

## Soutenance de thèse de doctorat (PhD)

Application of Artificial Intelligence in the exploitation of deflection measurements  
for the mechanical characterization of pavement structures

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- Rapporteur : Prof. Simona Fontul
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- Examineur : Prof. Yide Wang
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- Co-directrice de thèse : Dr Franziska Schmidt
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Sep. 30th, 2024

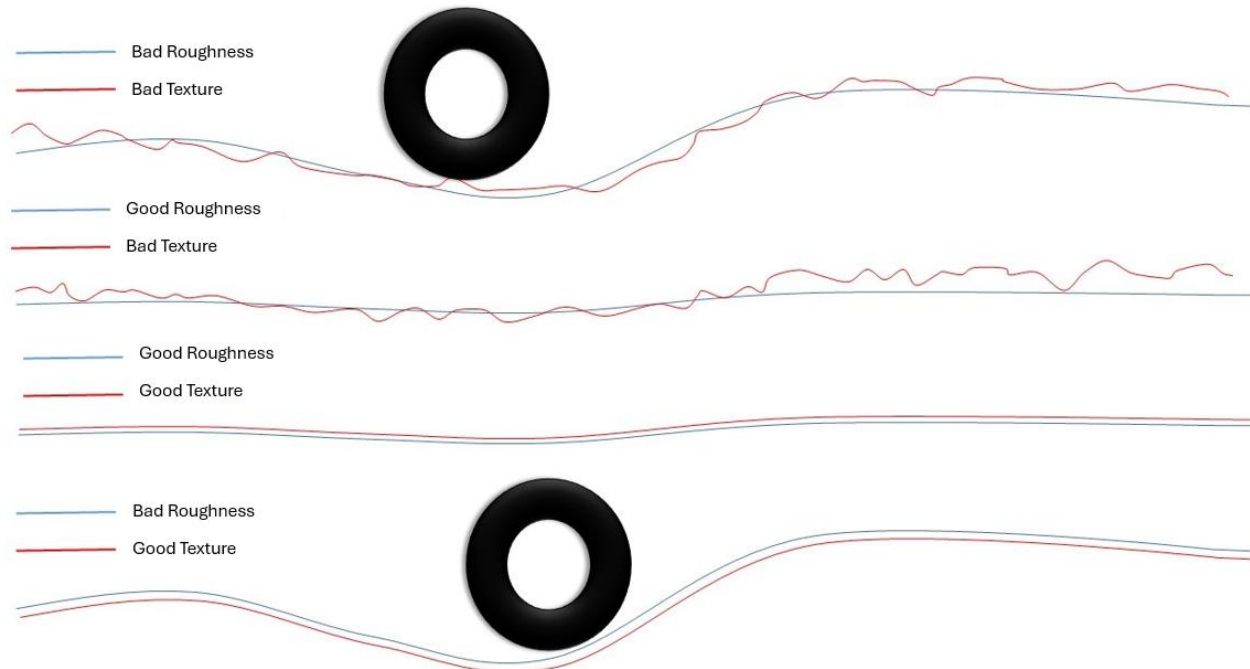
1. Global problem statement
2. The state of the art
3. Research gaps = Thesis objective
4. AI-based intelligent solution
5. Systematic methodology
6. Results & discussion
7. Research limitations & challenges
8. Conclusion, perspective & valorization



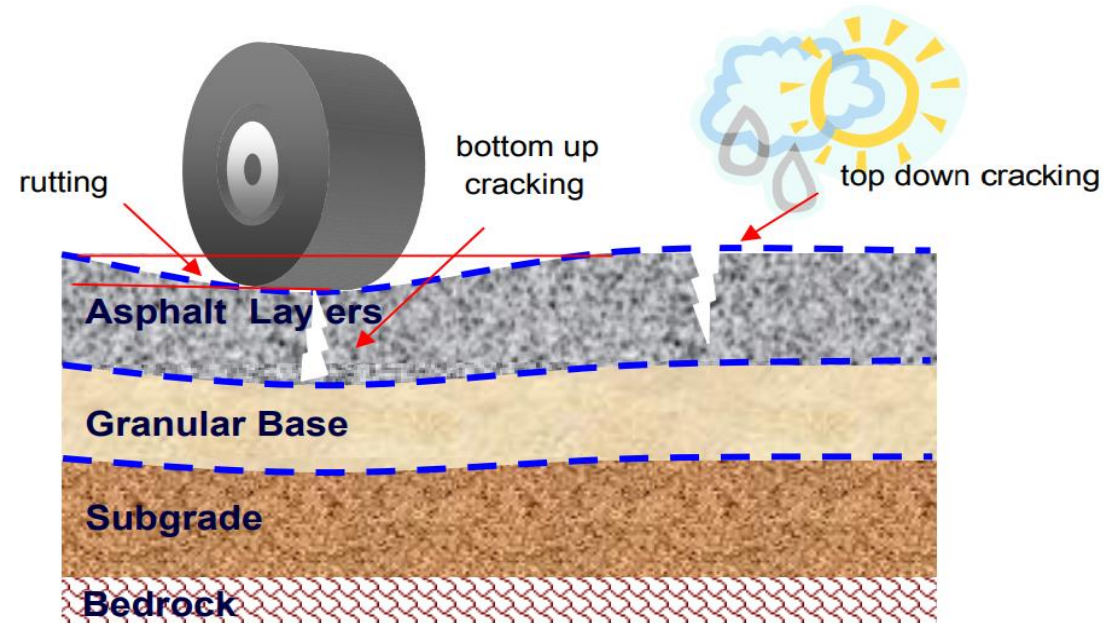
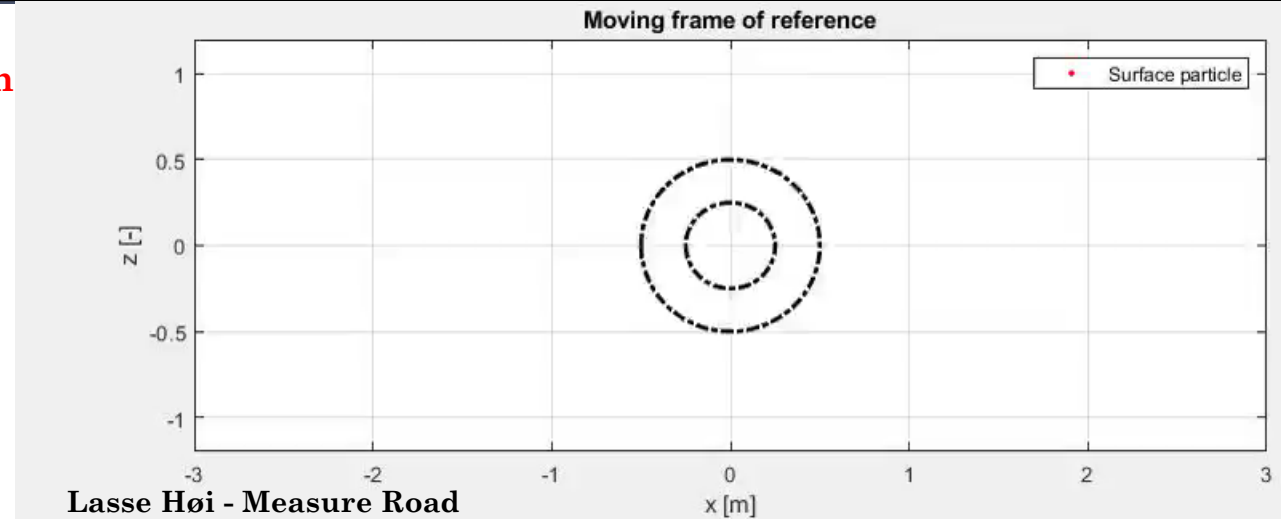
# Introduction

- Context and implications
- Causes and consequences

- ▶ Road Authorities: critical progressive infrastructure **deterioration**
- ▶ Insufficient **DATA**: allowing for long-term predictive maintenance
- ▶ **PMS indicators**: Relies on functional assessment & distress data
- ▶ Both might not completely capture the true **structural integrity**
- ▶ Gaps: Structural **bearing capacity** assessment at Network-level

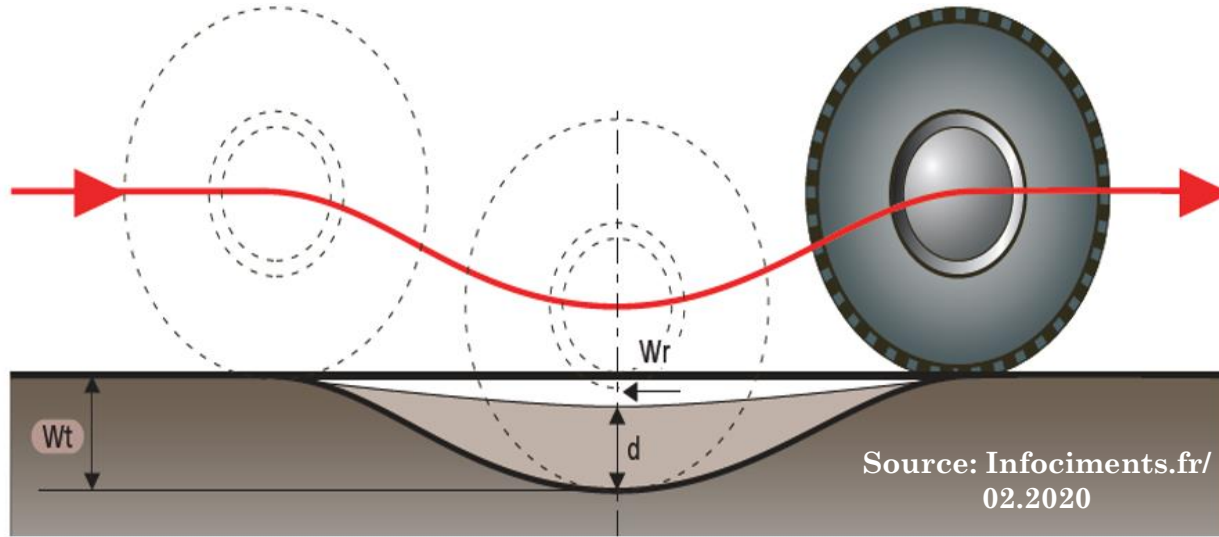


Functional assessment (serviceability)



Surface cracking (distress)

## NDT Deflection measurement



$(E_i)$ : Fundamental mechanical property

Inverse Model (Backcalculation)

