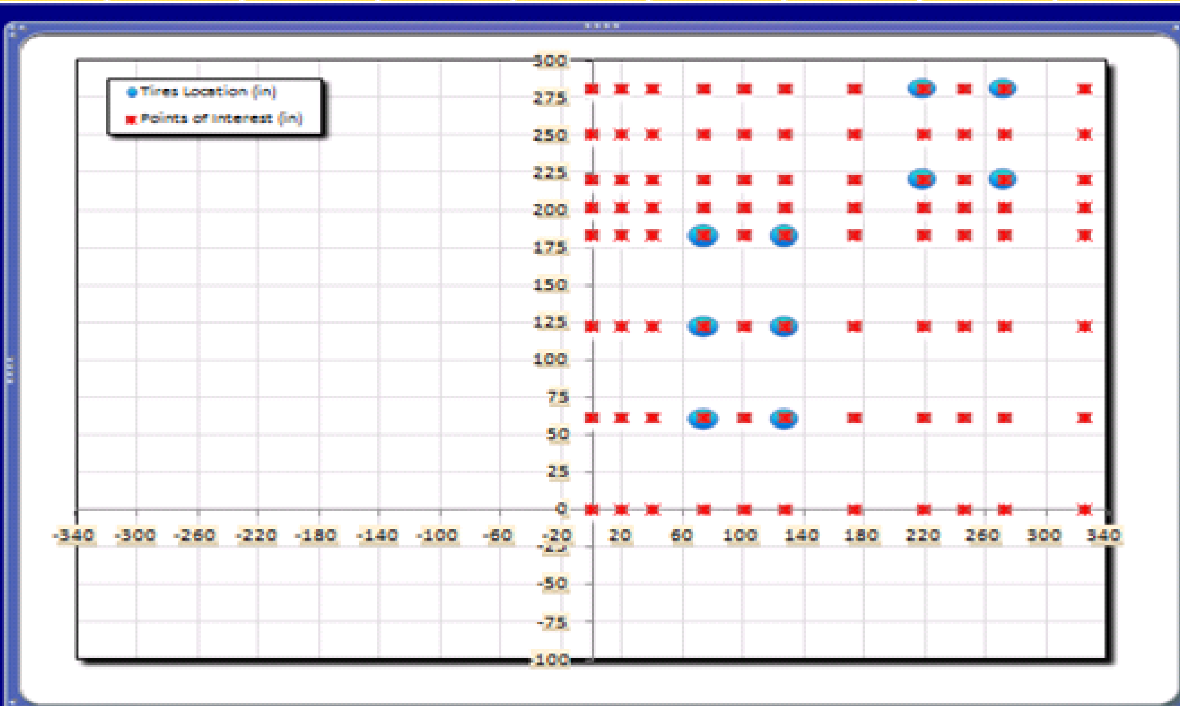
Stress Analysis

Computation of Depths (in)

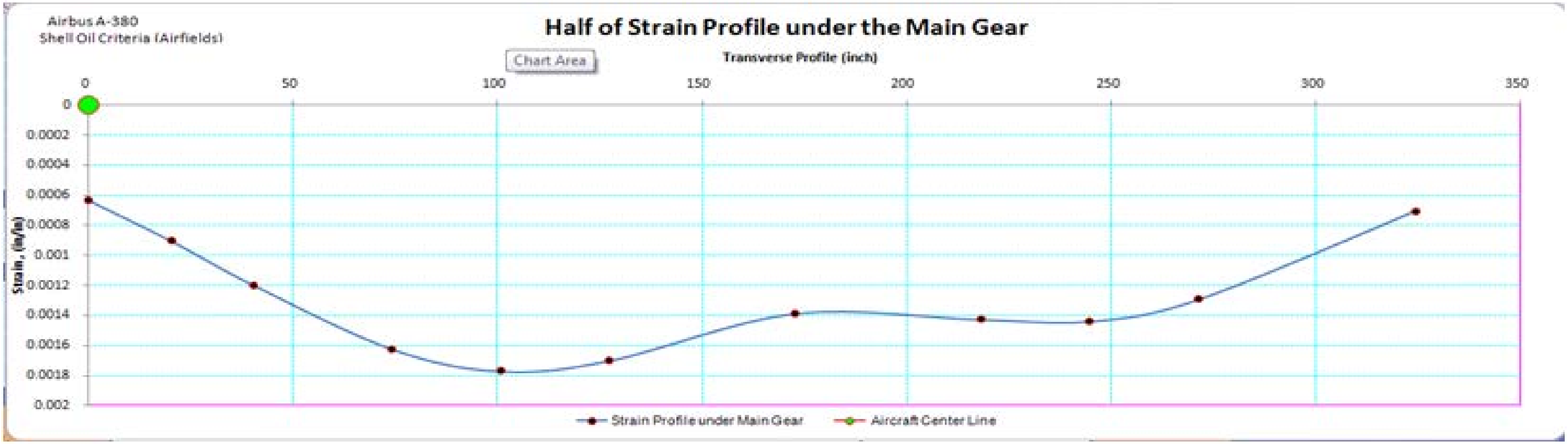
	Depth 1	Depth 2	Depth 3	Depth 4	Depth 5	Depth 6	Depth 7	Depth 8	Depth 9	Depth 10
Z	145.4									

