Analysis of Critical Load Arrangements for Stacked Containers for the Design of Roller Compacted Concrete Industrial Pavements

Presented by
Halil Ceylan, Ph.D., Dist.M.ASCE, Director, PROSPER

Emin Sengun, Ph.D., Research Scholar
Sunghwan Kim, Ph.D., P.E.

Dept. of Civil, Construction and Environmental Engineering (CCEE)
Program for Sustainable Pavement Engineering and Research (PROSPER)
Institute for Transportation (InTrans)
Iowa State University (ISU)

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- We greatly appreciate all the guidance and input provided by the members of the RCC Pavement Council – particularly by Fares Abdo and Corey Zollinger – for this study

- We also acknowledge the contributions of PROSPER research team members at ISU for this study

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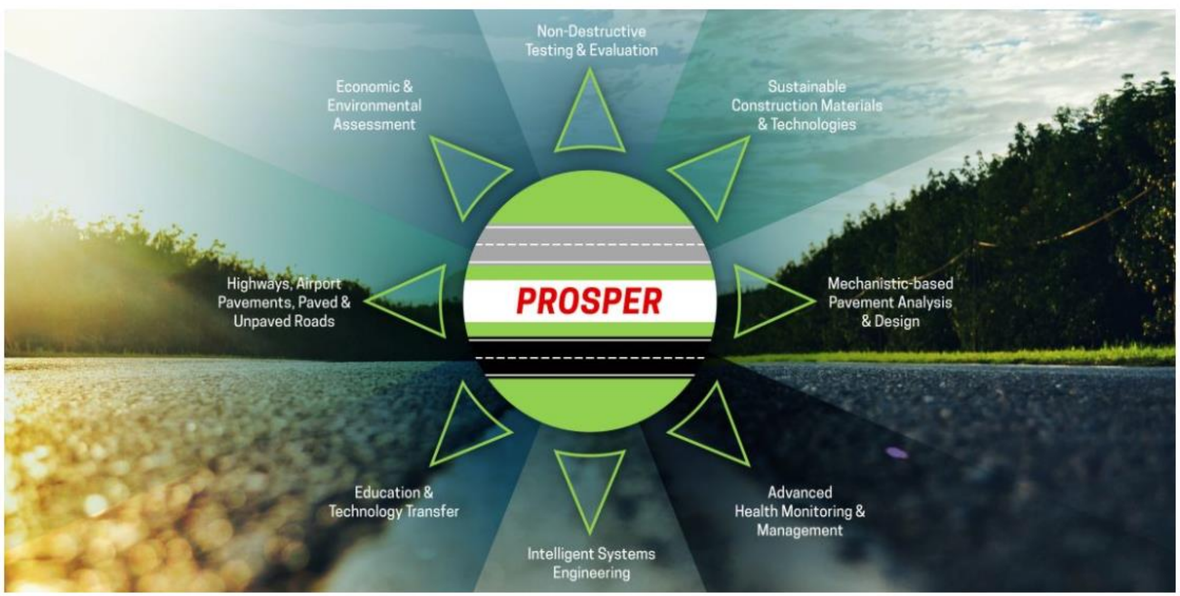


PROSPER Team Achievements / Highlights

- PI/Co-PI of **132 sponsored research projects**
  - **Approximately $23.4 million of project funds** including matching funds
  - Sponsored by the FHWA, the FAA, NSF, NCHRP, IA DOT, IHRB, MN DOT, MN LRRB, WI DOT, IL DOT, PCA, and other funding agencies
- **Over 390 peer-reviewed research publications** authored and co-authored (~90% has been co-authored with my graduate students and research staff) and **two US patent applications** (published and pending)
- **Over 400 technical lectures** including **over 145 invited talks and several keynote lectures**
- **Over 6,700 citations with an h-index of 42** (as of February 2023 from Google Scholar)
- **More than 40 news media/TV coverages** (including NBC's Today Show and NBC's Nightly News with Lester Holt, Discovery Channel's Daily Planet Show, The Weather Channel Live, Engineering News Record (ENR) and so on) featuring Dr. Ceylan's research
- More than 30 national and international professional committees and organizations
- Have collaborated with over 100 researchers from over 30 institutions

On NBC's TODAY Show
& Nightly News
with Lester Holt
(January 26, 2018)

Could heated airport runways melt away your winter travel headaches?

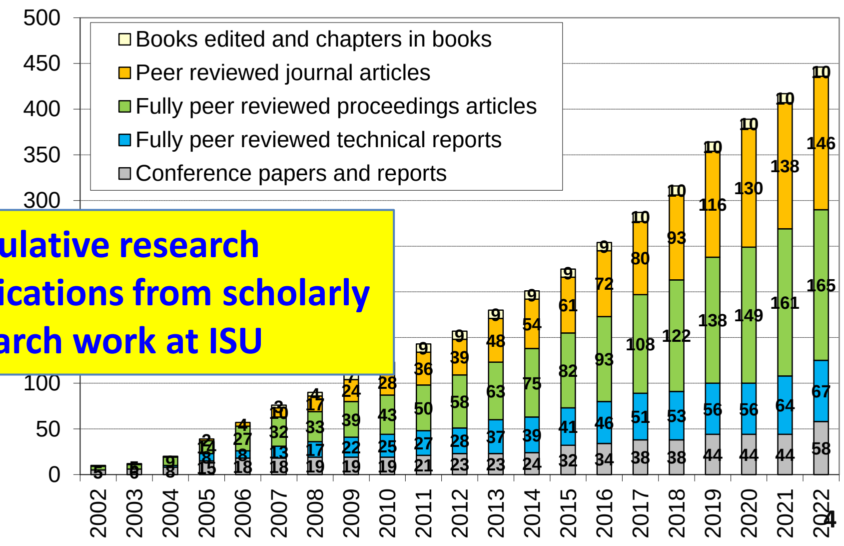
Jeff Rossen and Lindsey Bomnin
TODAY
Jan. 26, 2018 at 6:42 AM

There have been thousands of flight delays and cancellations due to winter weather this year, and it's only January. Not only that: snow and ice at airports can send planes skidding off slippery runways.

Get Jeff Rossen's new book, "Rossen to the Rescue," here.

What if there were something that could fix all that? At Des Moines International Airport in Iowa, TODAY national investigative correspondent Jeff Rossen got a look at a new technology in action: heated runways and tarmacs.

share link



Cumulative research publications from scholarly research work at ISU

Problem Statement

- Containers transmit load to the pavement via their footprint, which are slightly elevated 0.5 in by corner castings measuring 7 in x 6.38 in

- When multiple containers a stacked atop one another, this small contact area result in high pavement surface stresses

- Asphalt surfaced pavements may perform poorly under this condition, resulting in the casting depressing the pavement

- Due to its high flexural, compressive, and shear strengths of roller-compacted concrete (RCC) might be a great choice for unreinforced pavements subject to highly concentrated loads

Objective

- The initial phase of a long-term effort to develop RCC pavement design for stacked containers is to identify container loading configurations that result in the greatest stresses and deformations in the pavement systems

Outline

- Evaluation of Existing Port/Industrial Pavement Design Guides
  - Design Principles
  - Limitations
- Analysis of Critical Load Arrangements for Stacked Containers
  - Methodology
  - FEM-ISLAB2005 Analysis
- Summary and Future Work

Outline

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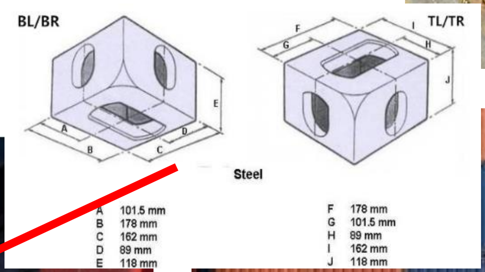
Container Stacking

- In recent times, containers have been stacked up to 8 high and this way become more common
- The pavement designer should consider pressure applied by container corner castings in designing the pavement for container storage area



(Zen et al., 2018)

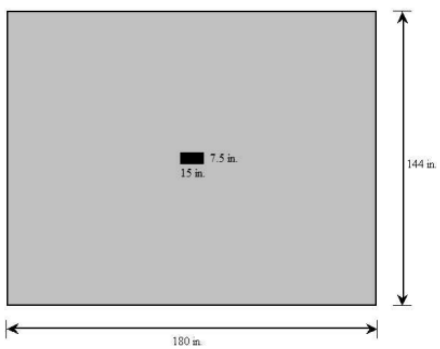
Design Principles

- In order to calculate the stresses induced by a load it is necessary to know;
  - The size of the loads ✓
  - The size of the contact area ✓
  - The location of loads (interior, edge, or corner)
  - The arrangement of loads (single, dual, quadrable strip, unform or trapezoidal load)

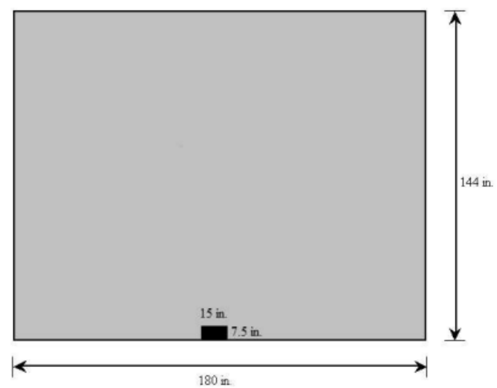
Design Principles (Cont'd)

- Three load locations are considered in design as follows;