$(E_i)$   
Modulus Estimation

Reference (2) : J-M, Simonin, 2021, correction

## Traditional NDT deflection devices operational limitations



Static  
Benkelman



Stationary (Impulse)  
FWD



Slow move 8 km/h  
Deflectograph



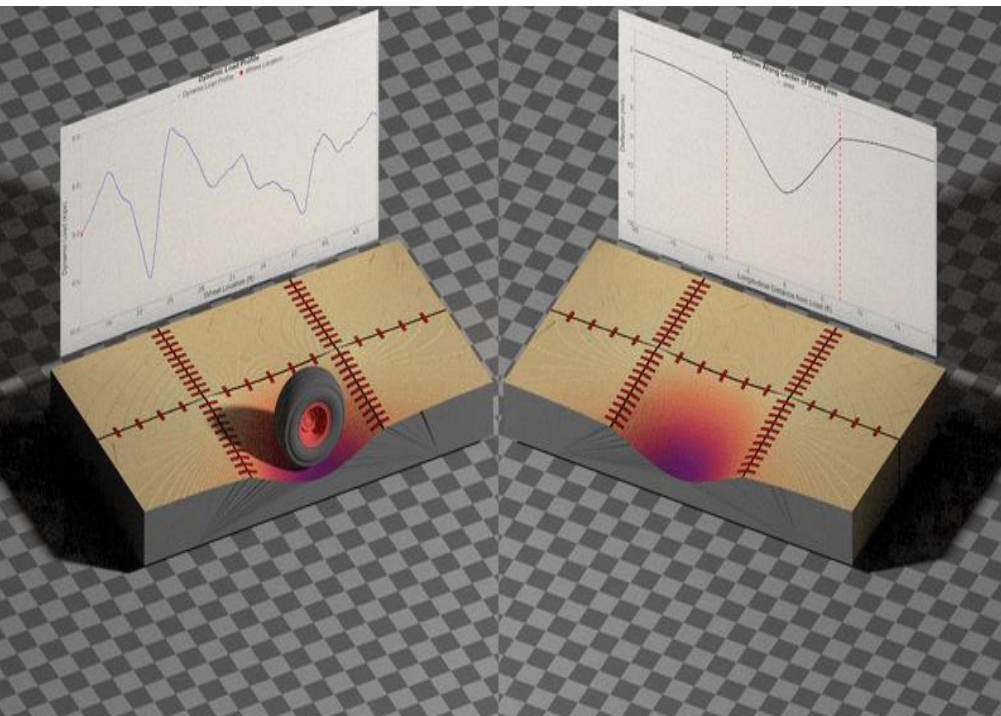
Constant move 8 km/h  
Curviameter

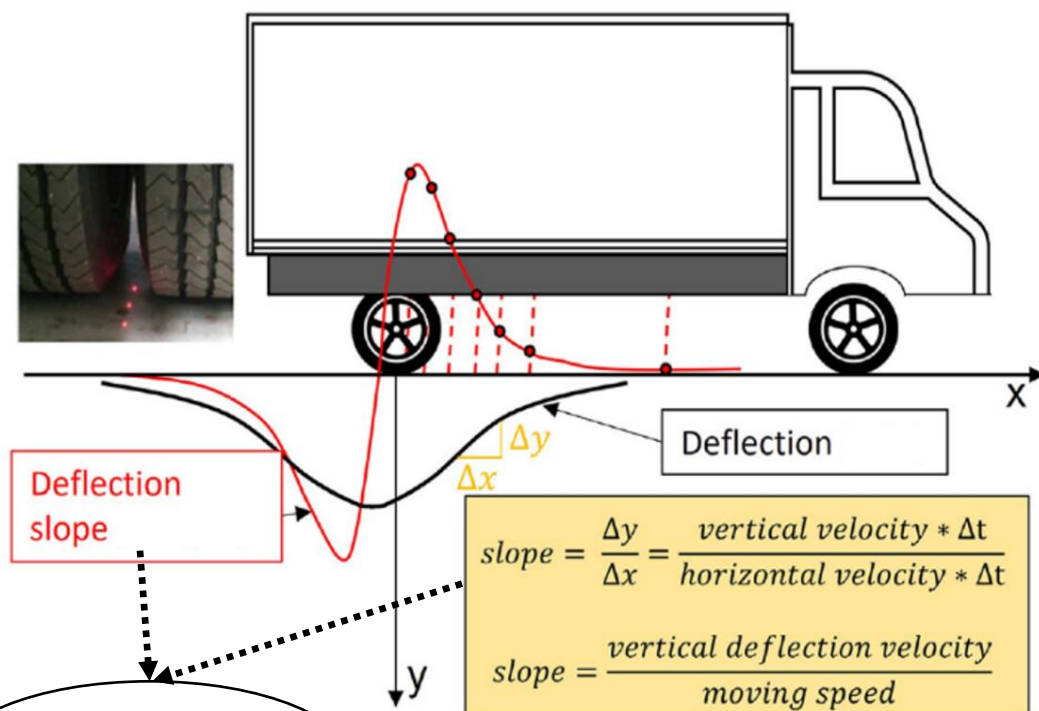
## TSDDs overcome FWD limitations via:

- ❖ Continuous bearing capacity assessment
- ❖ Measurement at traffic speed (+80 km/h)
- ❖ Secure with no traffic disruption
- ❖ Cost-effective for projects and networks levels



Reference (3): Katicha, and Flintsch, Ten years TSD research.....

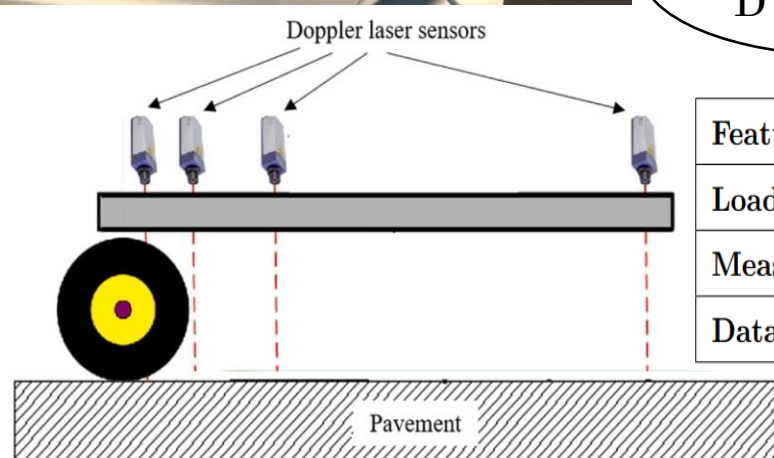
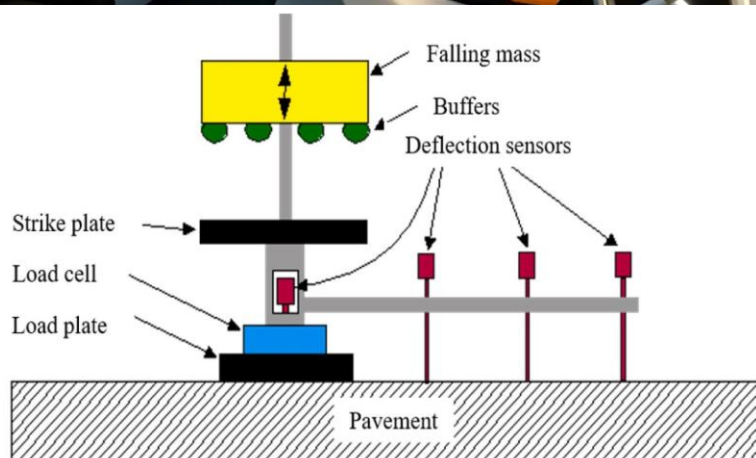




Deflection ( $\mu\text{m}$ )

$$D = \int_x^\infty S \cdot dx$$

Reference (5): Flintsch et al, Ten Years of TSD



Feature	(FWD)	(TSD)
Loading mechanism	Single plate (stationary)	Dynamic or moving tires
Measured parameter	Pavement deflection	Deflection slope
Data conversion	No conversion required	Integration, (information loss)

(a) The measuring schematic of the FWD

(b) The measuring schematic of the TSD

Reference (4): F. Xiao, Tongji University, Measurement, 2021

- ✓ TSD efficiently collects structural data at traffic speeds
- ✗ Processing, analyzing & interpreting TSD data: key challenges!

**Strategic**

**Industrial**

**Research**

**Priorities**

## This is a workshop!



**What is your opinion about ...**

1. Choosing a method to calculate deflections?
2. Using slope values instead of deflections?
3. Establishing international standards for TSD measurements?