Computation Points (in)

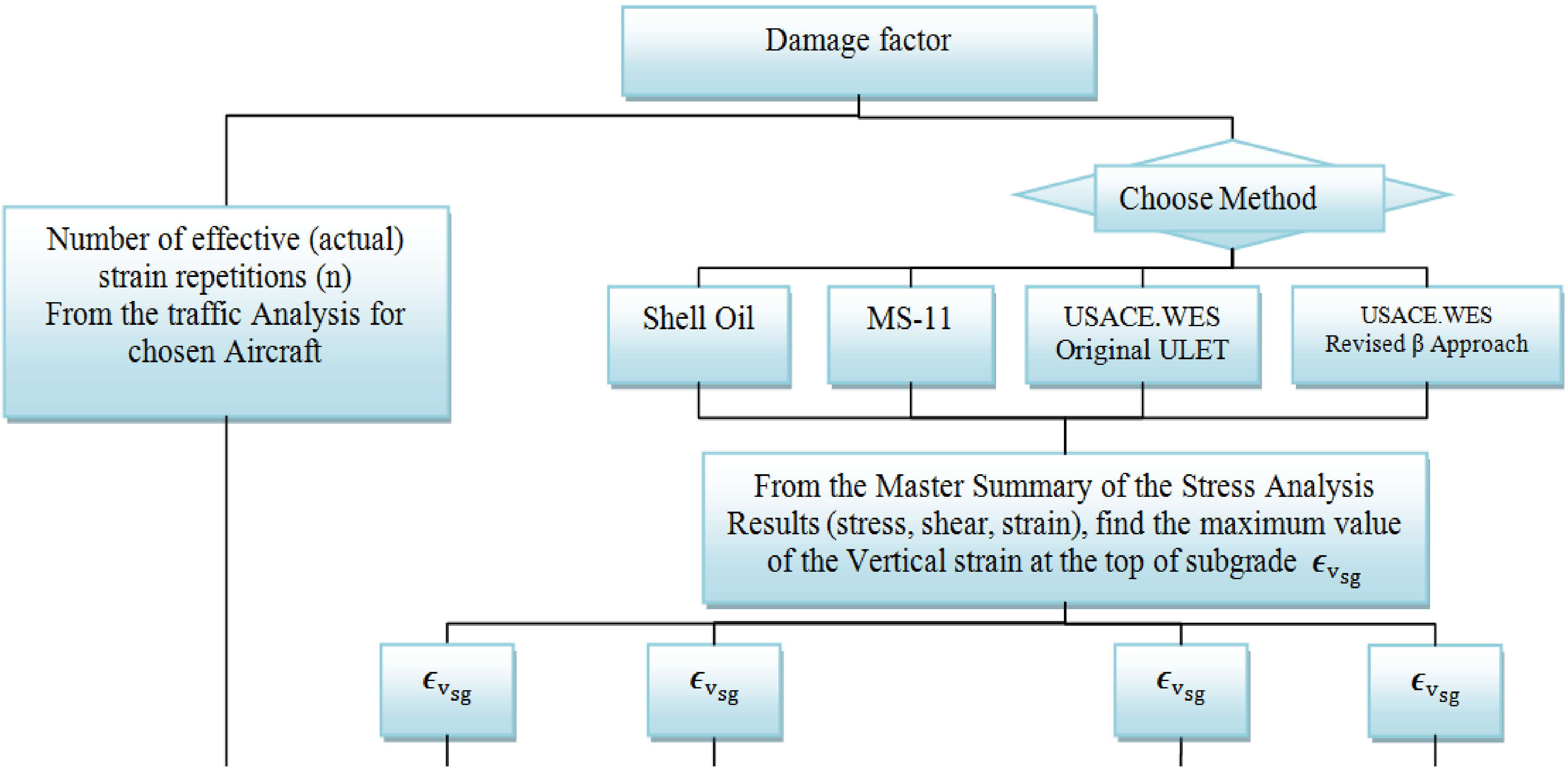
		x_{i1}	x_{i2}	x_{i3}	x_{i4}	x_{i5}	x_{i6}	x_{i7}	x_{i8}	x_{i9}	x_{i10}	x_{i11}
y_{i1}	0	0	20.16	40.32	74.25	100.8	127.35	172.8	218.25	244.8	271.35	324.45
y_{i2}	61											
y_{i3}	122											
y_{i4}	183											
y_{i5}	201.45											
y_{i6}	219.9											
y_{i7}	250.4											
y_{i8}	280.9											