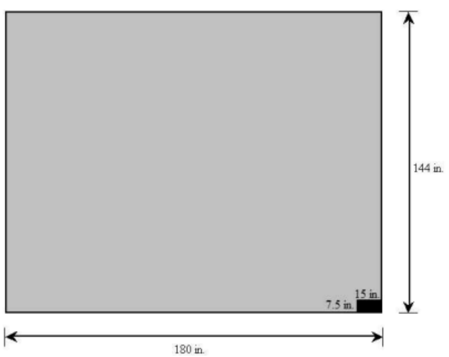
Internal



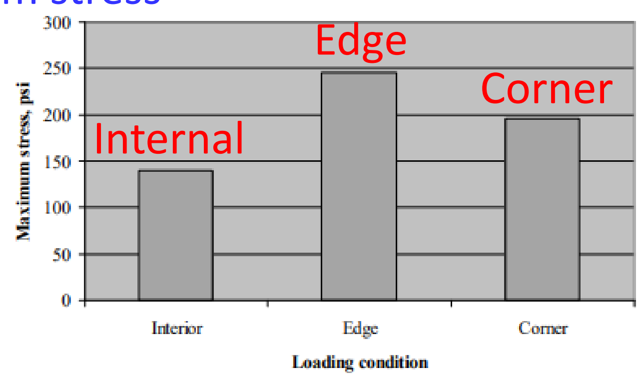
Edge



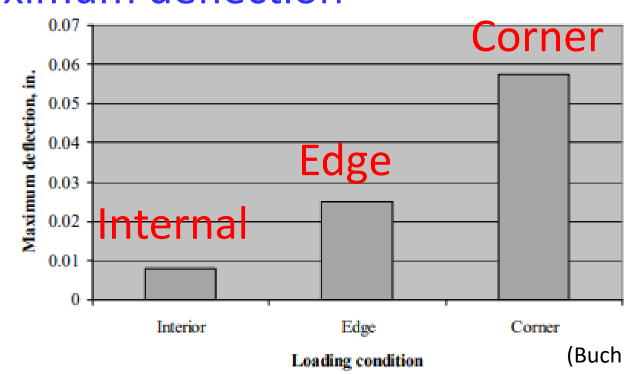
Corner



Maximum stress



Maximum deflection

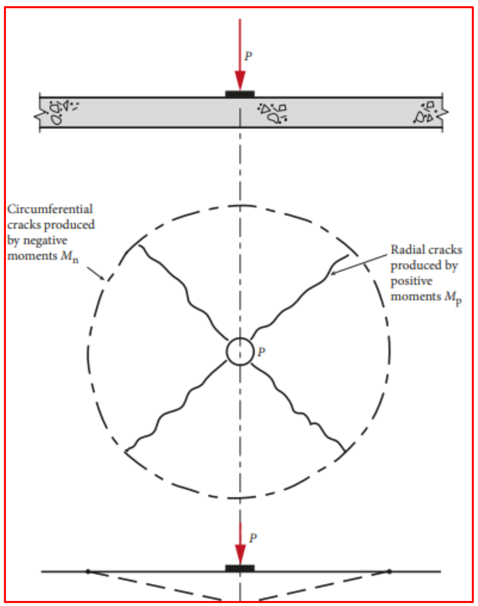


(Buch et al., 2004)

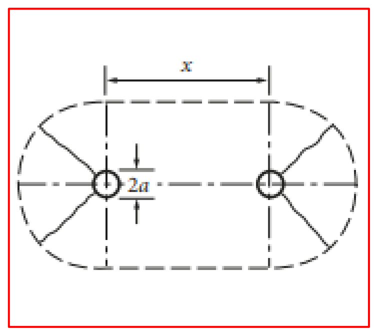
Design Principles (Cont'd)

- Load arrangements also significantly affect the design outputs;

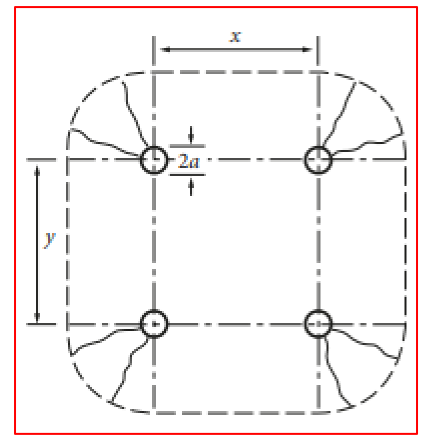
Single



Dual



Block



Existing Design Manuals

- Existing port/industrial pavement design manuals often construct container storage areas by assuming that critical loads (dynamic loads) originate by container handling equipment (reach stacker, straddle carriers, etc.)

- Several existing design guidelines that consider container stacking loads for pavements are as follows;

    - BPA (British Port Association) Method- *The Structural Design of Heavy-Duty Pavements for Ports and Other Industries*
    - Concrete Society TR-34 Method- *Concrete Industrial Ground Floors-A guide to design and construction*
    - French LCPC Method- *Dimensionnement Structurel Des Chaussses Routieres*
    - Spanish ROM Method- *Guidelines for the Design and Construction of Port Pavements*
    - ACI 330.2R* - *Guide for the Design and Construction of Concrete Site Paving for Industrial and Trucking Facilities*

* It just provide allowable loads for concentrated loads such as dolly wheels and sand shoes of semi-trailer legs on small areas

Existing Design Manuals (Cont'd)

❑ Limitation of Existing Stacked Container Design Manuals

	British BPA Method	Concrete Society TR-34	French LCPC Method	Spanish Method	ACI* 330.2R
Calculation Models	Design chart (FE based-Geostudio)	Closed-form formulas	Alize Software (FE-Burmister)	Catalog base	Design chart (not mention containers)
Pavement Type	All pav. (especially Rigid Pav.)	Rigid Pav.	Flexible and Semi-rigid, Rigid (further analysis required)	All pav. (RCC included)	Rigid Pavements
Container corner casting arrangement (single, dual, block)	Single	Single, dual, block	Single, dual, block	Single	Single
Container corner casting location (interior, edge corner)	Interior	Interior, Edge, Corner	Interior	Interior	Interior, Corner
Joint LTE/Joint spacing	No	No	No	No	No

Existing Design Manuals (Cont'd)

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Joint LTE/Joint spacing	**No**	**No**	**No**	**No**	**No**

Existing Design Manuals (Cont'd)

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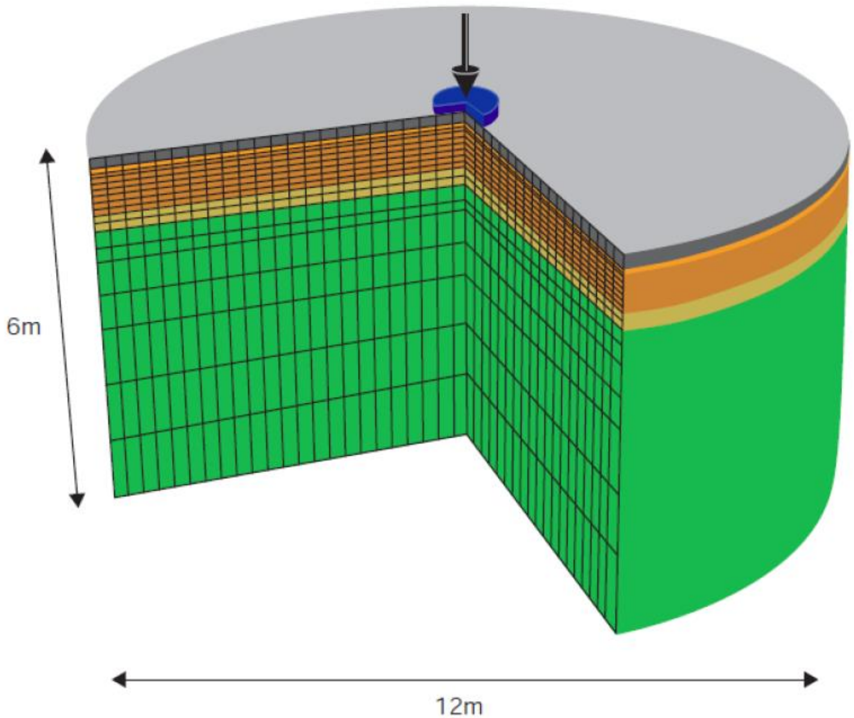
Container corner casting location (interior, edge, corner)	**Interior**	**Interior, edge, corner**	**Interior**	**Interior**	**Interior, corner**
Joint LTE/Joint spacing	No	No	No	No	No

Existing Design Manuals (Cont'd)

British BPA methods*

*Sigma/w module of GeoStudio software[1]

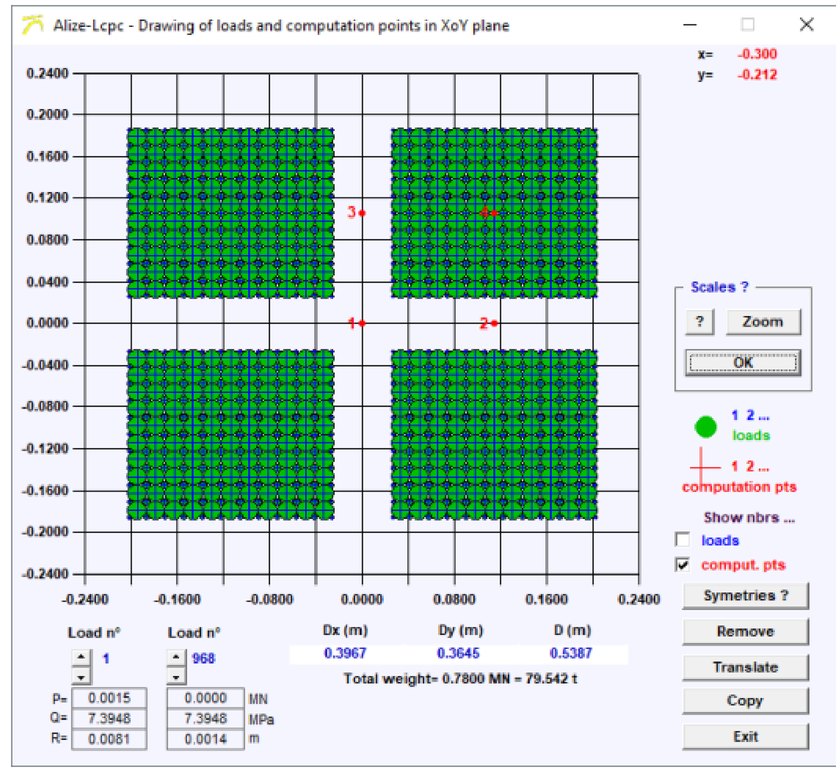


Assumptions:

1 - Interior container corner casting location

French LCPC methods**

**Alize software[2]



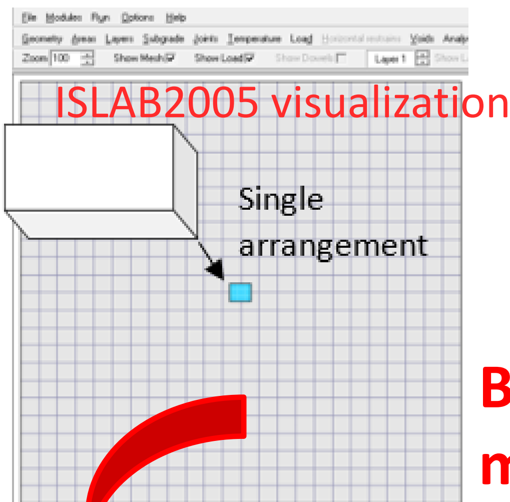
Assumptions:

1 - Interior container corner casting location

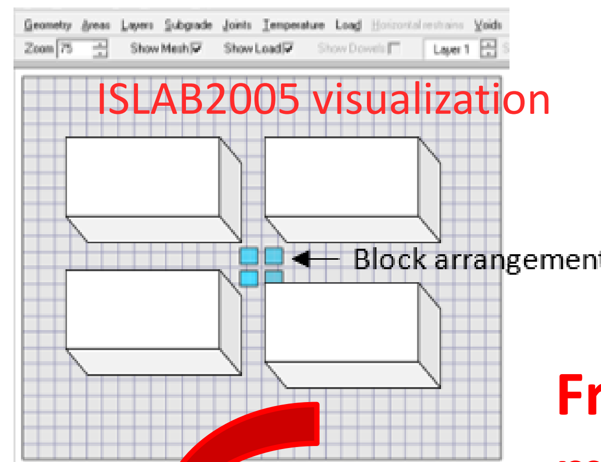
[1]J. Knapton, The Structural Design of Heavy Duty Pavements for Ports and Other Industries, Leicester, UK, 2007

[2]Alize LCPC, French Institute of Science and Technology for Transport and, Development and Networks- Alize LCPC User Manual, v.1.5, French, 2016

Proposed Design Approach

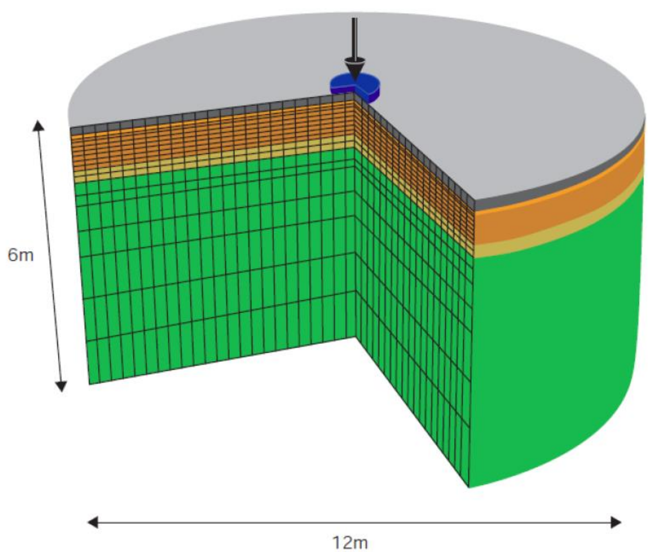


British BPA methods

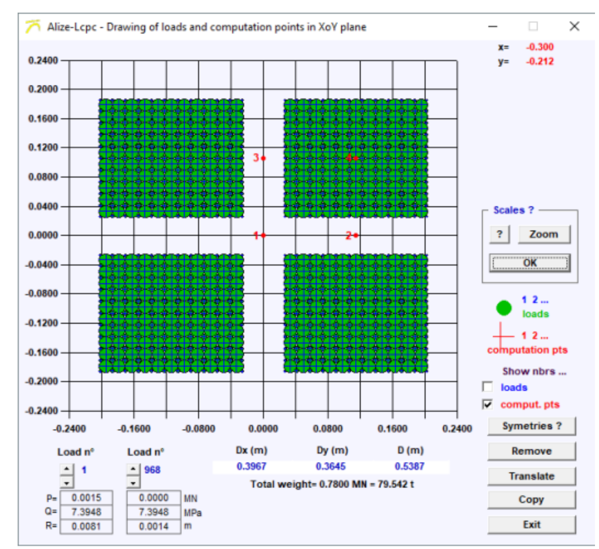


French LCPC methods

Assumptions:
2 - Single
container
corner load
arrangement



Assumptions:
2 - Block
container
corner load
arrangement



Proposed Design Approach (Cont'd)

❑ Limitation of Existing Stacked Container Design Manuals

	British BPA Method	Concrete Society TR-34	French LCCP Method	Spanish Method	ACI* 330.2R	Proposed Design Model
Calculation models	Design chart (FE based-Geostudio)	Closed-form formulas	Alize Software (FE-Burmister)	Catalog base	Design chart (not mention containers)	FEM-based (ISLAB2005)
Pavement type	All pav. (especially Rigid Pav.)	Rigid Pav.	Flexible and Semi-rigid, Rigid (further analysis required)	All pav. (RCC included)	Rigid Pavements	Roller-Compacted Concrete/ Plain Rigid Pavement
Container corner casting arrangement (single, dual, block)	Single	Single, dual, block	Single, dual, block	Single	Single	Combined with single dual and block arrangement
Container corner casting location (interior, edge corner)	Interior	Interior, Edge, Corner	Interior	Interior	Interior, Corner	Combined with interior, edge and corner
Joint LTE/Joint spacing	No	No	No	No	No	Yes

Outline

- Evaluation of Existing Port/Industrial Pavement Design Guides
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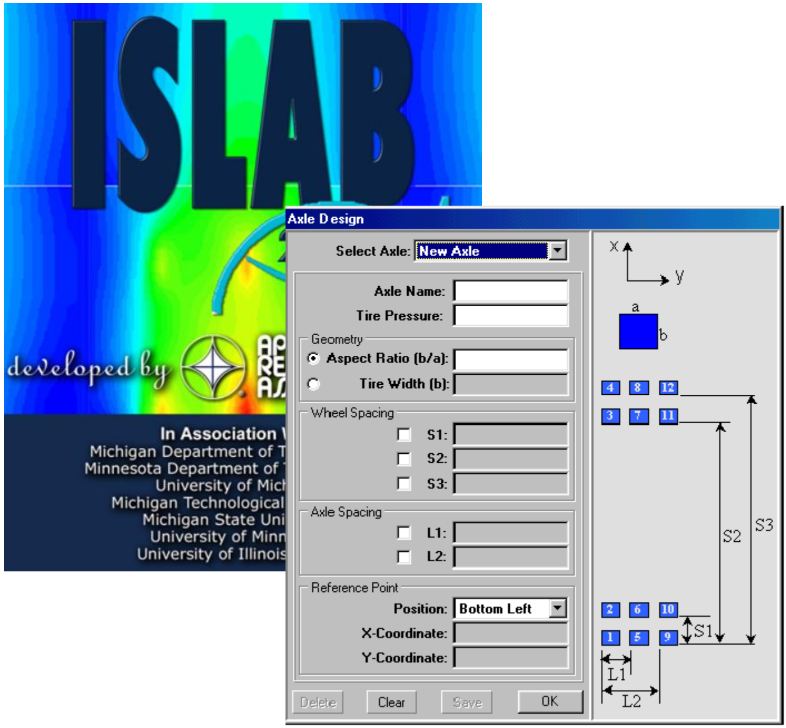
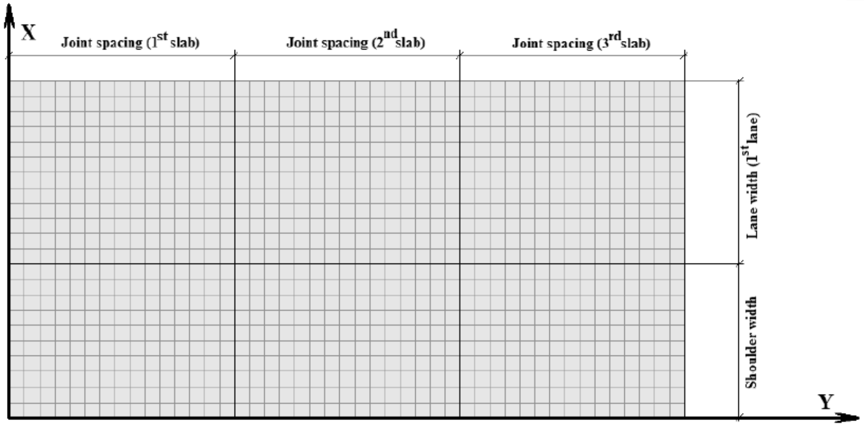
Calculation Model

- A significant advantage of FEA methodology over closed-form formulas is its capability for modeling detailed loading conditions (e.g., heavy cargo), material behavior (e.g., nonlinearity), pavement geometric and structural features (e.g., load transfer at the joints)