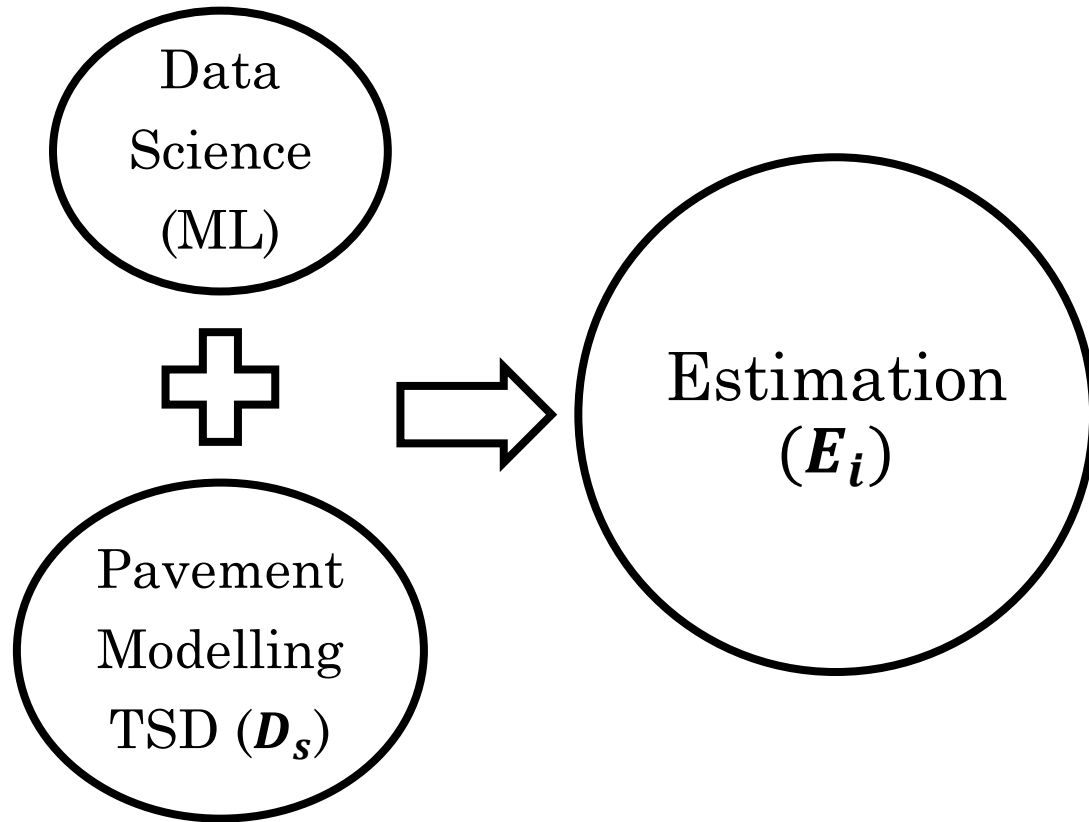
Dr. Dirk Jansen

TRB Annual Meeting - US, Washington, D.C, January 2019

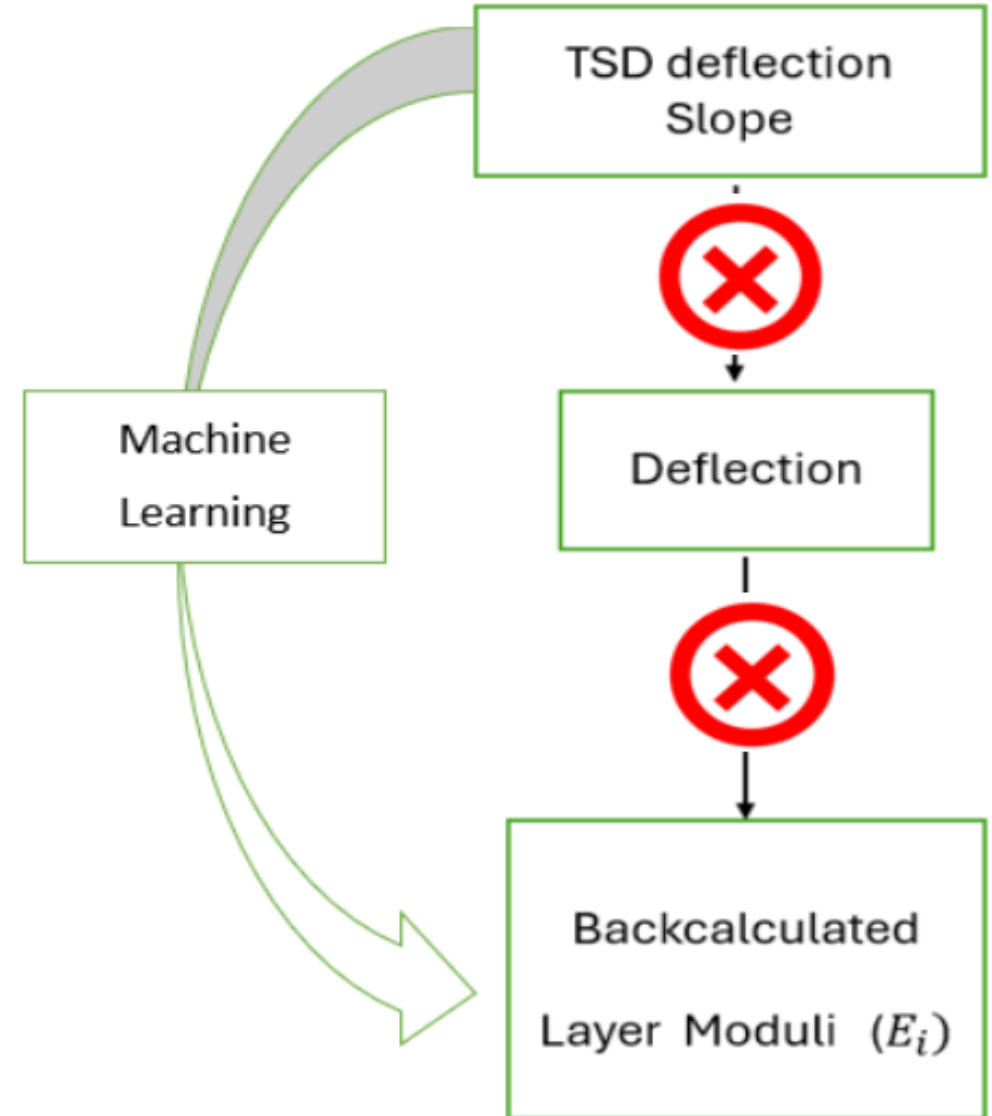


## ► Main Objective :

Develop an ML-based intelligent framework



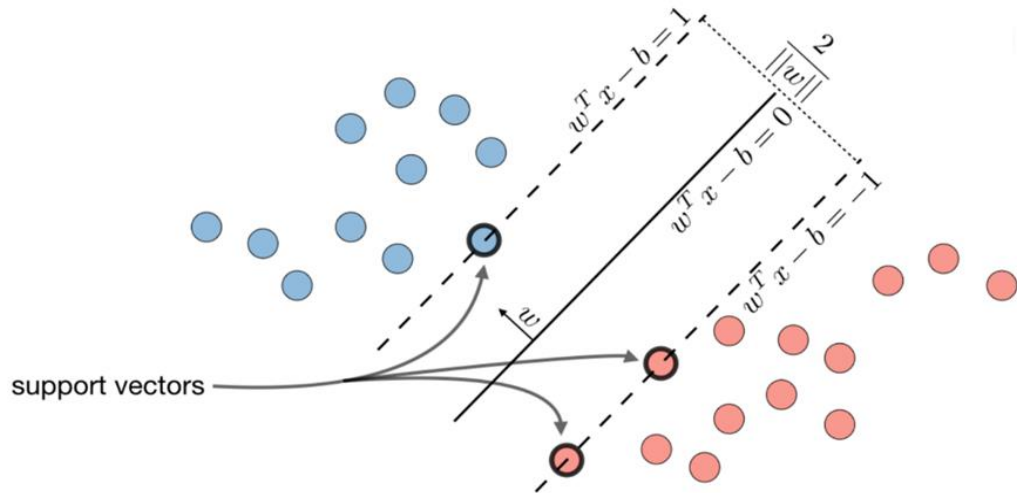
## ► Thesis proposition :



# Method

- ML: Rational and significance
- Research methodology

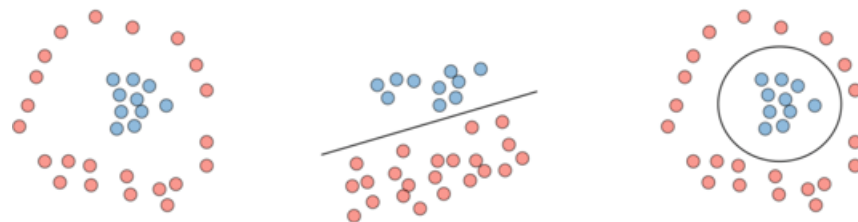
- ▶ Generalized model
- ▶ Adaptable to varying data population; quality and quantity
- ▶ Effective in identifying complex patterns in data
- ▶ High accuracy and high computational efficiency



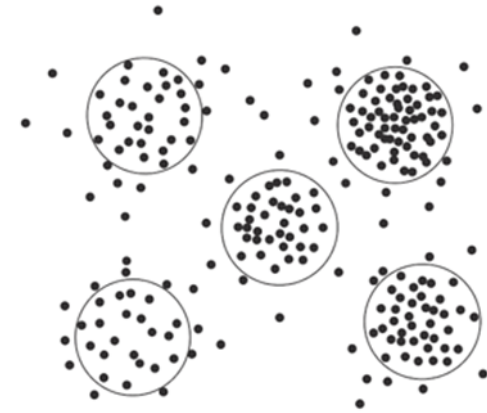
Finds the optimal hyperplane that maximizes/approximates  
Hard and soft **margins**

RBF (Kernel)