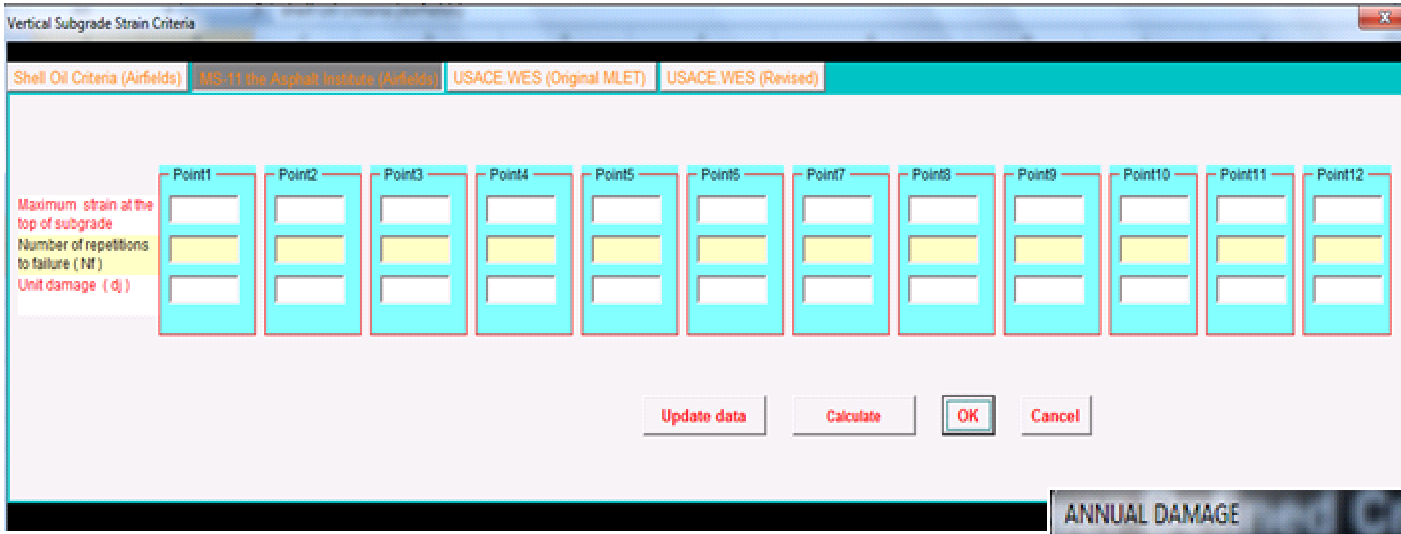
Stress Analysis



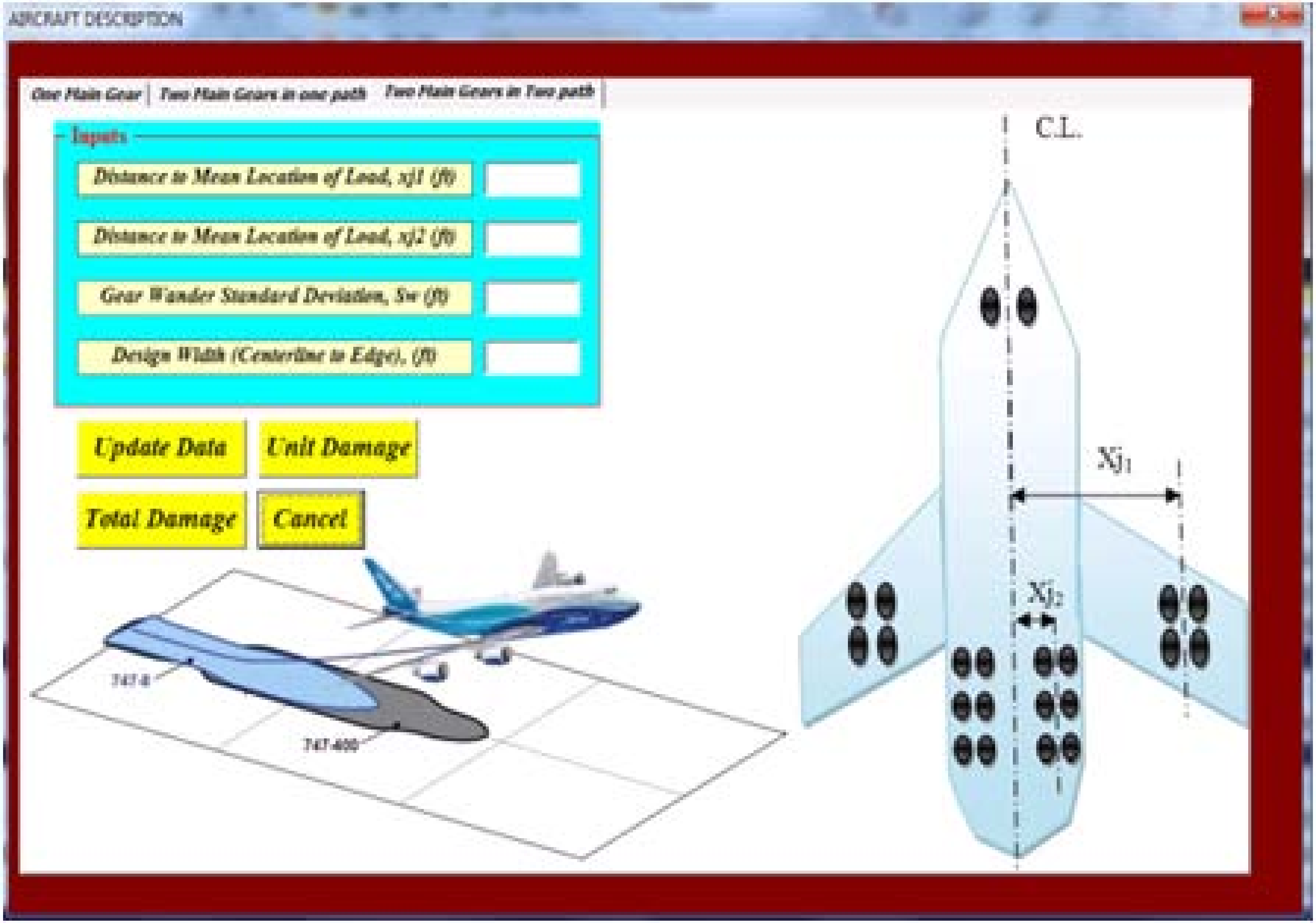
Vertical subgrade strain criteria



Rutting Design Criteria



Rutting Design Criteria



Rutting Design Criteria

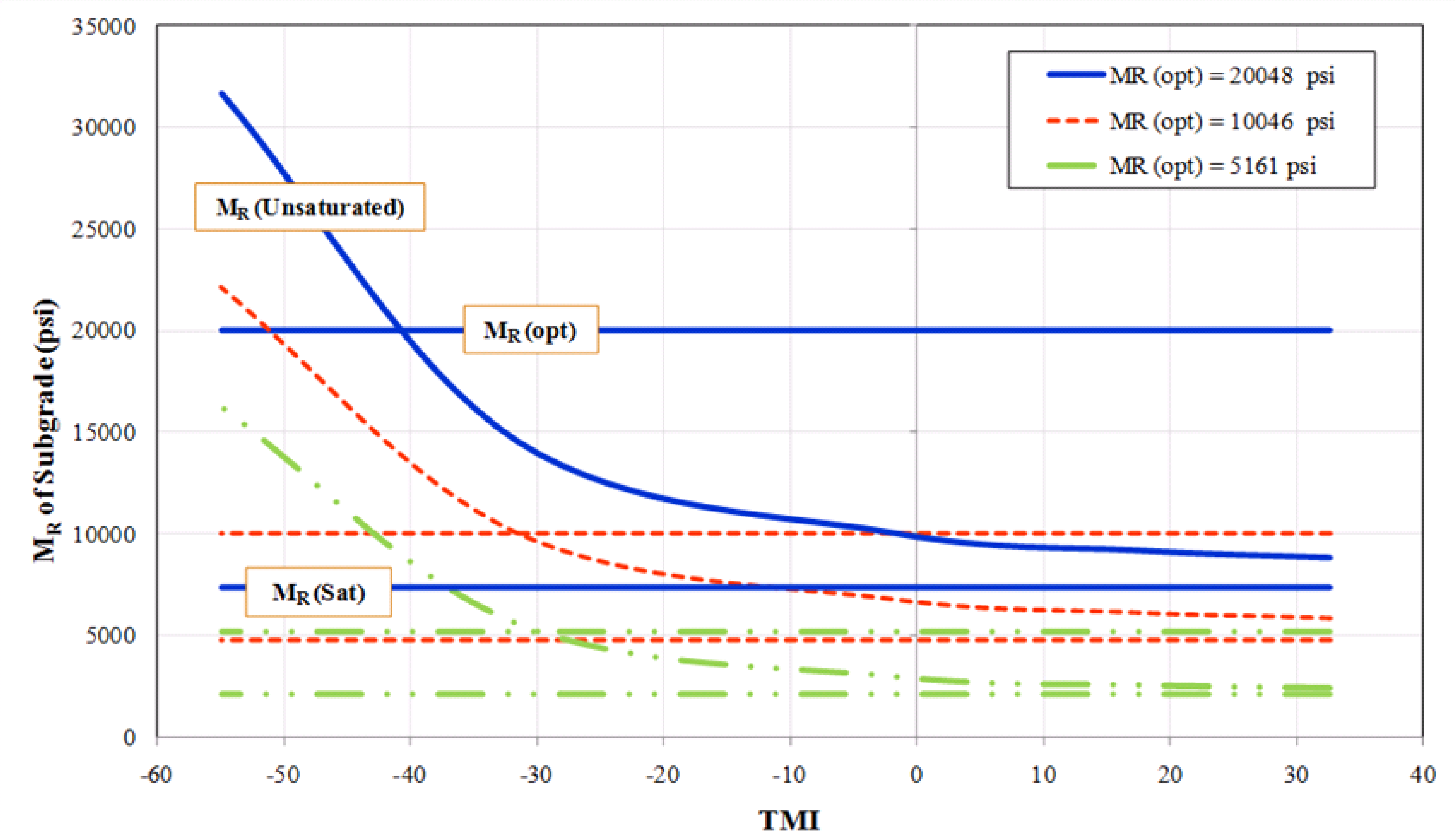
Year	Annual Traffic (Pass)	Annual Max Damage (%)	Cumulative Traffic (Pass)	Cumulative Max Damage (%)	Interval of the Max Damage, Xj- max (ft)
1	4040	31.17	4040	31.17	± 0.5
2	4121	31.79	8161	62.96	± 0.5
3	4203	32.43	12364	95.38	± 0.5
4	4287	33.07	16651	128.46	± 0.5
5	4373	33.74	21024	162.19	± 0.5
6	4460	34.41	25484	196.60	± 0.5
7	4550	35.10	30034	231.70	± 0.5
8	4641	35.80	34674	267.50	± 0.5
9	4733	36.52	39407	304.02	± 0.5
10	4828	37.25	44235	341.26	± 0.5
11	4925	37.99	49160	379.25	± 0.5
12	5023	38.75	54183	418.00	± 0.5
13	5124	39.53	59307	457.53	± 0.5
14	5226	40.32	64533	497.85	± 0.5
15	5331	41.12	69863	538.97	± 0.5
16	5437	41.95	75300	580.92	± 0.5
17	5546	42.78	80846	623.70	± 0.5
18	5657	43.64	86503	667.34	± 0.5
19	5770	44.51	92273	711.85	± 0.5
20	5885	45.40	98158	757.26	± 0.5

part IV: the results

Resulting subgrade modulus after considering the environmental effects for 5 cities