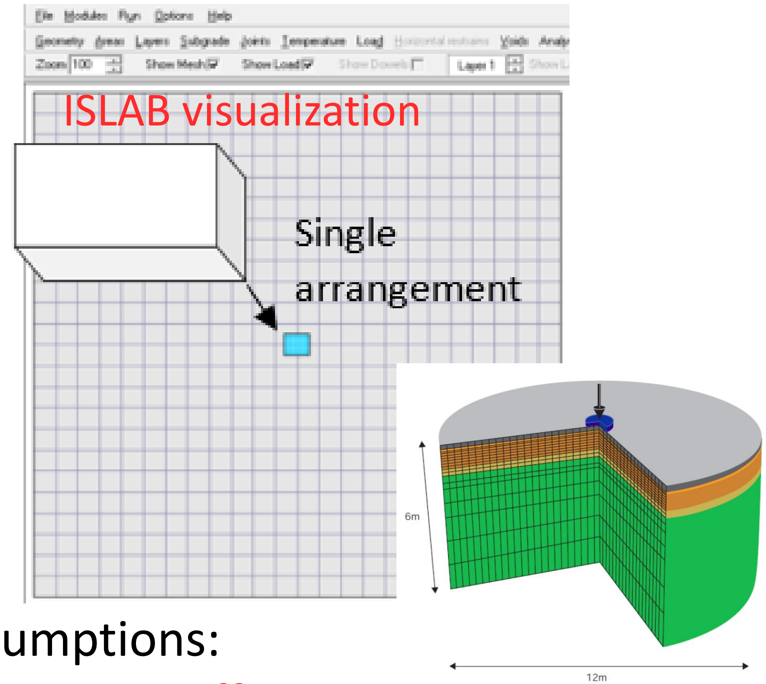
- ISLAB2005 designed specifically for simulating rigid pavement structures using finite element method under traffic and climate loads.
- It is used to calculate rigid pavement structural response in AASHTOWare Pavement ME software system



Critical Load Arrangements for Stacked Containers

- **Existing Design Manual Critical Load Arrangement Assumptions for Stacked Containers**

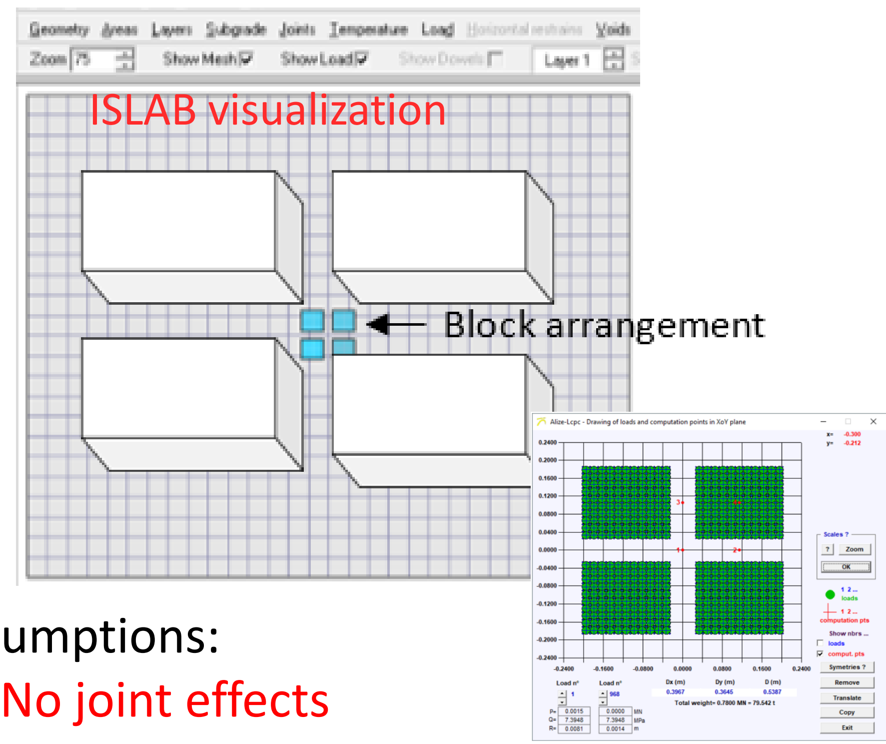
British BPA methods



Assumptions:

- No joint effects
- Interior container corner casting location
- Single container corner load arrangement

French LCPC methods



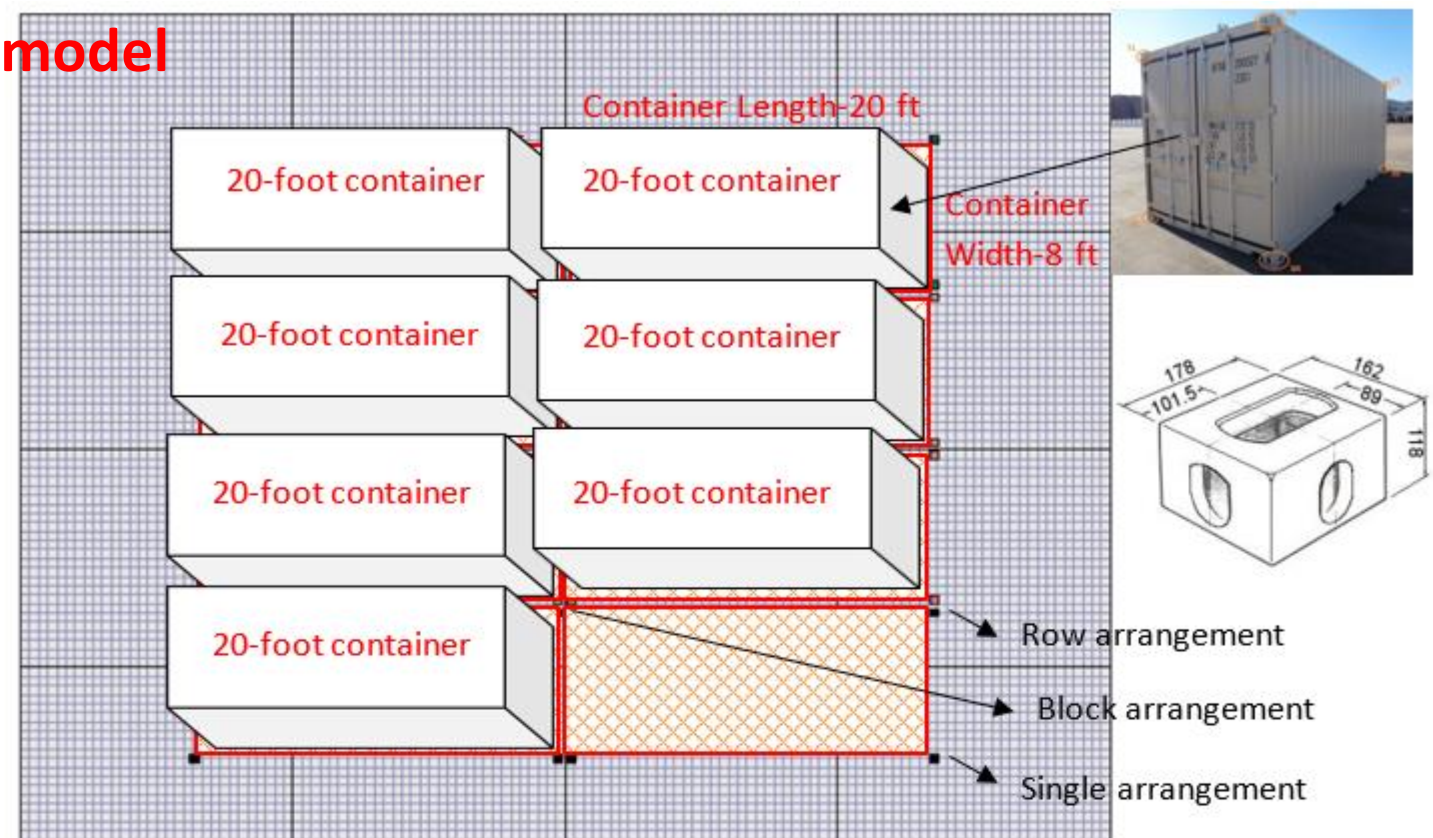
Assumptions:

- No joint effects
- Interior container corner casting location
- Block container corner load arrangement

Critical Load Arrangements for Stacked Containers (Cont'd)

- **Proposed Critical Load Arrangement Assumptions for Stacked Containers**
  - This study is focused on determining critical stress and deformation values for a pavement system that supports 20-foot containers placed on a rigid plate with an assumed joint spacing of 5 m by 5 m.

Proposed model



- **Methodology**
  1 - The layer thicknesses and properties presented were selected based on typical RCC applications described in the literature

Layer Properties		
	RCC surface layer	Aggregate base layer
Thickness	25 cm (10 in)	15 cm (6 in)
Elastic modulus	27.5 GPa (4x10^6 psi)	0.2 GPa (30,000 psi)
Poisson's ratio	0.15	0.20
Coefficient thermal expansion (CTE)	9x10^{-6} cm/cm/-^{0}C (5x10^{-6} in/in-^{0}F)	3.6 x10^{-6} cm/cm/-^{0}C (2x10^{-6} in/in-^{0}F)
Unit weight	2,400 kg/m^3 (0.087 lb/in^3)	1,690 kg/m^3 (0.0612 lb/in^3)
Subgrade Properties		
Subgrade k values	27,800 kN/m^2/m (100 psi/in)	
Layer Geometry		
Slab number	Transverse direction 4, Longitudinal direction 4	
Slab size (Joint configuration)	~5 m x 5 m (180 x180 in)	
Stacked container inputs		
Corner casting dim.	178 mm x 162 mm (7.0 x 6.38 in)	
Average weight	156 kN/container	
Stacking height	5	

Critical Load Arrangements for Stacked Containers (Cont'd)

- **Methodology**

  2 - Joint design was taken into consideration

  - Load transfer between joints for RCC is provided by aggregate interlock

ISLAB2000 gives you four choices:

- Rigid – Restores full structural continuity, as if joints did not exist; used to describe mismatched joints.
- Agg Interlock – Load transfer is provided through aggregate interlock.
- Doweled – Load transfer is provided by dowels.
- Dowel + Agg – Load transfer is provided by a combination of dowels and aggregate interlock.