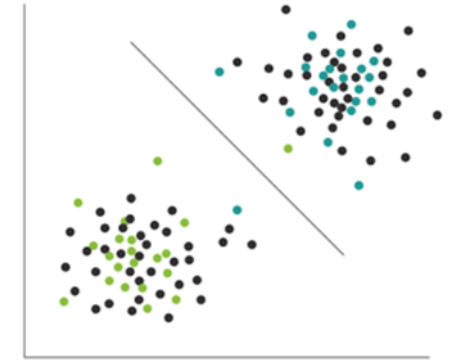
Higher dimensional  
space  $\phi(x)$



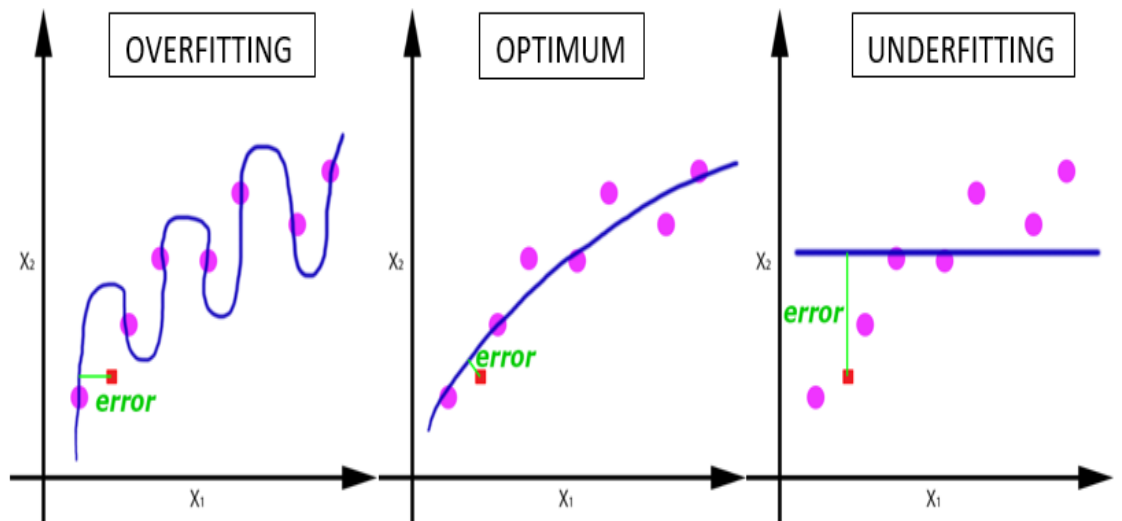
Unsupervised

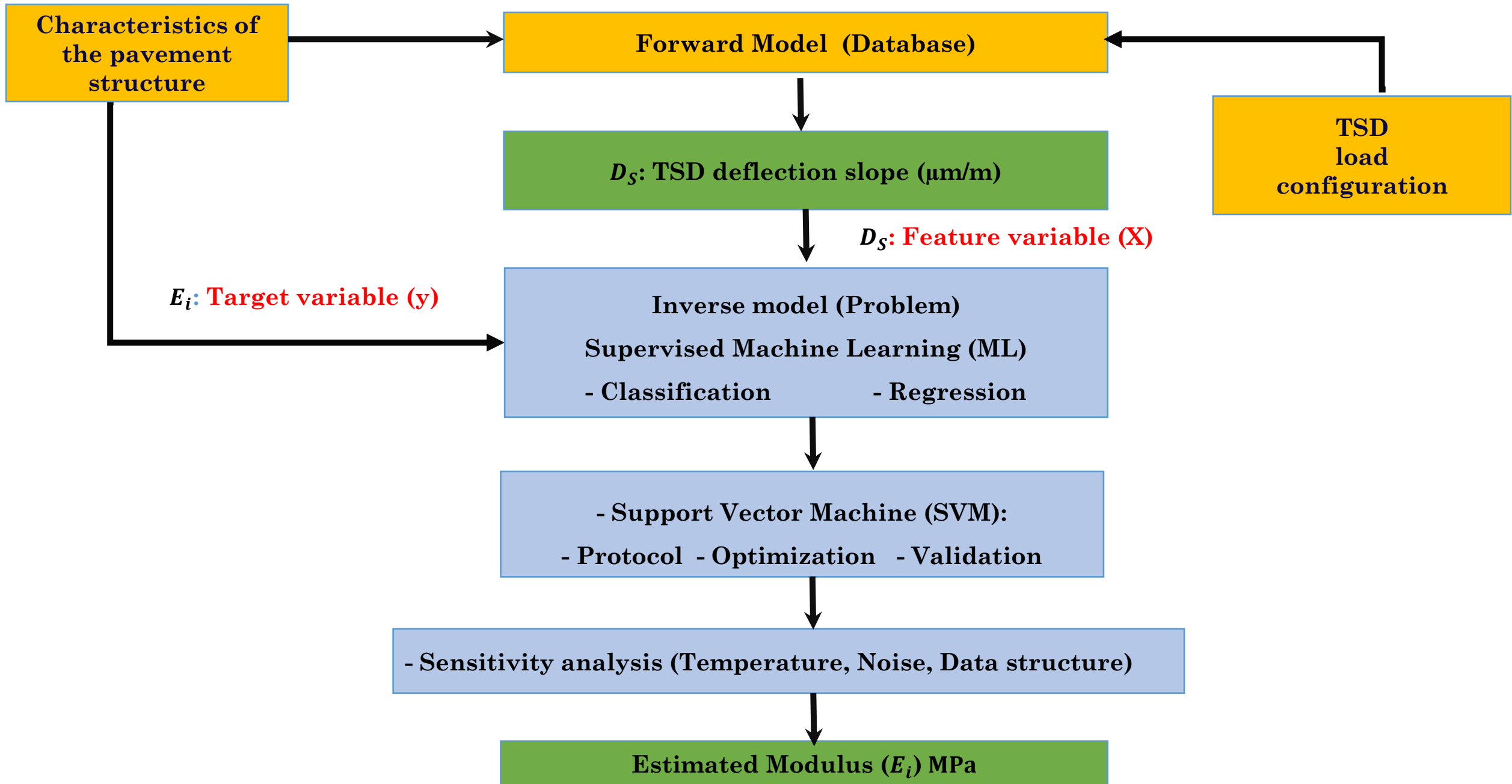


Supervised



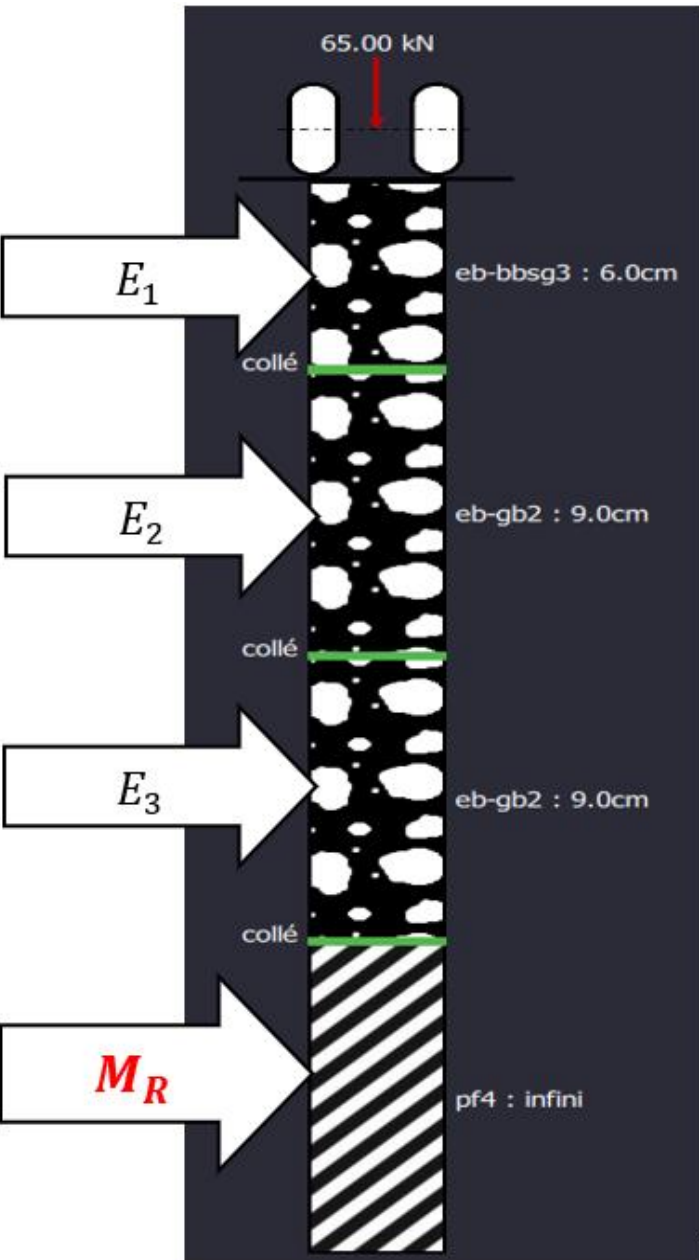
SVM GridSearchCV Scikit-learn hyperparameter tuning





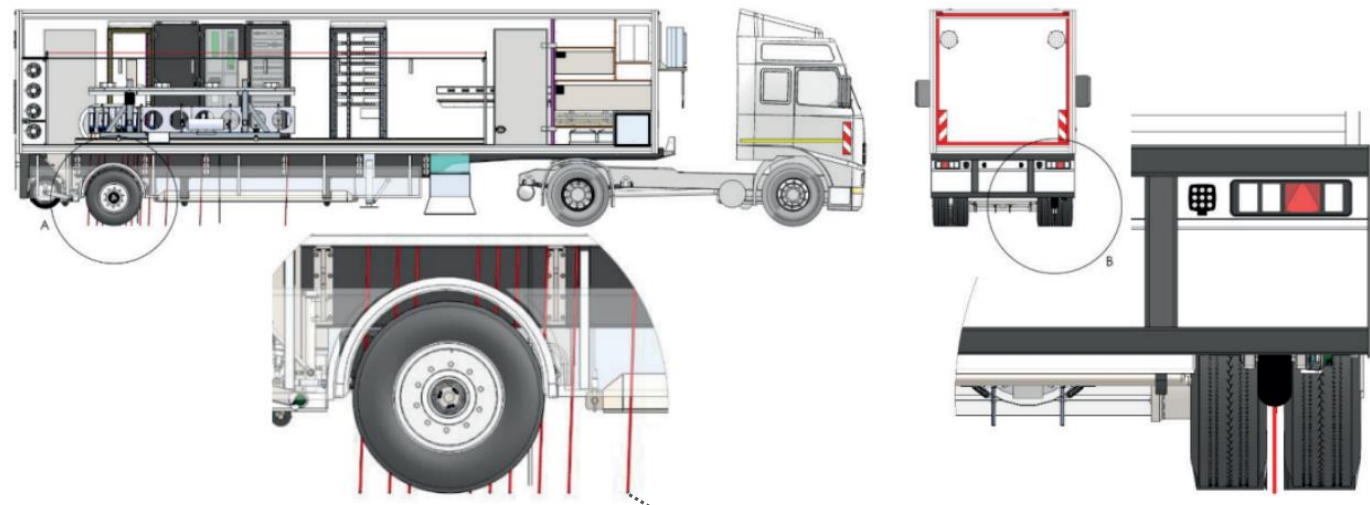
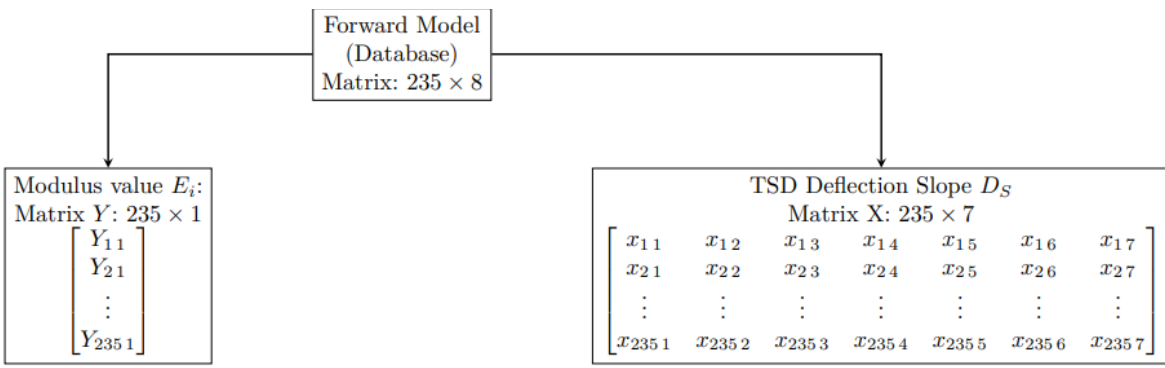
# Forward Model

- Numerical simulation
- Synthetic database



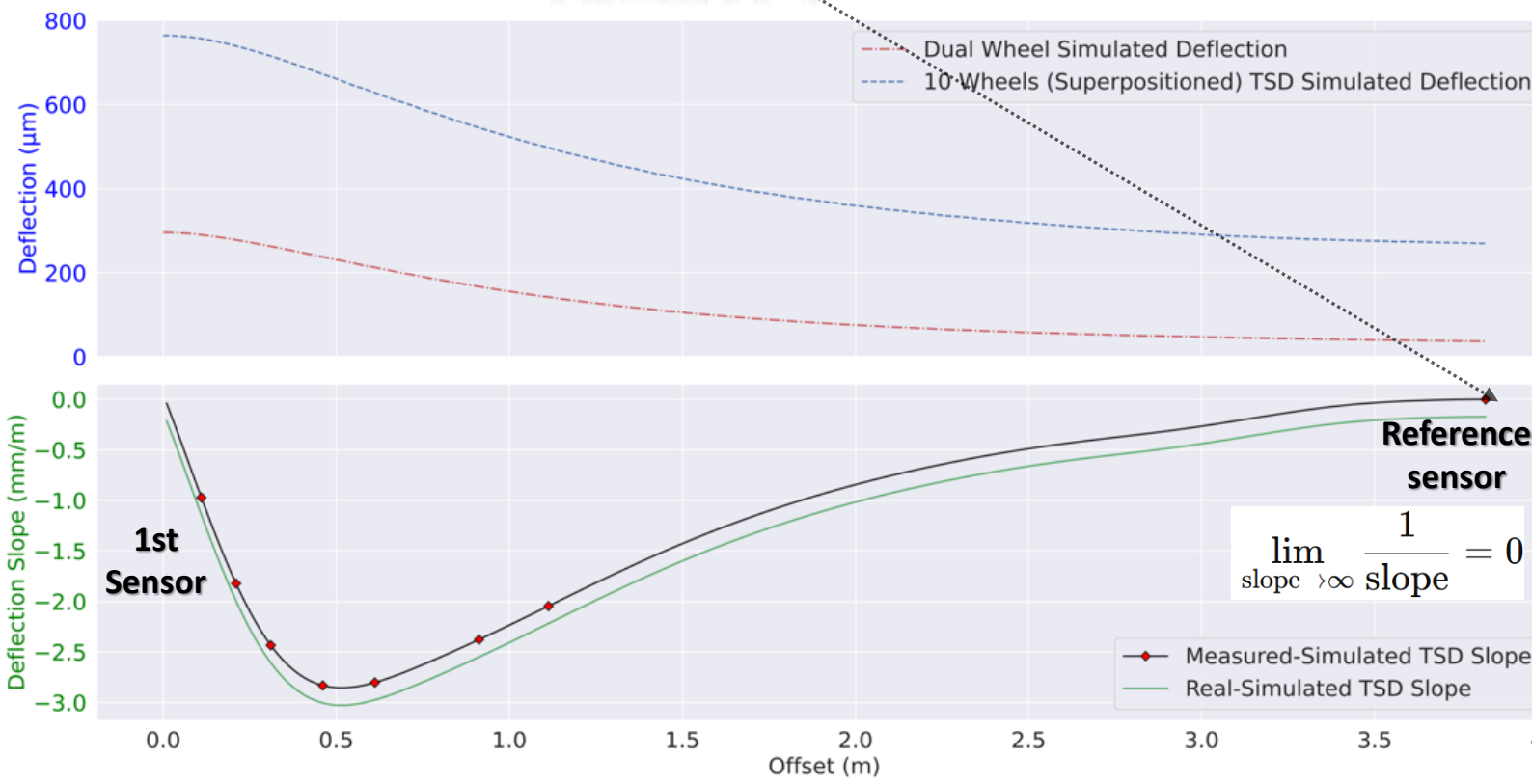
- ▶ Alize-LCPC: Trademark developed by the Univ. Gustave Eiffel
- ▶ French industry standard for pavement modeling/design for +30 years
- ▶ **Burmister** pavement model: Multi-layered, linear elastic, isotropic approach with infinite in-plane layers