M_R (opt)	M_R (Sat)	M_R for Unsaturated Soil Conditions									
		Athens		Miami		Dallas		L.A.		Phoenix	
		S_r	M_R	S_r	M_R	S_r	M_R	S_r	M_R	S_r	M_R
5161	2073	97.2	2424	96.2	2575	93.6	2984	82.4	5593	60.4	16261
10046	4788	96.4	5834	95.5	6111	93.6	6763	86.1	10046	69.4	22174
20048	7384	96.4	8799	95.6	9158	93.8	10020	86.1	14544	69.0	31637

Resulting subgrade modulus after considering the environmental effects for 5 cities

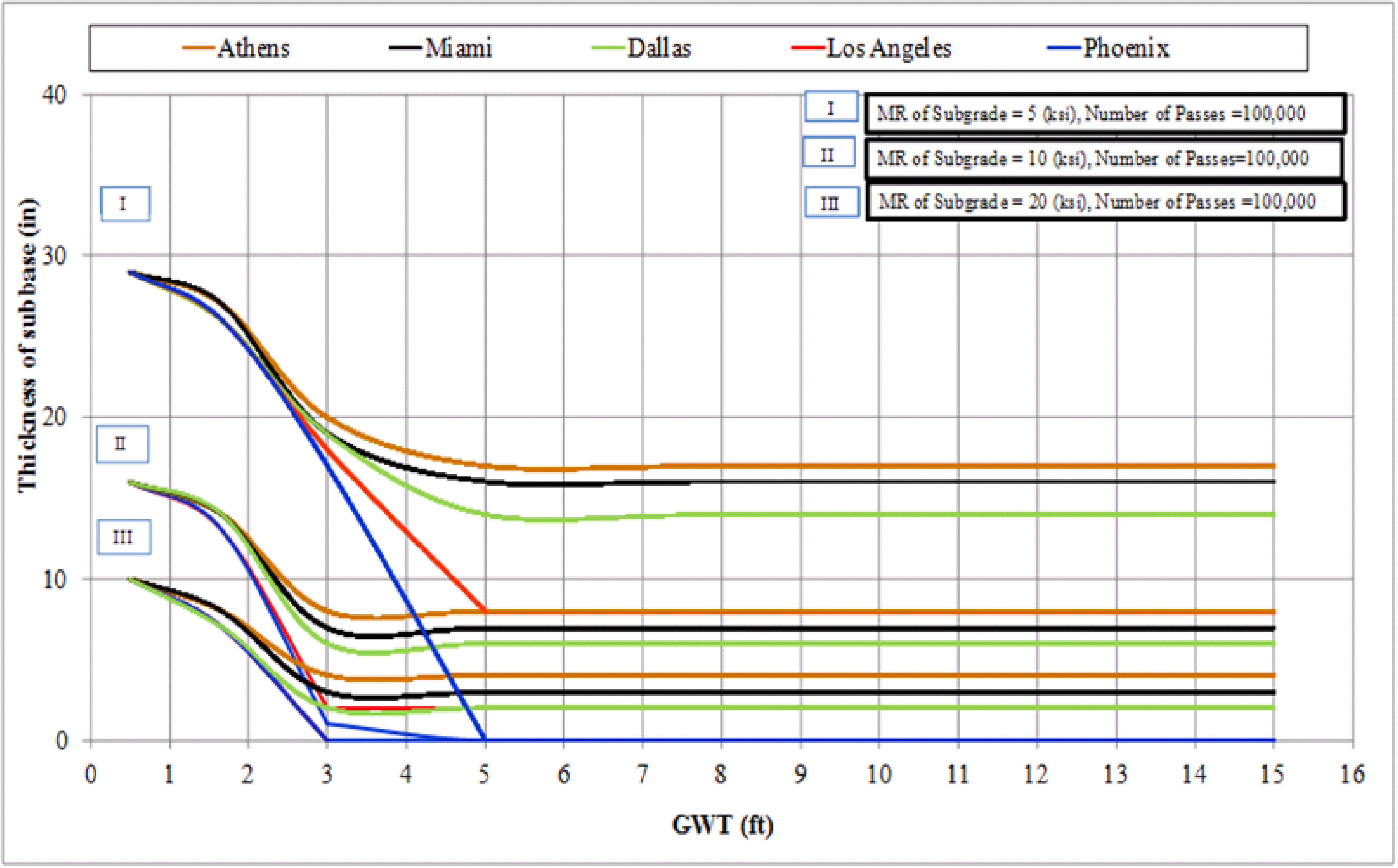


Cost savings are proportional to savings of subbase thickness

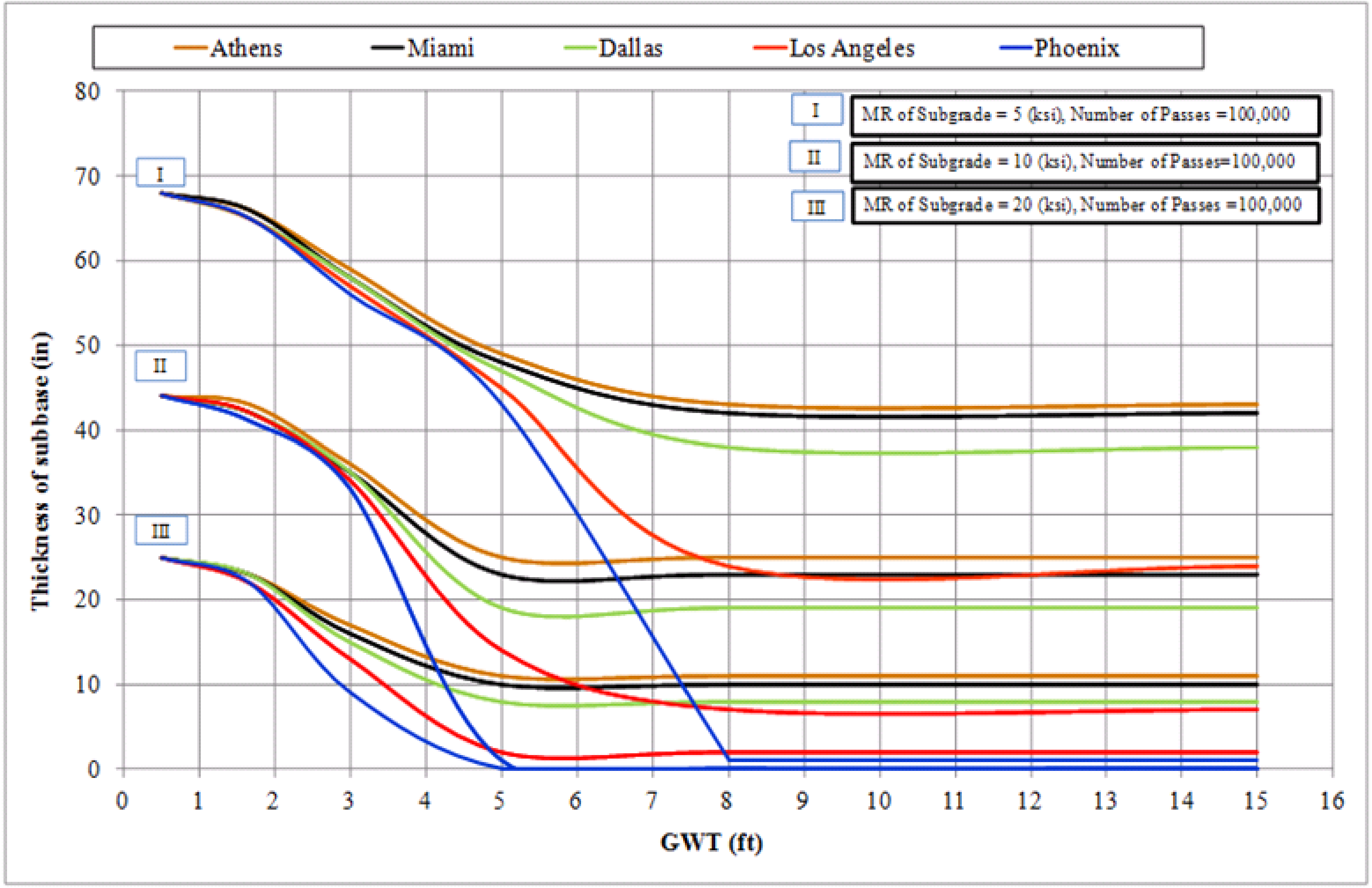
Subbase thickness (in) for selected aircrafts

Number of Passes	M_R of Subgrade (psi)	GWT (ft)	Thickness of subbase (in)														
			Boeing B737-600					AIRBUS INDUSTRIE A300-C4					BOEING B747-400				
			Athens	Miami	Dallas	L.A.	Phoenix	Athens	Miami	Dallas	L.A.	Phoenix	Athens	Miami	Dallas	L.A.	Phoenix