$$AGG = \left(\frac{\frac{1}{LTE} - 0.01}{0.012} \right)^{-\frac{1}{0.849}} \cdot k \cdot l$$

Where			
	AGG	=	AGG factor
	LTE	=	Load transfer efficiency, percent
	ℓ	=	Radius of relative stiffness, in
	k	=	Modulus of subgrade reaction

$$l = \sqrt[4]{\frac{E \cdot h^3}{12(1-\mu^2) \cdot k}}$$

Where			
	ℓ	=	Radius of relative stiffness, in
	E	=	Elastic modulus of layer 1
	h	=	Thickness of layer 1
	μ	=	Poisson's ratio for layer 1
	k	=	Modulus of subgrade reaction

Critical Load Arrangements for Stacked Containers (Cont'd)

- **Methodology**

  2 - Joint design was taken into consideration (Cont'd)

  - The value of the AGG factor parameter is dependent on the stiffness of the joint, load transfer efficiency and the modulus of subgrade reaction.
  - Five different load transfer efficiency (LTE) percent values were selected
    - 0 %, 25%, 50%, 75%, 100%

$$AGG = \left(\frac{\frac{1}{LTE} - 0.01}{0.012} \right)^{-\frac{1}{0.849}} \cdot k \cdot l$$

Where			
	AGG	=	AGG factor
	LTE	=	Load transfer efficiency, percent
	ℓ	=	Radius of relative stiffness, in
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$$l = \sqrt[4]{\frac{E \cdot h^3}{12(1-\mu^2) \cdot k}}$$

Where			
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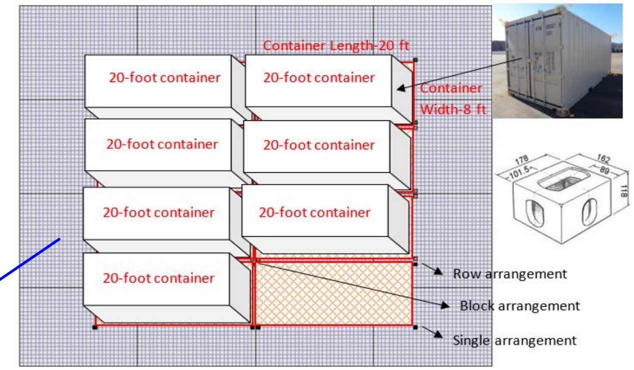
	h	=	Thickness of layer 1
	μ	=	Poisson's ratio for layer 1
	k	=	Modulus of subgrade reaction

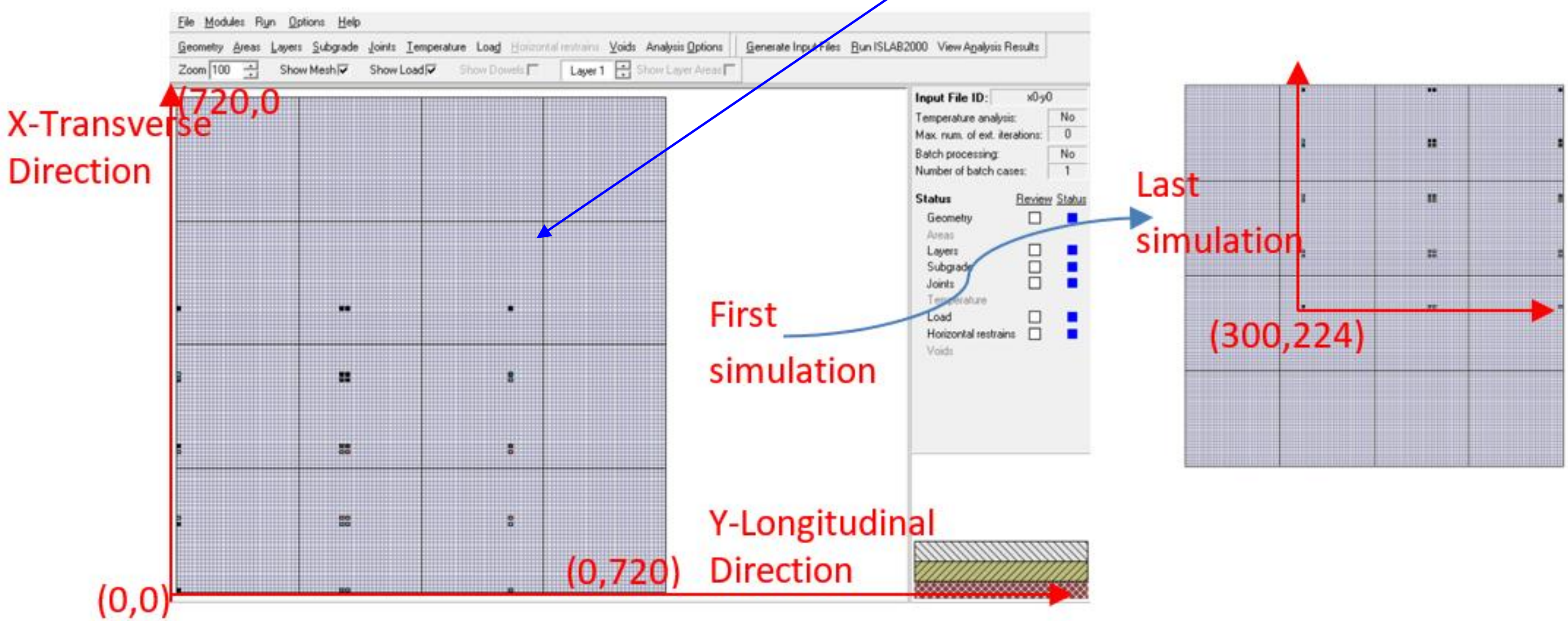
Critical Load Arrangements for Stacked Containers (Cont'd)

- **Methodology**

  3 - Seeking stacked container arrangements that would generate the maximum critical stress values for each selected percentage of LTE

  - Beginning from zero, load points in the x (transverse) and y (longitudinal) directions were moved two inches in both directions

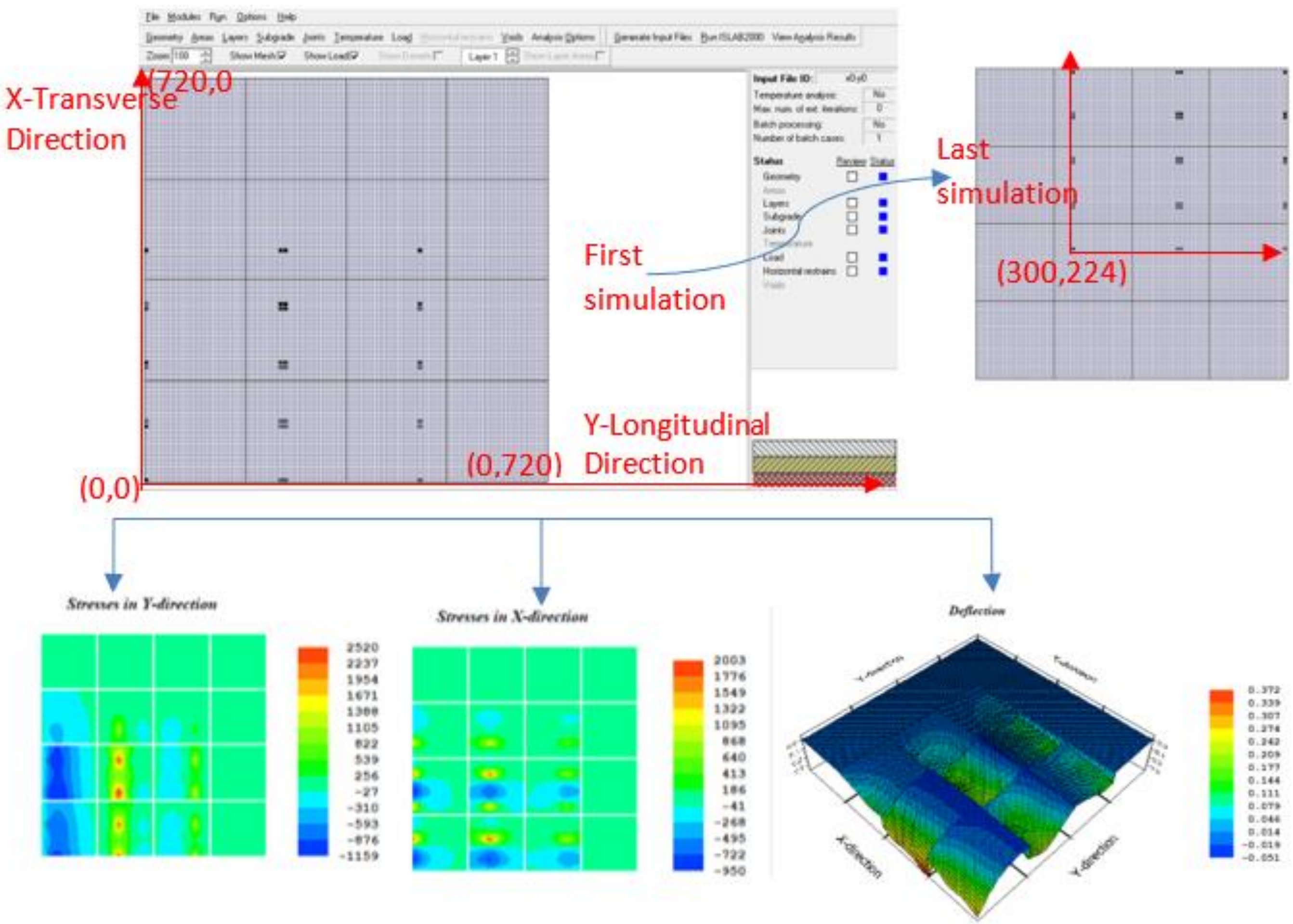




Critical Load Arrangements for Stacked Containers (Cont'd)

- **Methodology**

  4 - Transverse and longitudinal stress values, as well as deformation values, were obtained for each case separately



This study involved conducting **16,800 finite element simulations for each LTE value**, resulting in a total of 84,000 simulations!