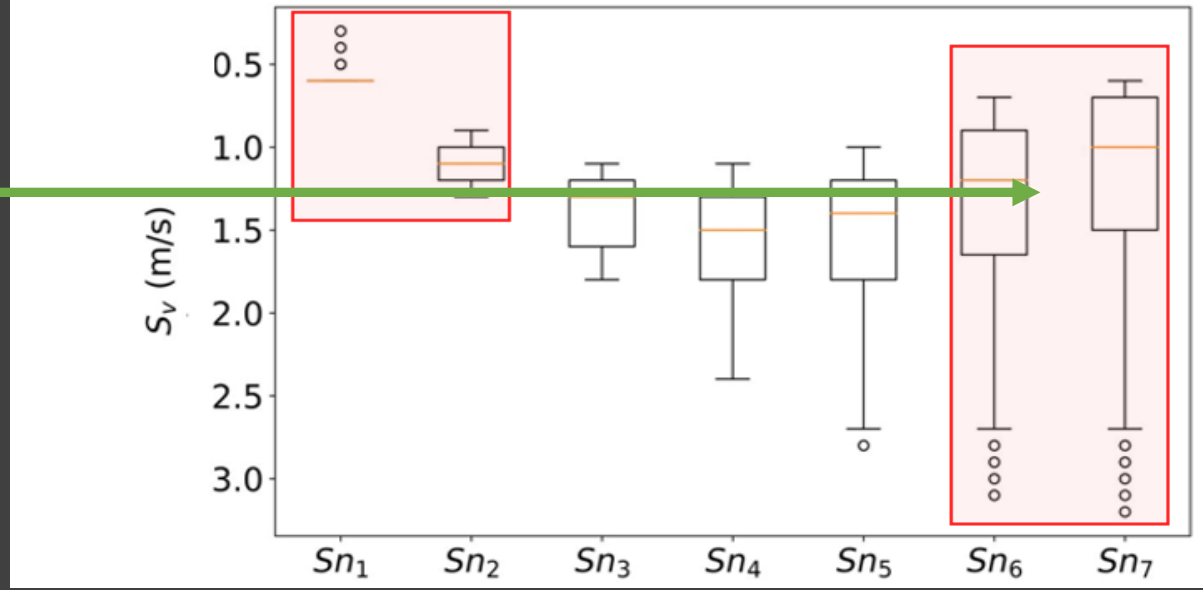
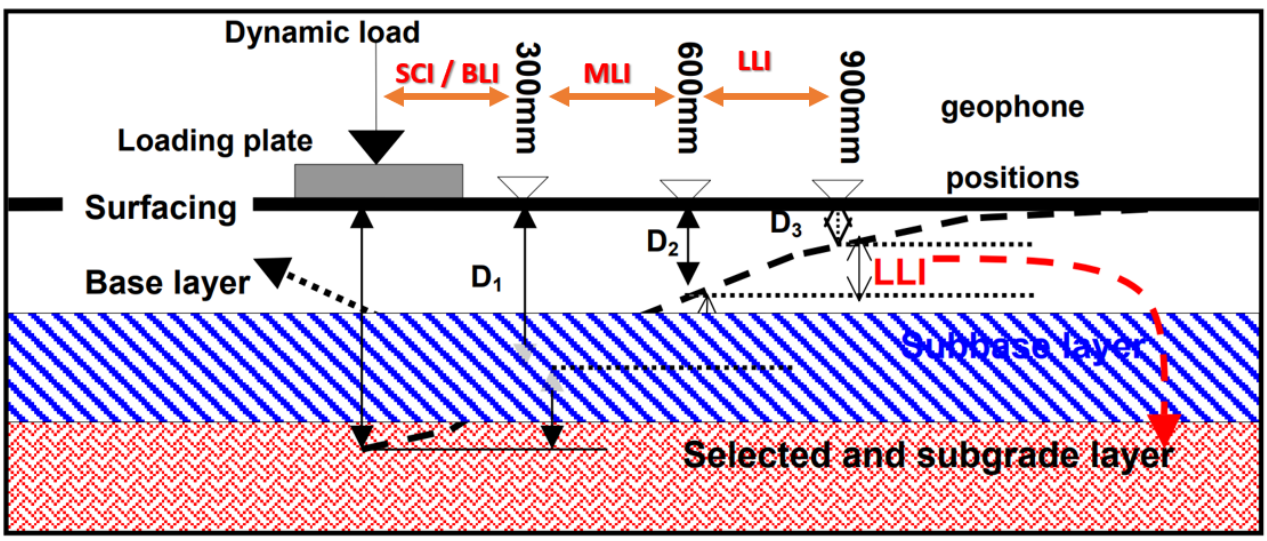
Layer (i)	Thickness (m)	Material	$E_i$ (MPa)	$\nu$	Interface	°C
1	0.06	HMA	7000	0.35	(1) bound	15
2	0.09	BC-g2	9300	0.35	(1) bound	15
3	0.09	BC-g2	9300	0.35	(1) bound	15
4	$\infty$	$M_R$	16-250	0.35	(1) bound	15



## TSD assumptions & observations

- ▶ Loading mechanism: Superposition
- ▶ TSD Reference Sensor: Uncertainty
- ▶ Sensor Positioning: Variability

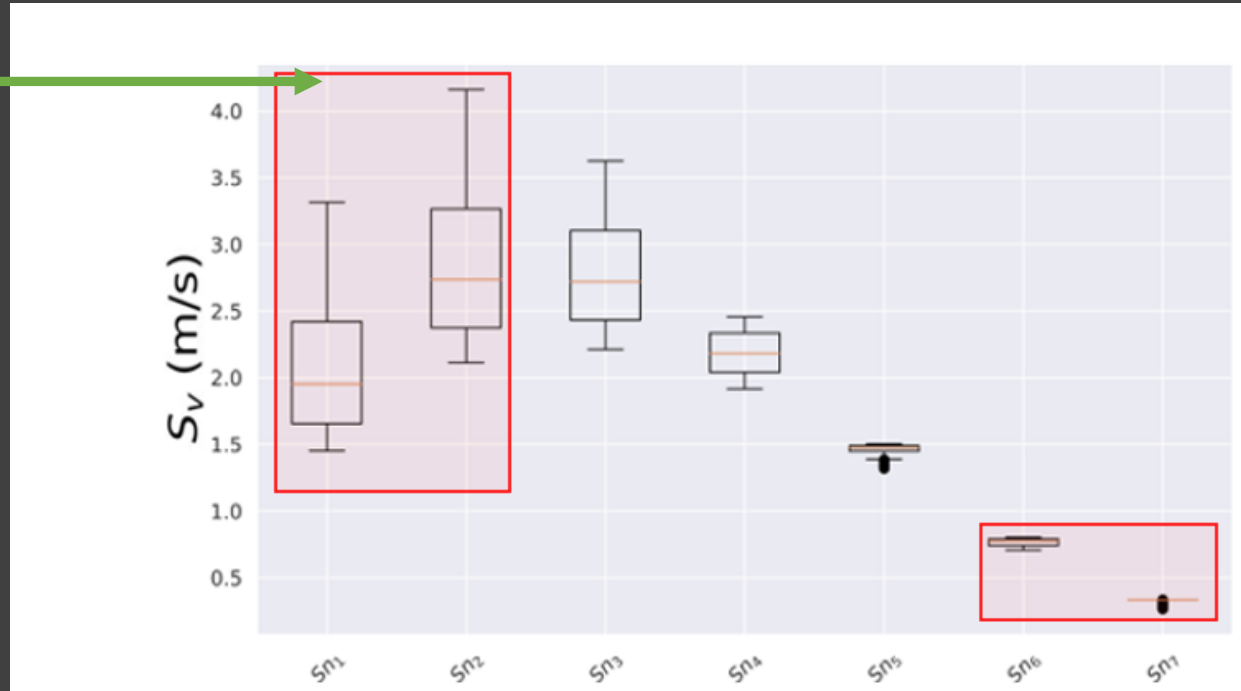




Deflection bowl parameter structural condition rating criteria for various pavement types

	Structural condition rating	Deflection bowl parameters				
		$D_0$ ( $\mu\text{m}$ )	RoC (m)	BLI ( $\mu\text{m}$ )	MLI ( $\mu\text{m}$ )	LLI ( $\mu\text{m}$ )
Granular base	Sound	<500	>100	<200	<100	<50
	Warning	500-750	50-100	200-400	100-200	50-100
	Severe	>750	<50	>400	>200	>100
Cementitious base	Sound	<200	>150	<100	<50	<40
	Warning	200-400	80-150	100-300	50-100	40-80
	Severe	>400	<80	>300	>100	>80
Bituminous base	Sound	<400	>250	<200	<100	<50
	Warning	400-600	100-250	200-400	100-150	50-80
	Severe	>600	<100	>400	>150	>80

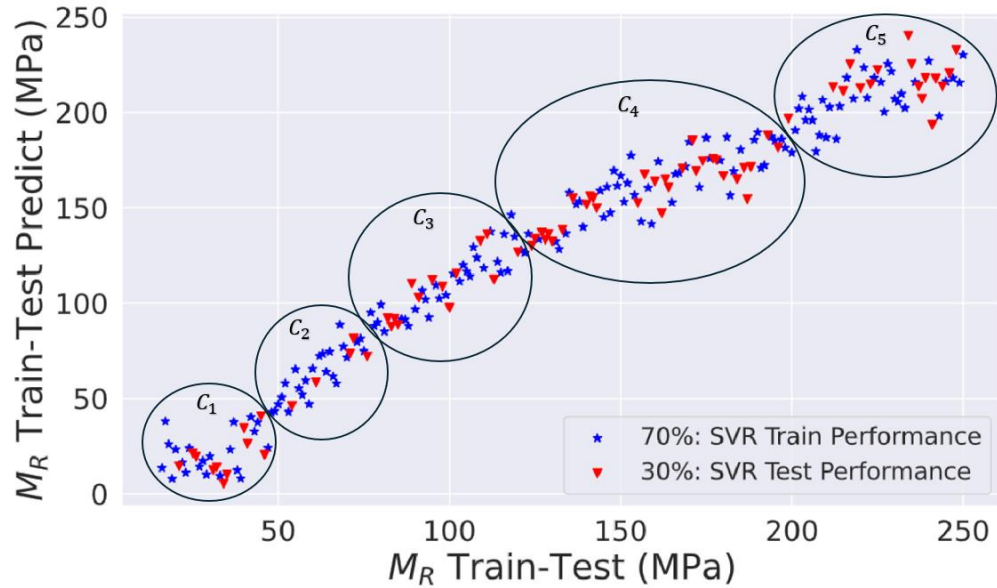
Note: These criteria can be adjusted to improve sensitivity of benchmarking.