100,000	5	0.50	29	29	29	29	29	68	68	68	68	68	95	95	95	95	95
		1.67	27	27	26	26	26	66	66	65	65	65	93	93	93	92	92
		3.00	20	19	19	18	17	59	58	58	57	56	86	86	85	84	84
		5.00	17	16	14	8	0	49	48	47	45	43	76	75	74	72	71
		8.00	17	16	14	8	0	43	42	38	24	1	60	58	56	51	36
		15.00	17	16	14	8	0	43	42	38	24	1	58	54	48	30	4
	10	0.50	16	16	16	16	16	44	44	44	44	44	54	54	54	54	54
		1.67	14	14	14	13	13	43	42	42	42	41	52	52	52	51	51
		3.00	8	7	6	2	1	36	35	35	34	33	45	45	44	43	42
		5.00	8	7	6	2	0	25	23	19	14	1	33	32	29	27	19
		8.00	8	7	6	2	0	25	23	19	7	0	31	29	25	10	1
		15.00	8	7	6	2	0	25	23	19	7	0	31	29	25	10	1
	20	0.50	10	10	10	10	10	25	25	25	25	25	35	35	35	35	35
		1.67	8	8	7	7	7	23	23	23	22	22	33	32	32	32	31
		3.00	4	3	2	0	0	17	16	15	13	9	26	25	25	24	23
		5.00	4	3	2	0	0	11	10	8	2	0	14	13	10	5	0
		8.00	4	3	2	0	0	11	10	8	2	0	14	13	10	5	0
		15.00	4	3	2	0	0	11	10	8	2	0	14	13	10	5	0