Critical Load Arrangements for Stacked Containers (Cont'd)

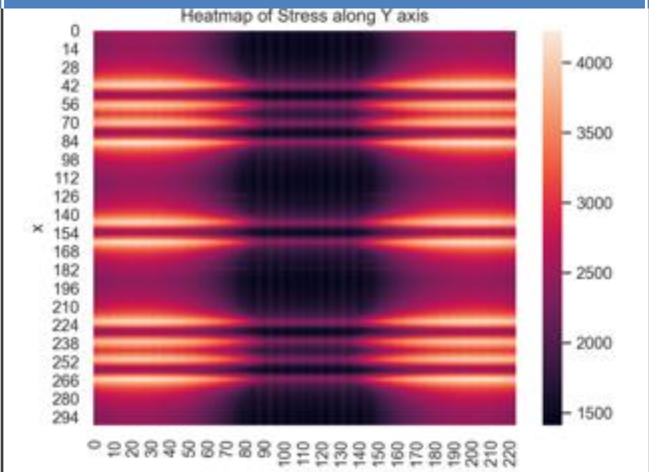
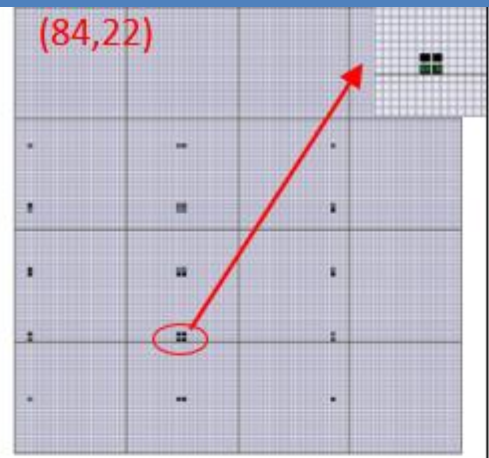
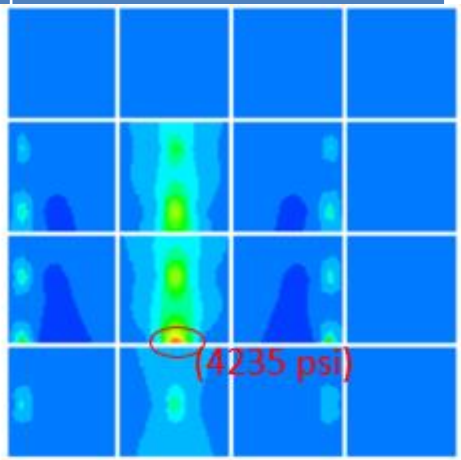
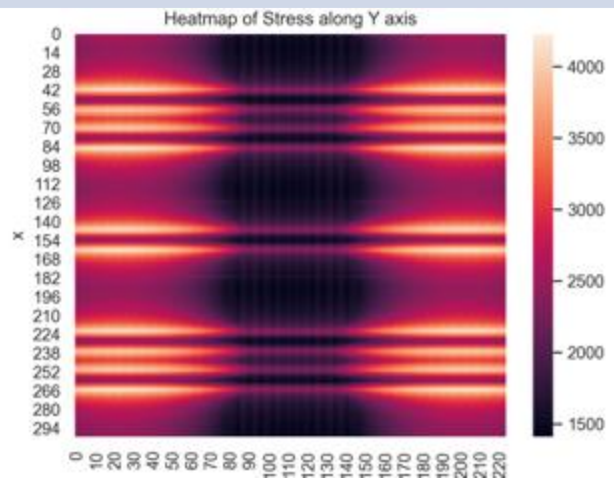
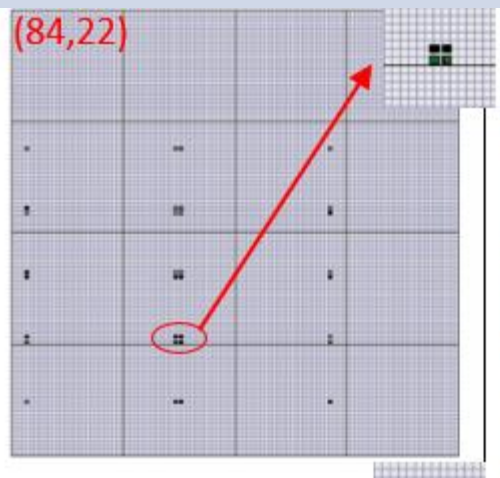
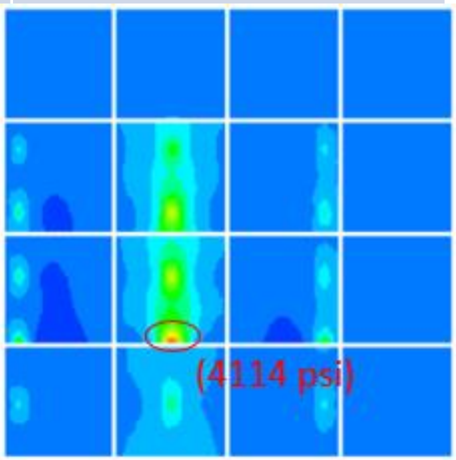
- **Methodology**

  5 - Generate heatmaps that identified critical stacked container arrangements with the highest stress values

Critical Load Arrangements for Stacked Containers (Cont'd)

- **Analyses Results**

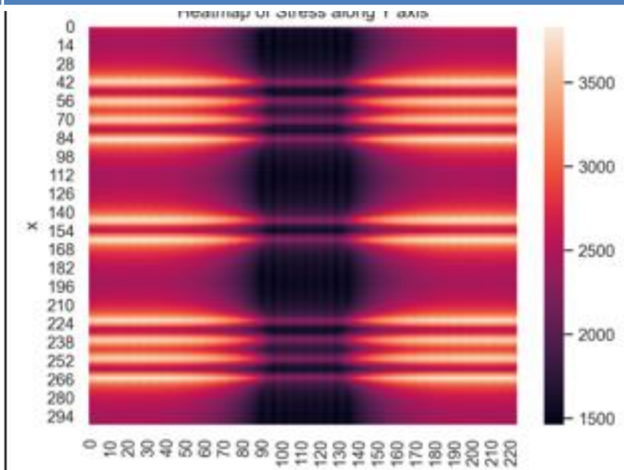
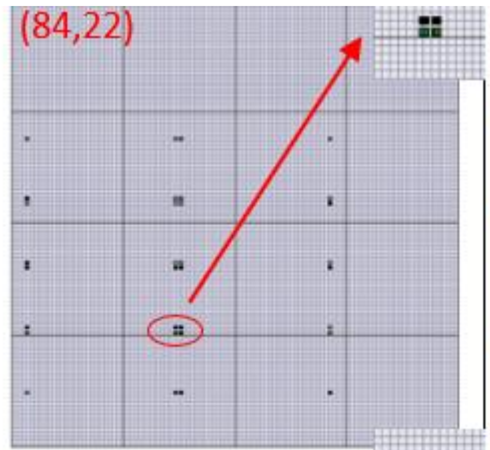
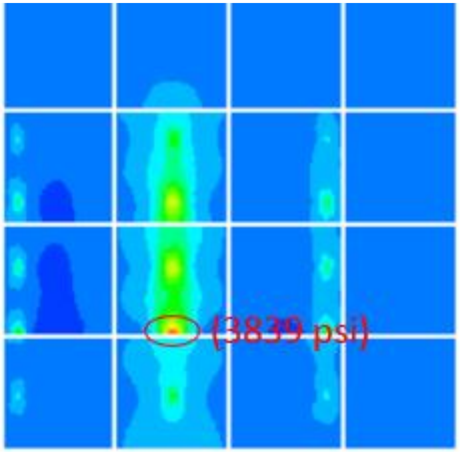
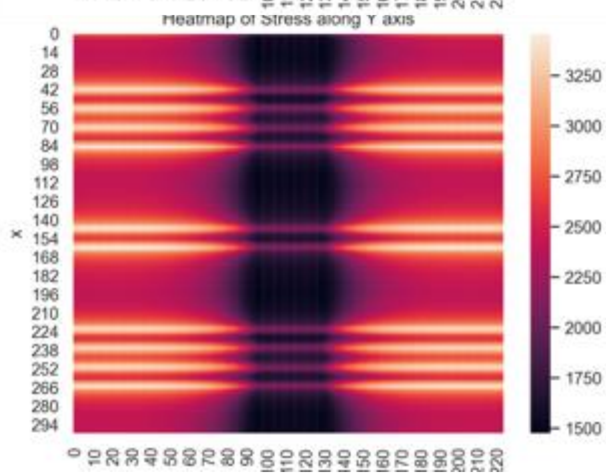
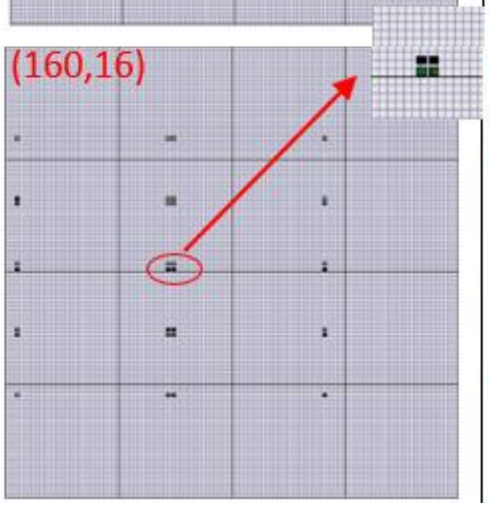
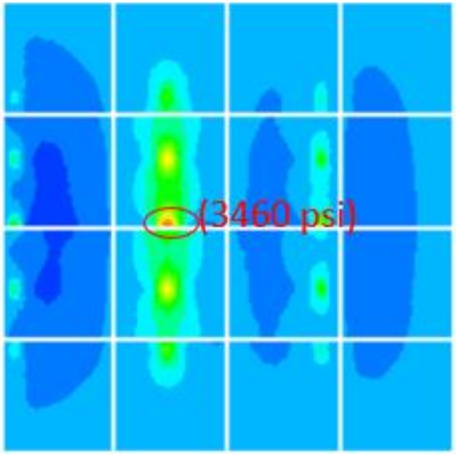
16,800 simulations for each LTE value