# Inverse problem

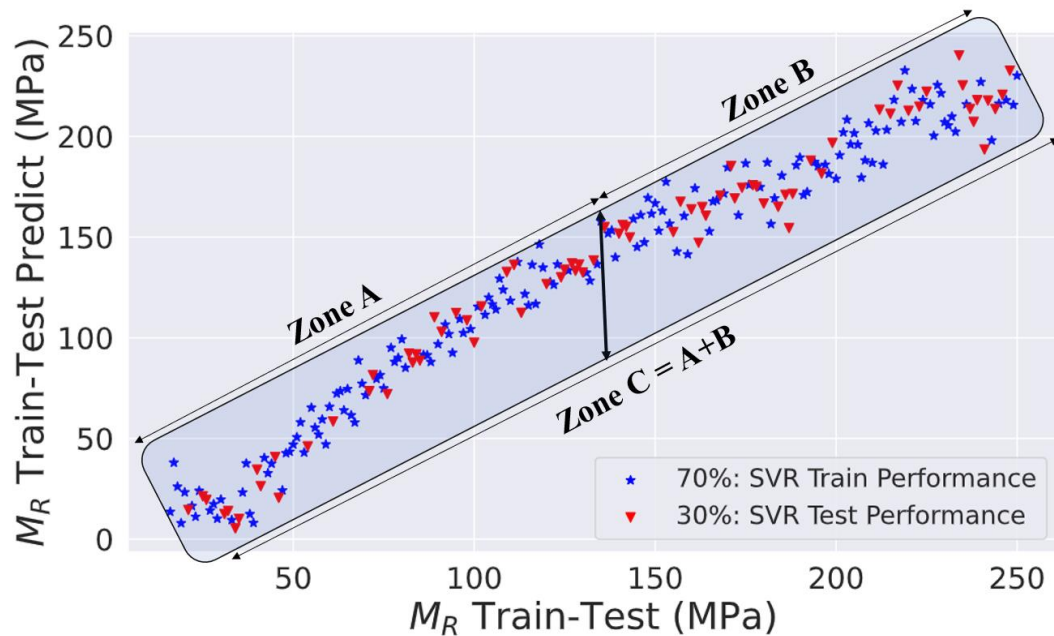
- Modulus estimation observations
- Advanced parametric study (optimization)



$M_R$ Value (MPa)	(16 - 49)	(50 - 79)	(80 - 119)	(120 - 199)	(200 - 250)
N° Class	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$

**(TTV) Framework:**

- ▶ **Generalizability** and **Robustness** test of the model
- ▶ Stratified Train-Test-Split: 70% training, 30% testing
- ▶ Five iterations with 5/10 fold cross-validation for accuracy



Regression analysis: Training Testing Validation Framework

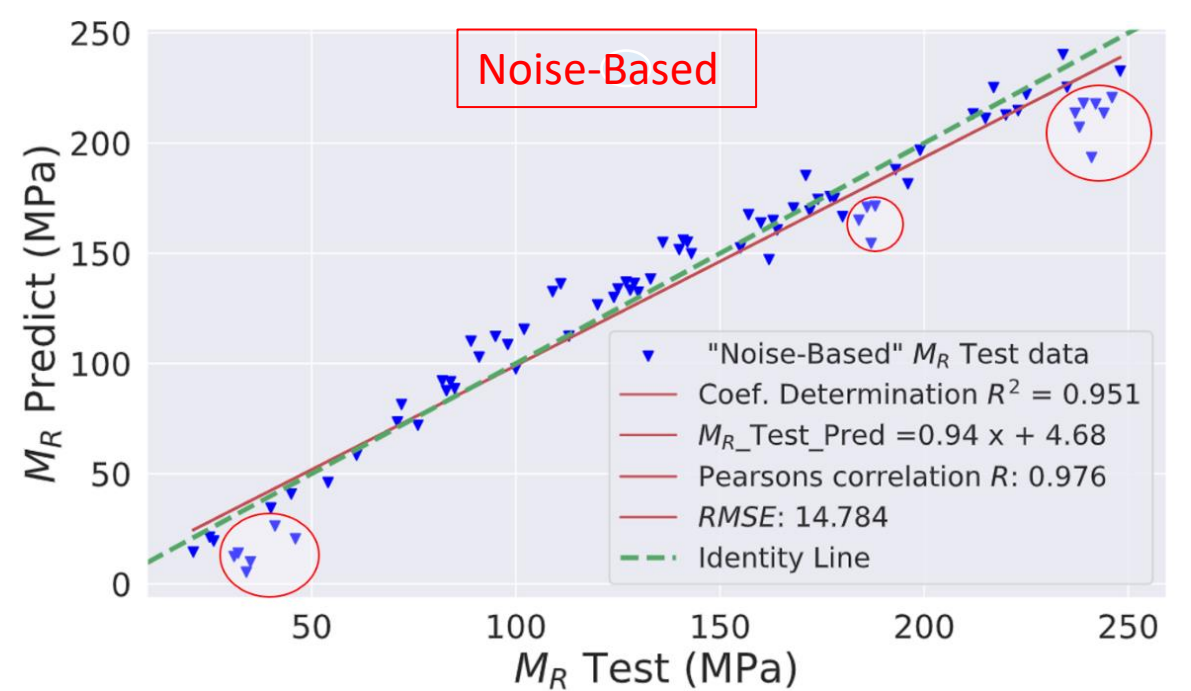
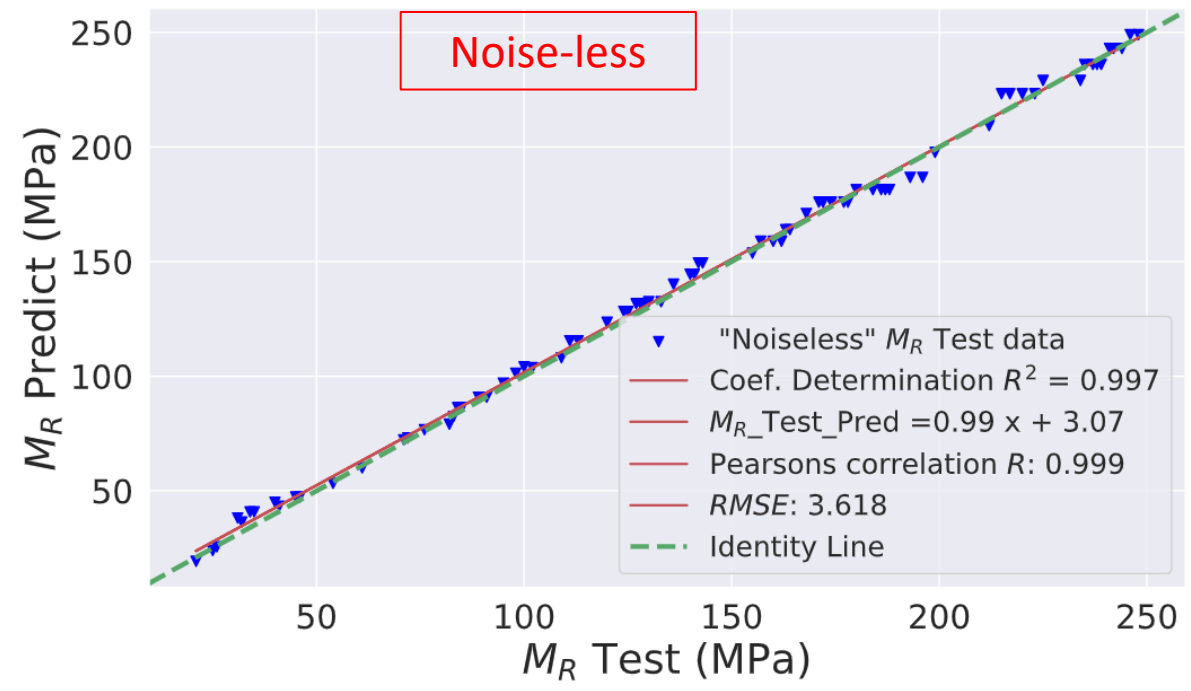
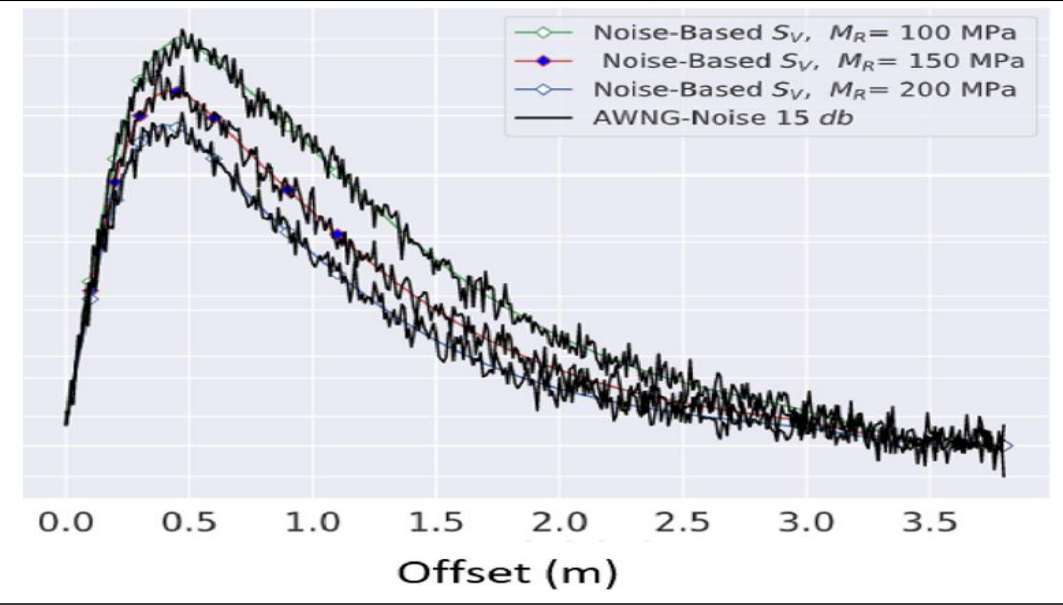
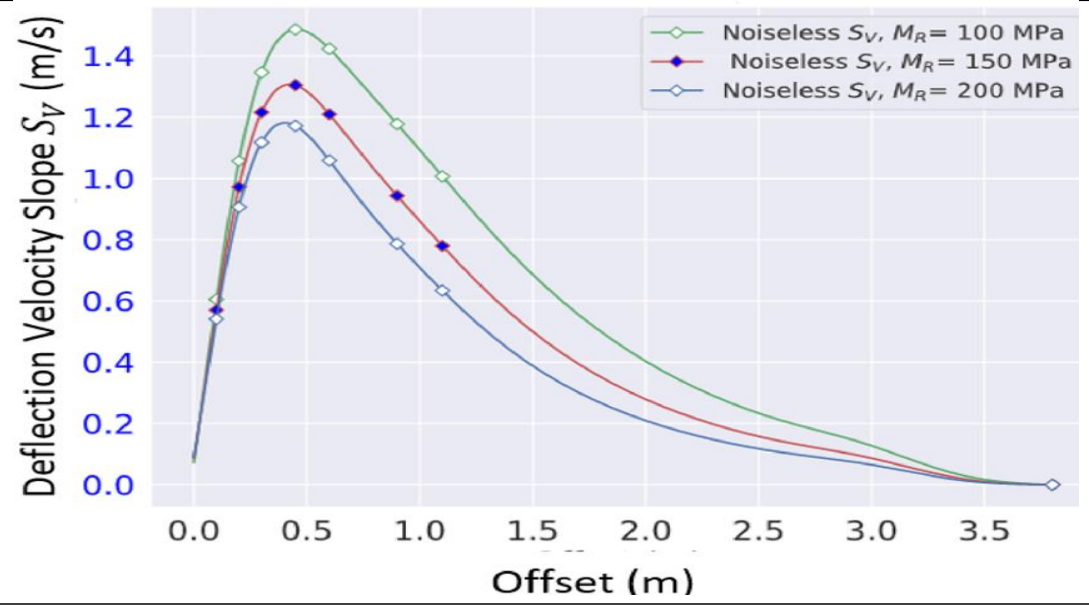
Iteration	Training Zone	Testing Zone	Testing Objective
1	[C] (70%)	[C] (30%)	Overall Performance
2	[A]	[B]	Highest band
3	[B]	[A]	Lowest band