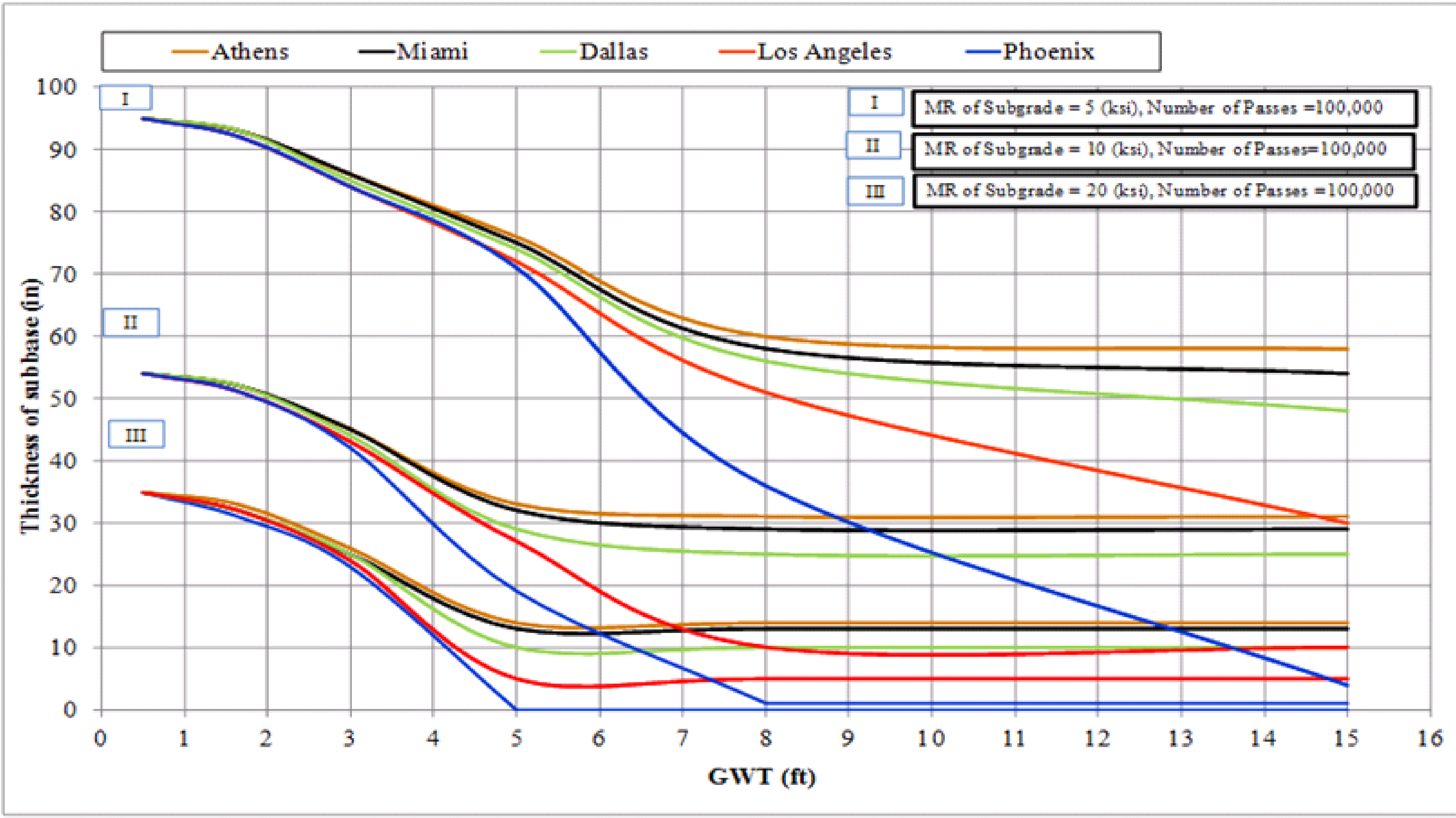
Required subbase thickness (in) for Boeing B737-600