LTE	Heatmaps	Critical Stacked Container Arrangements	Critical Stresses in Y-Direction
0%			
25%			

Critical Load Arrangements for Stacked Containers (Cont'd)

- **Analyses Results**

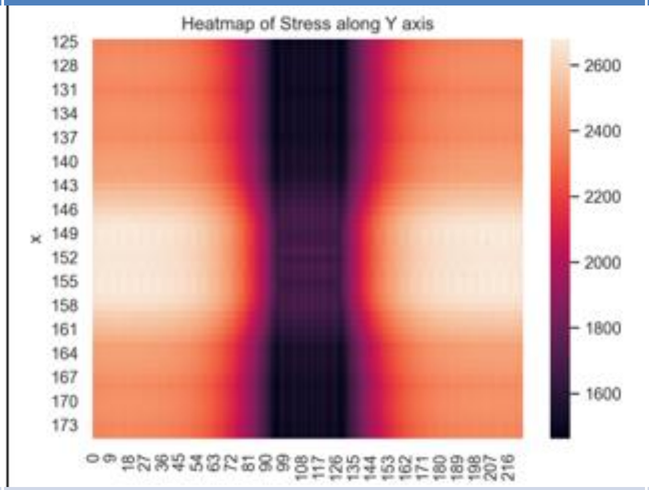
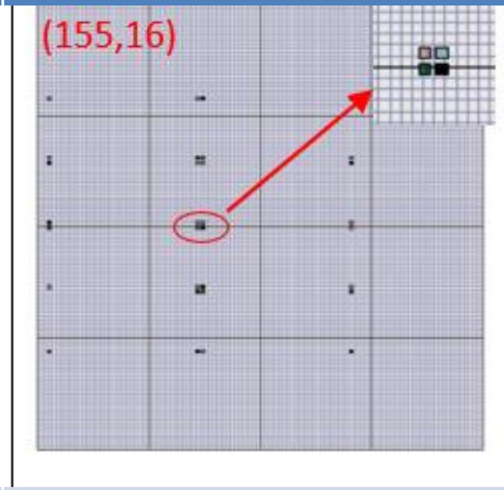
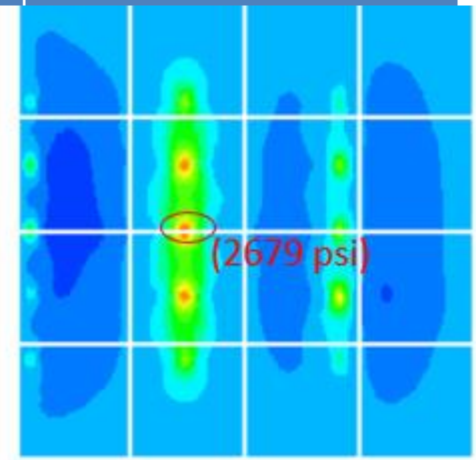
16,800 simulations for each LTE value

LTE	Heatmaps	Critical Stacked Container Arrangements	Critical Stresses in Y-Direction
50%			
75%			

Critical Load Arrangements for Stacked Containers (Cont'd)

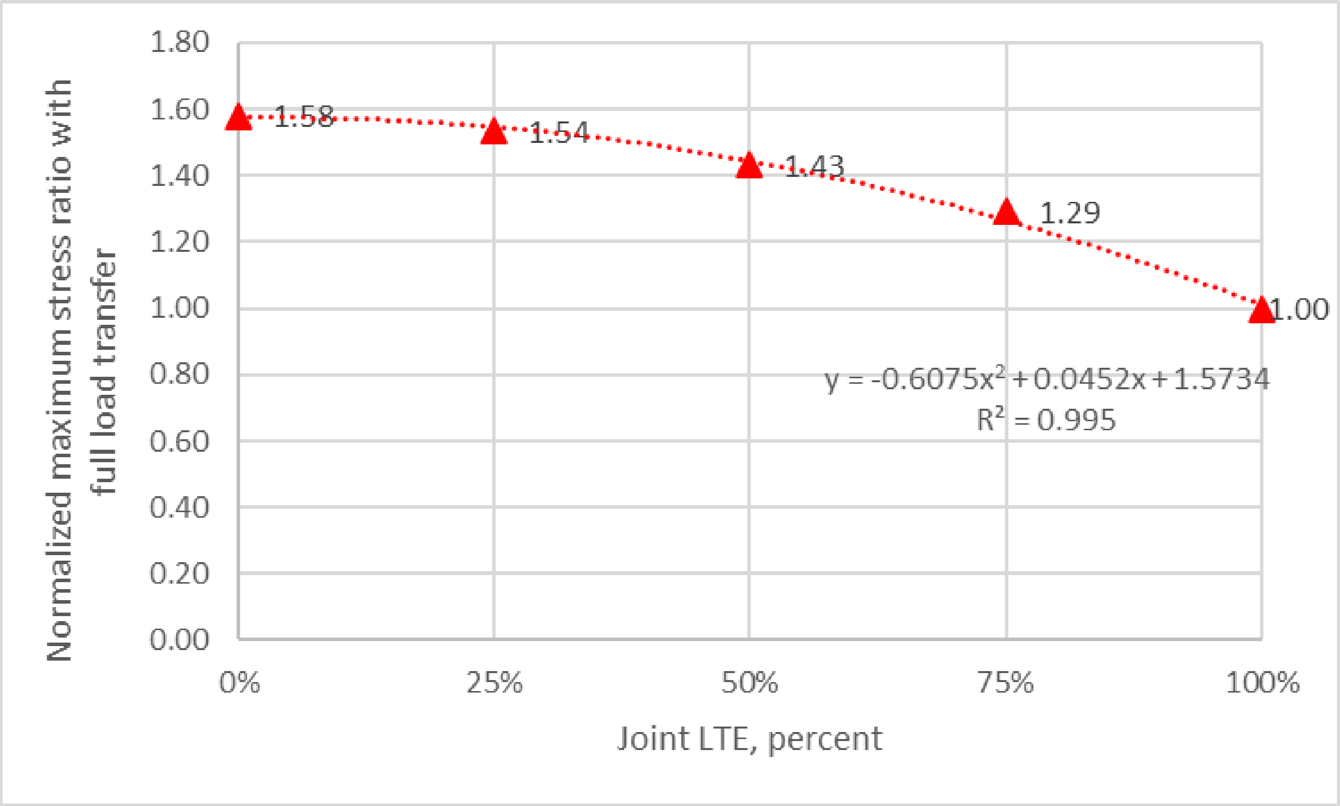
- **Analyses Results**

16,800 simulations for each LTE value

<table>
<tr><th>LTE</th><th>Heatmaps</th><th>Critical Stacked Container Arrangements</th><th>Critical Stresses in Y-Direction</th></tr>
<tr><td>100%</td><td>
</td><td>
</td><td>
</td></tr>
</table>

Critical Load Arrangements for Stacked Containers (Cont'd)

- The increase in the maximum/critical stresses with the decrease in the % LTE
- When there is no load transfer between adjacent slabs (% LTE = 0), and full load transfer exists (% LTE = 100), critical stress ratios increase by up to 58%, resulting in a need for thicker pavement design



Outline

- Evaluation of Existing Port/Industrial Pavement Design Guides
  - Design Principles
  - Limitations

- Analysis of Critical Load Arrangements for Stacked Containers
  - Methodology
  - FEM-ISLAB2005 Analysis

- Summary and Future Work

Summary

- The development of an RCC pavement design for stacked containers involves a multi-step process

- Existing design manuals that consider stacked container designs were thoroughly reviewed
  - The most important limitation of current design manuals is that they do not consider joints, a critical and unique feature of rigid pavements
  - Different calculation models such as finite-element models or closed-form formulas or empirical formulas
  - Different approaches to critical container load location and arrangement

- Beginning with the determination of the critical container load arrangement
  - Consideration of joint effect and in-situ field stacked container arrangement
  - ISLAB 2005 FE software
  - ~85,000 simulations
  - Determination of critical load arrangements for stacked containers for each LTE value

Future Work

1. Developing a new design model for stacked containers
   i. Geometric features
   ii. Layer properties
   iii. Subgrade models
   iv. Joints / Load transfer properties
   v. Load configurations
2. Determining critical container stacking arrangement (~16,800 simulation for each LTE)
   i. Max. transverse stress at the bottom of the RCC layer
   ii. Max. longitudinal stress at the bottom of the RCC layer
   iii. Max. deflection
3. Parametric studies on critical container stacking arrangement
   i. Layer thickness
   ii. Layer properties
   iii. Subgrade k values
   iv. Stacking heights / weights
4. Calculation of the pavement response at the bottom the RCC layer for each case
   i. Max. transverse stress
   ii. Max. longitudinal stress
   iii. Max. deflection
5. Establishing permissible stresses by using transfer functions
   i. Permissible flexural tensile str.
   ii. Permissible punching shear str.
   iii. Permissible bearing str.
6. Comparison of permissible stresses of materials with stresses from container stacking
7. Creating design chart or website

Future Work - A Comparison of Thickness Design

- Pavement Design for Stacked Containers

Design Criteria

- Stacking Arrangement: Height of five containers (mix), layout in block
- Commercial use
- Corner casting measure: 178 mm x 162 mm
- Average weight: 156 kN/container (35,000 lbs)
- Subgrade: Good (CBR >5%, E> 50 Ma)