# Numerical: Inverse problem

Regression

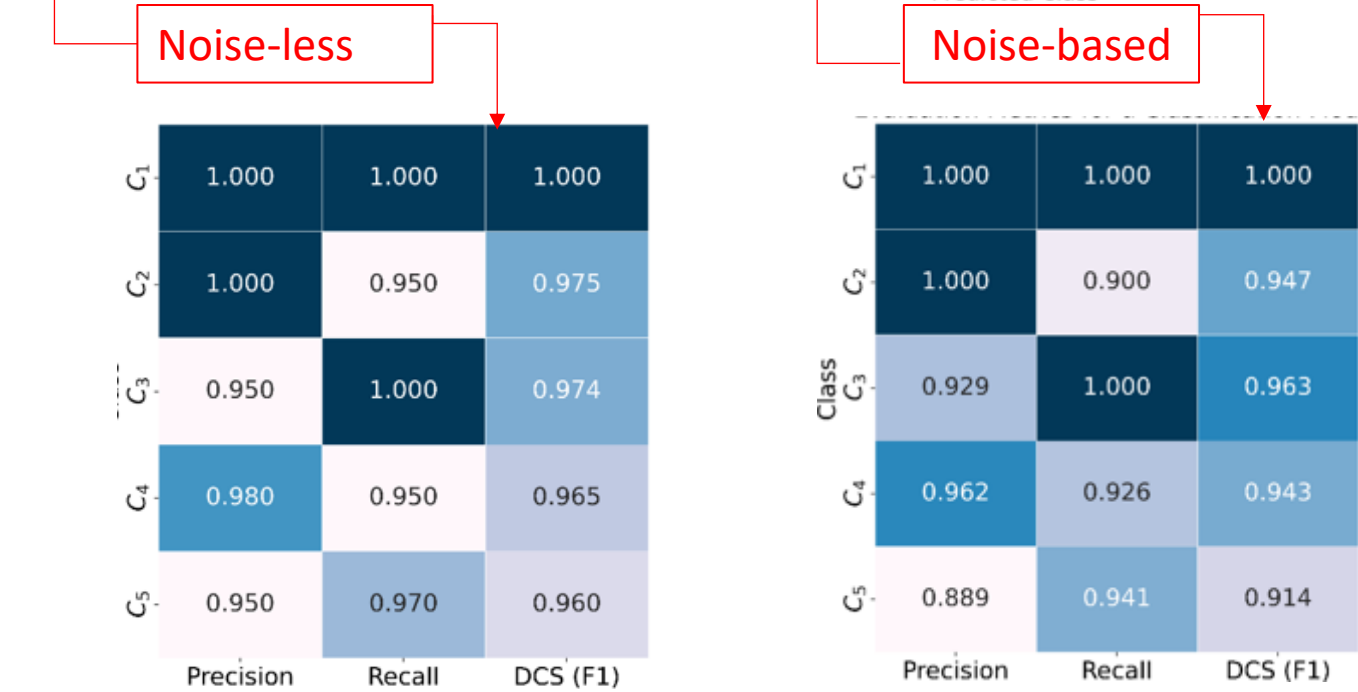
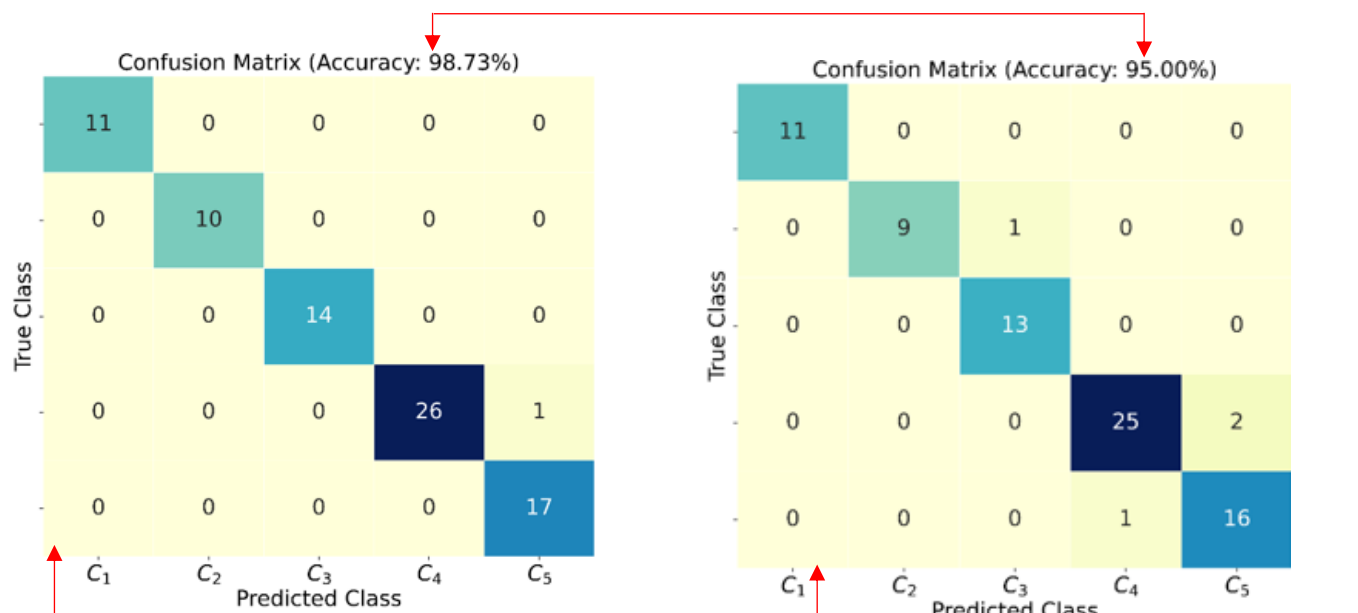
Classification

Optimization

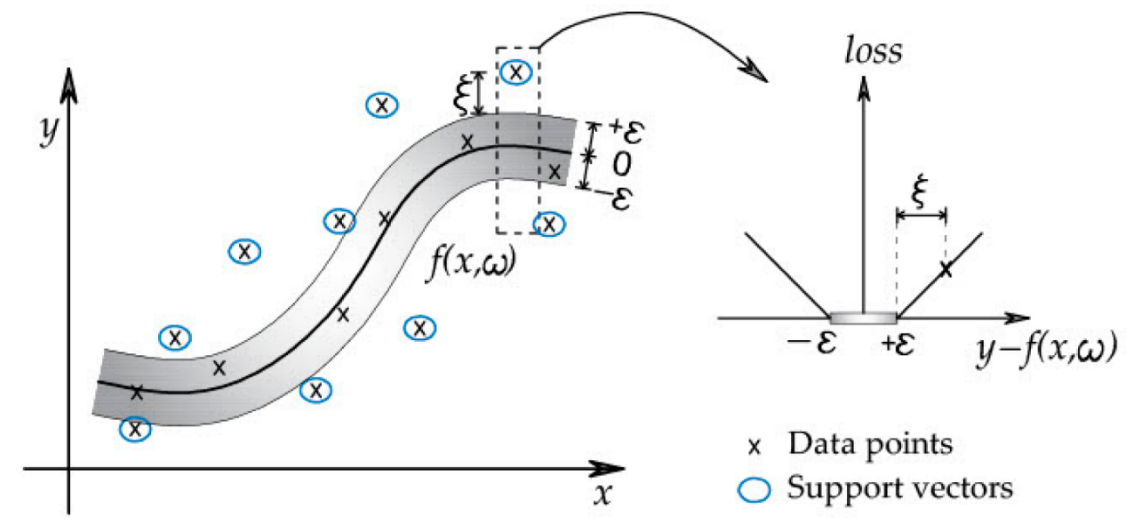
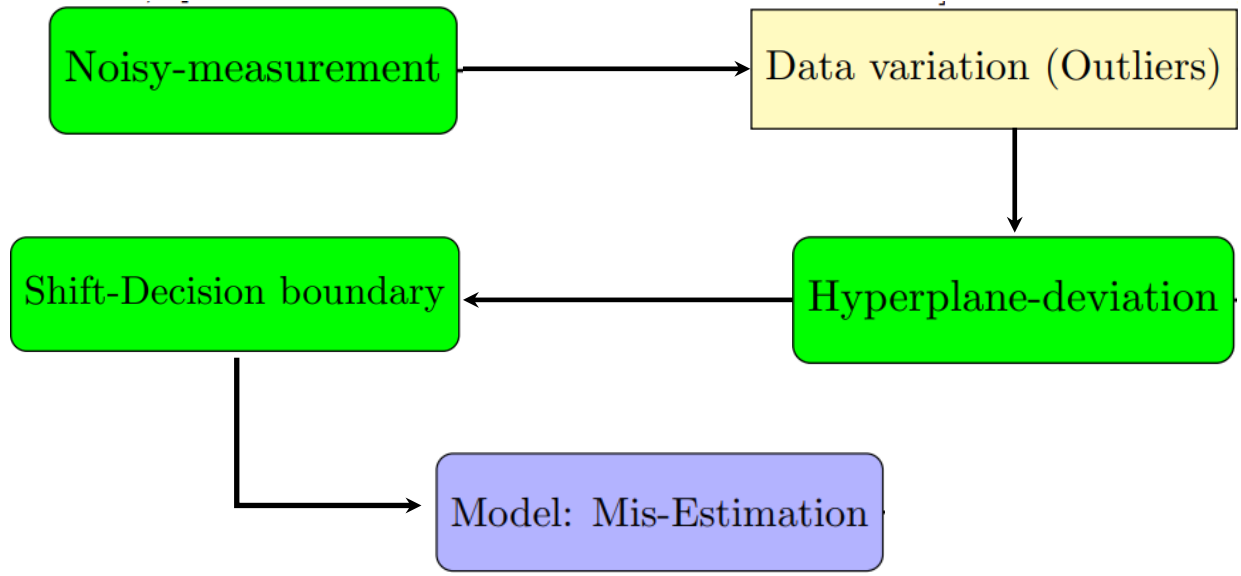


Calculation of evaluation metrics

Metric	Formula	Description
Precision	$\frac{TP}{TP+FP}$	Proportion of correctly identified positive cases
Recall	$\frac{TP}{TP+FN}$	Proportion of actual positive cases identified correctly
DSC (F1 score)	$\frac{2 \times TP}{2 \times TP + FP + FN}$	Harmonic mean of precision and recall



- ▶ Class (5) misclassifications : (High MPa)  
**Relatively less critical**
- ▶ Class (2) misclassifications: (Lower-MPa)  
**More critical**
- ▶ Why the misclassification happened?