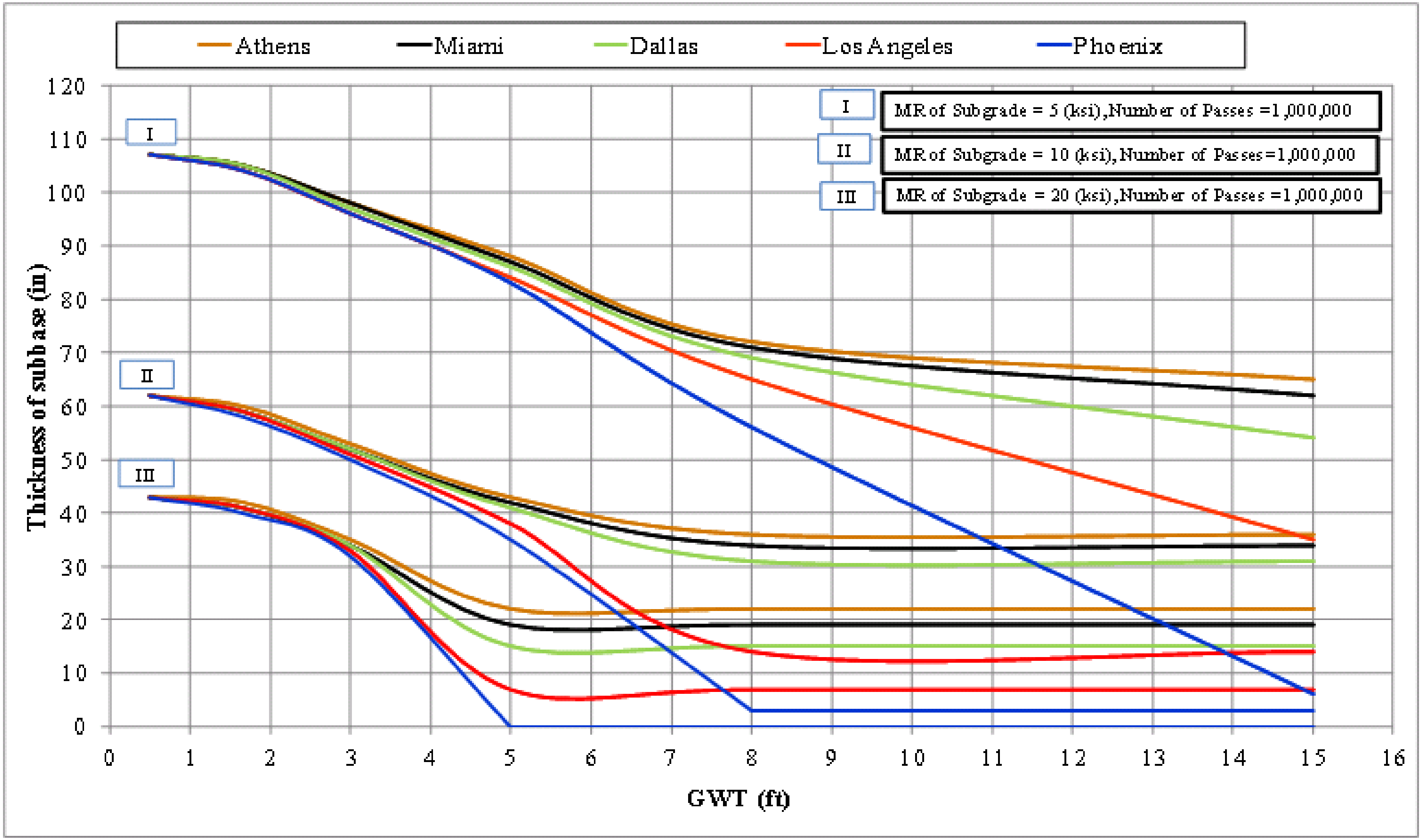
Required subbase thickness (in) for Airbus A300-C4



Required subbase thickness (in) for Boeing B747-400 N = 100,000



Required subbase thickness (in) for Boeing B747-400 N = 1’000,000



part V: summary and conclusions

ZAPMEDACA software/program is a powerful analytical tool that incorporates environmental effects in airfield design

This has not been accomplished by any other airfield pavement design procedure used in the world!!

Savings of subbase material up to 2.5 feet for lighter B-737 aircraft to as much as 3 to 8 feet for heavier B-747 aircraft may occur when unsaturated soil mechanics / environmental conditions are incorporated in the pavement design process.

Savings are obvious when design thicknesses are compared to those obtained with the classical assumption used in most pavement design methods that rely upon fully soaked evaluation of all unbound material layers.

Results generated from this study provide quantitative evidence of the significant savings that may be accrued in the design, construction and rehabilitation of airfield pavements by using unsaturated soil mechanics principles in the design methodologies

part VI:
recommendations

Several major additions need to be made to enhance ZAPMEDACA:

- Consider a wider range of computational improvements
- Additional distress types
- Real time environmental model changes in unbound layers for flexible airfield pavement systems
- Addition of the latest FAA criterion (FAARFIELD)

Controlled full-scale field tests to validate the results of ZAPMEDACA analysis are necessary but the analysis is valid for any climatic condition

International airfield pavement design agencies responsible for airfield operation should carefully re-evaluate the current state of the practice and move to incorporate more precise and rational theories and methodologies

part VII:
acknowledgments

I would like to acknowledge the general guidance, valuable input and recommendations given by Prof. Matt Witczak, the data provided by Dr. Ray Rollings, and to my former PhD student and co-author, Dr. Carlos Cary.

part VIII:
muchas gracias!