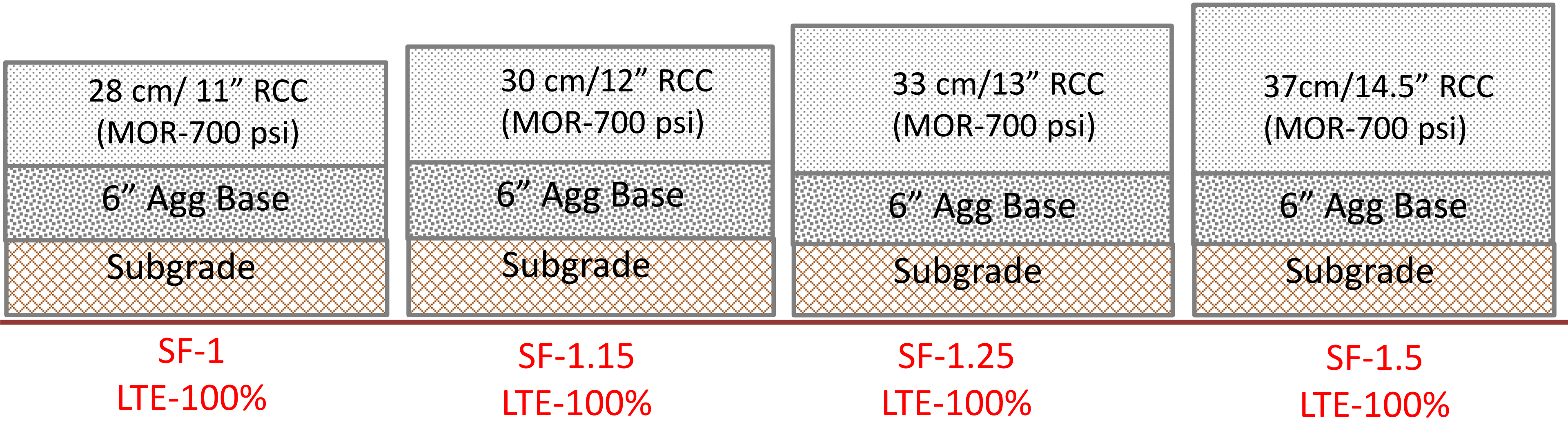
❑ Pavement Design for Stacked Containers

Specific assumptions made for each design manual

Design Manuals	- Container Stacking
British BPA method	ESWL for container stacking 156x 5=780 kN From the design chart, 55 cm -C8/10 base thickness
Concrete Society TR-34	Concrete grade C35/45 $f_{ctd,fl}$= 2.7 MPa (charc. flex. str. of concrete) E_c= 34,000 MPa (elastic modulus) k= 0.054 MPa/mm (subgrade reaction) Material safety factor: 1.5 Load Safety factor: 1.2 Radius of patch load:~ 81 mm Distance between loads-x 180 mm Distance between loads-y 189 mm
Concrete Society TR-66	X
French Model	Since the French method is program-based (Alize software), the assumptions and outputs are taken from the PIANC report.
Spain Method	For catalogue selection; Commercial Usage Storage Area Traffic class A Subgrade class E3
US ACI 330.2r	X
US RCCPave (PCA)	X
US Pavement Designer	X
US USACE method	X

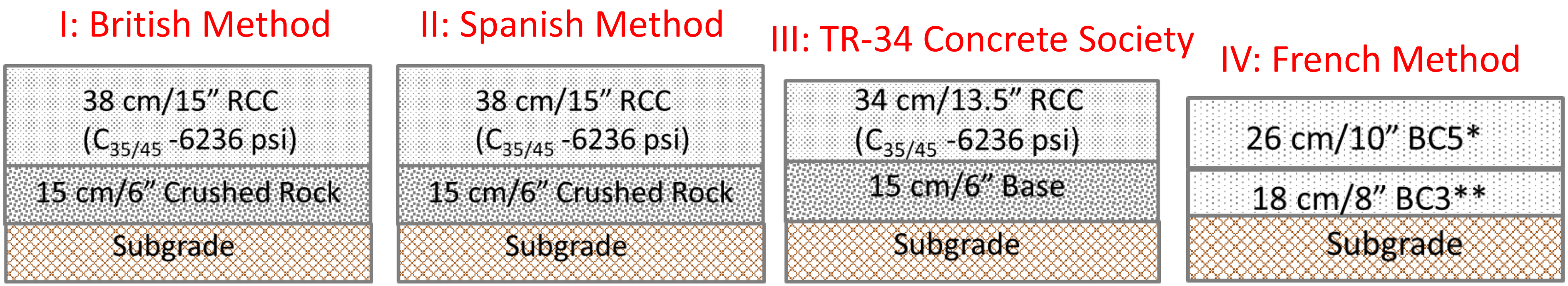
Future Work - A Comparison of Thickness Design

Calculated thickness design from proposed model



Future Work - A Comparison of Thickness Design

Comparison of existing RCC design manuals for stacked containers



* $C_{32/40}$ (5,510 psi concrete)

** $C_{25/30}$(4,786 psi concrete base)

Future Work - A Comparison of Thickness Design

I: British Method

38 cm/15" RCC ($C_{35/45}$ -6236 psi)
15 cm/6" Crushed Rock
Subgrade

II: Spanish Method

38 cm/15" RCC ($C_{35/45}$ -6236 psi)
15 cm/6" Crushed Rock
Subgrade

III: TR-34 Concrete Society

34 cm/13.5" RCC ($C_{35/45}$ -6236 psi)
15 cm/6" Base
Subgrade

IV: French Method

26 cm/10" BC5*
18 cm/8" BC3**
Subgrade

* $C_{32/40}$ (5,510 psi concrete)
** $C_{25/30}$ (4,786 psi concrete base)

Proposed Method

28 cm / 11" RCC (MOR-700 psi)
6" Agg Base
Subgrade

SF-1
LTE-100%

30 cm / 12" RCC (MOR-700 psi)
6" Agg Base
Subgrade

SF-1.15
LTE-100%

33 cm / 13" RCC (MOR-700 psi)
6" Agg Base
Subgrade

SF-1.25
LTE-100%

37 cm / 14.5" RCC (MOR-700 psi)
6" Agg Base
Subgrade

SF-1.50
LTE-100%

Contact Information

Halil Ceylan, Ph.D., Dist.M.ASCE

Pitt-Des Moines, Inc. Endowed Professor of Civil, Construction and Environmental Engineering

ISU Site Director, PEGASAS - FAA COE on General Aviation

Director, Program for Sustainable Pavement Engineering & Research (PROSPER)

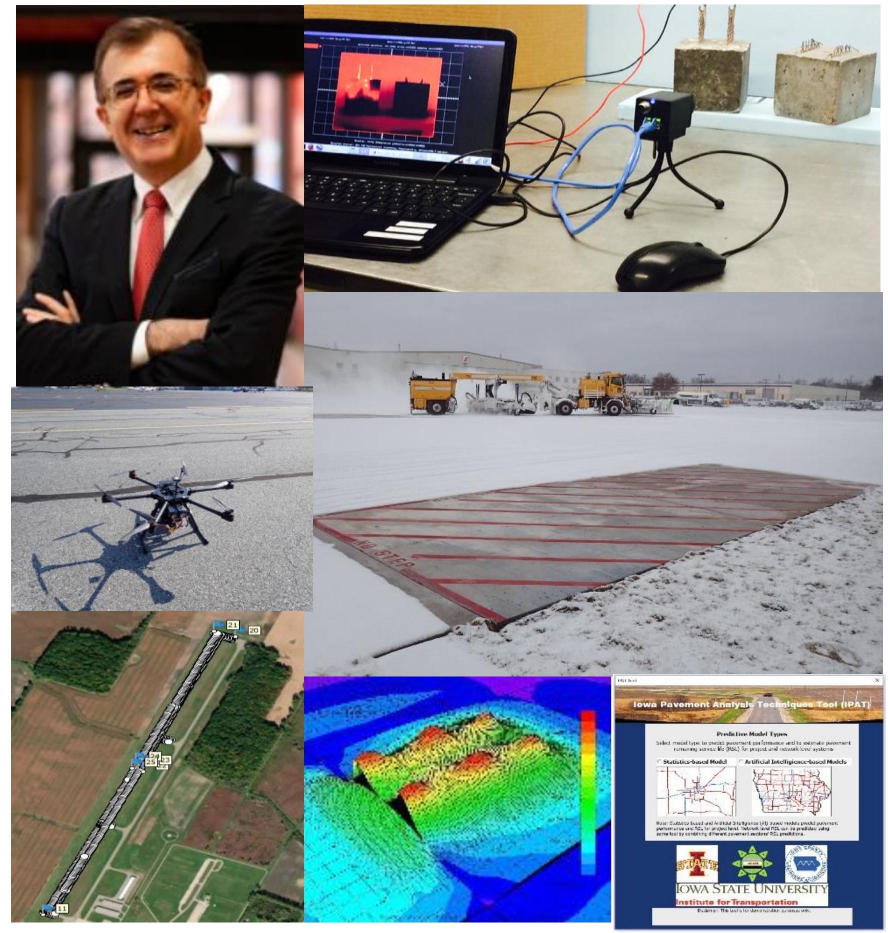
Institute for Transportation

410 Town Engineering Bldg.

Iowa State University
813 Bissell Road

Ames, IA 50011-1066

Phone: +1 (515) 294-8051
E-mail: hceylan@iastate.edu



Thank You! Questions & Comments?

Intermodal Terminal, **Denver, CO (built 1986)**

Conley Terminal, **Boston, MA (built 1986)**

Hardstand for military vehicle parking
Fort Lewis, WA (built 1985)

United States Army, **Fort Drum, NY (built 1988)**

Wood chip storage, **Vancouver, B.C. (built 1995)**

Compost processing, **Ontario, B.C. (built 1990)**

Wood chip storage, **Alberta (built 1992)**

Composting site, **Alberta (built 1992)**

Storage of coal, **Vancouver, B.C. (built 1992)**

(Photo source: Piggott R.W. (1999))