SVM GridSearchCV Scikit-learn hyperparameter tuning

Parameter	Flexibility	Accuracy	Functionality
$\uparrow C$	$\downarrow$	$\uparrow$	Regularization: Balance Over/underfitting
$\uparrow \gamma$ (gamma)	$\downarrow$	$\uparrow$	Control outliers impact on decision boundaries
$\uparrow \epsilon$ (epsilon)	$\uparrow$	$\downarrow$	Tolerance margin without error-penalty

SVM

Parameter	Noise-Less		Noise-Based	
	Initial Values Range	Optimized	Initial Values Range	Optimized
Kernel	Linear/Poly/RBF/Sigmoid	RBF	Linear/Poly/RBF/Sigmoid	RBF
$C$	[0.1 ; 1000]	100	[0.1 ; 1000]	10
$\gamma$	[0.01 ; 100]	1	[0.01 ; 100]	0.5
$\epsilon$	[0.001 ; 10]	0.01	[0.001 ; 10]	0.2

# Sensitivity analysis

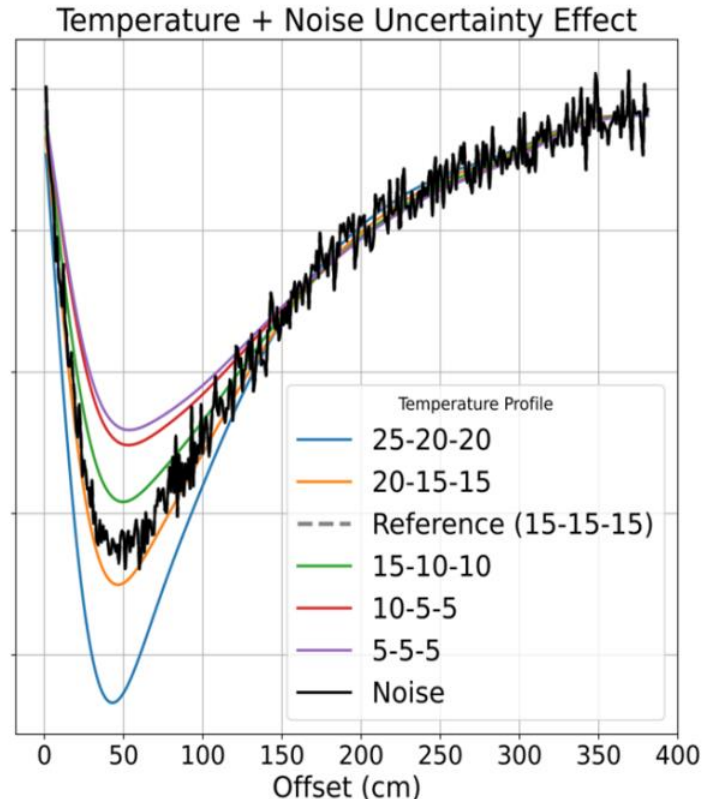
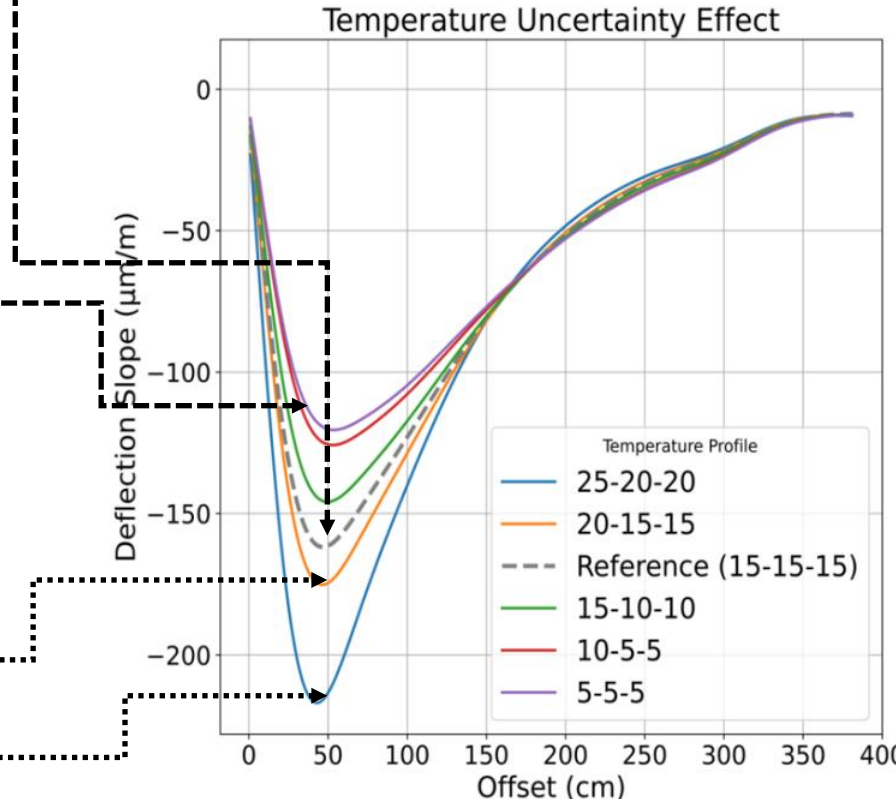
- Correlation analysis ( $\Theta \text{ } ^\circ\text{C} \propto E_i \propto D_S$ )
- Temperature uncertainty investigations

Layer (i)	Thickness (m)	Material	$E_i$ (MPa)	$\nu$	Interface	$^{\circ}\text{C}$
1	0.06	HMA	7000	0.35	(1) bound	15
2	0.09	BC-g2	9300	0.35	(1) bonded	15
3	0.09	BC-g2	9300	0.35	(1) bonded	15
4	$\infty$	$M_R$	16-250	0.35	(1) bonded	15

Correlation Analysis:  $\Theta \text{ } ^{\circ}\text{C} \propto E_i \propto D_S$

- Temperature **uncertainty** influence
- **Experimental** representative cases

Temp-Profil $\Theta \text{ } ^{\circ}\text{C}$			$E_i$			$M_R$
$L_1$	$L_2$	$L_3$	$E_1$	$E_2$	$E_3$	125
5	5	5	11405	15090	15090	125
10	5	5	9310	15090	15090	125
15	10	10	7000	11880	11880	125
20	15	15	4690	9300	9300	125
25	20	20	3245	6120	6120	125



$\theta$ °C			$E_i$ (MPa)			$M_R$	$\Delta$
$L_1$	$L_2$	$L_3$	$E_1$	$E_2$	$E_3$	(MPa)	%
-	-	-	-	-	-	139	11.2%
-	-	-	-	-	-	136	8.8%
-	-	-	-	-	-	116	7.2%
-	-	-	-	-	-	117	6.4%
-	-	-	-	-	-	102	18.4%

N/A

$\theta$ °C			$E_i$ (MPa)			$M_R$	$\Delta$
$L_1$	$L_2$	$L_3$	$E_1$	$E_2$	$E_3$	(MPa)	%
5	-	-	11405	-	-	136	8.8%
10	-	-	9310	-	-	134	7.2%
15	-	-	7000	-	-	118	5.6%
20	-	-	4690	-	-	121	3.2%
25	-	-	3245	-	-	105	16%

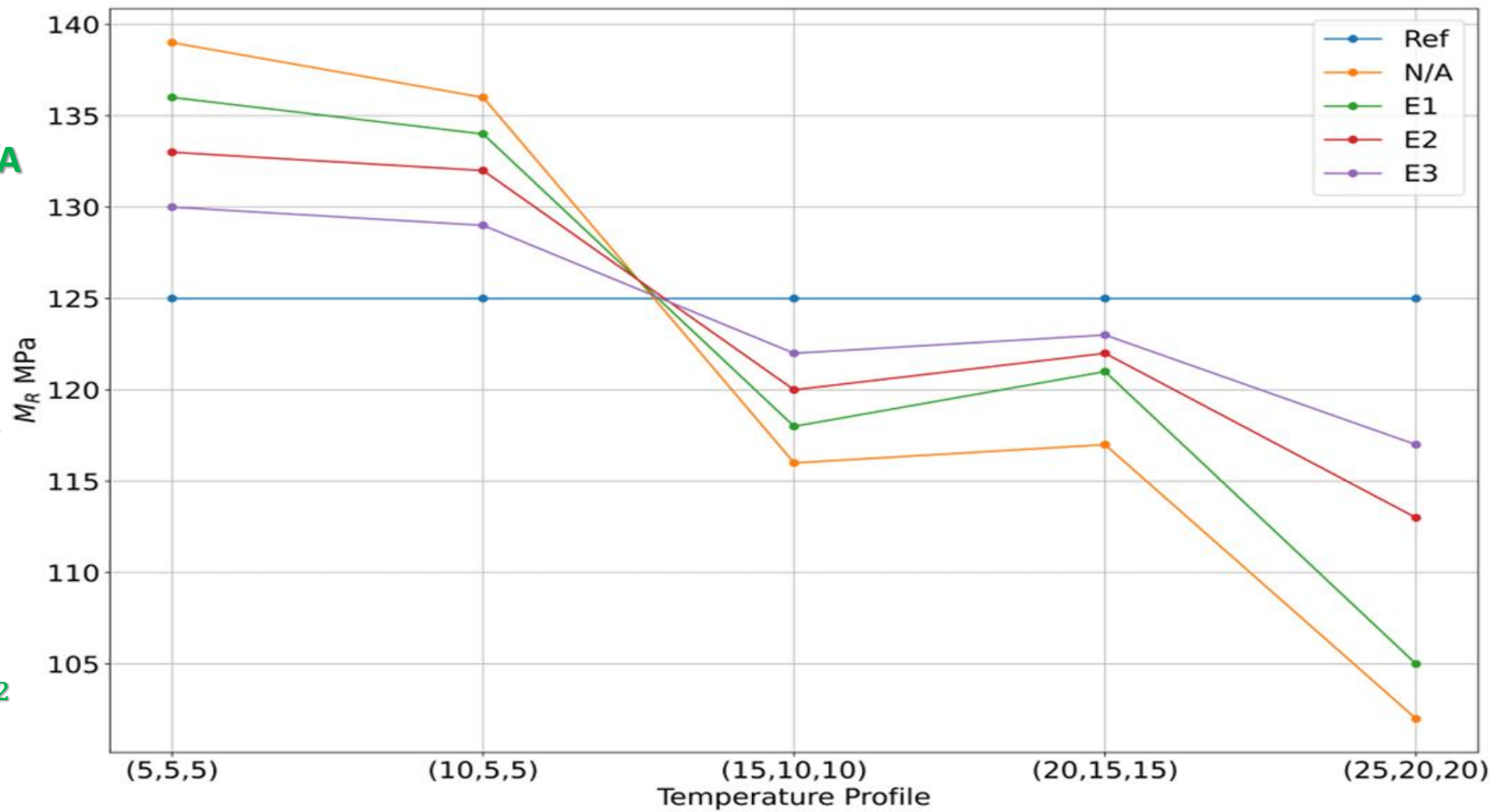
$E_1$

$\theta$ °C			$E_i$ (MPa)			$M_R$	$\Delta$
$L_1$	$L_2$	$L_3$	$E_1$	$E_2$	$E_3$	(MPa)	%
-	5	-	-	15090	-	133	6.4%
-	5	-	-	15090	-	132	5.6%
-	10	-	-	11880	-	120	4%
-	15	-	-	9300	-	122	2.4%
-	20	-	-	6120	-	113	9.6%

$E_2$

$\theta$ °C			$E_i$ (MPa)			$M_R$	$\Delta$
$L_1$	$L_2$	$L_3$	$E_1$	$E_2$	$E_3$	(MPa)	%
-	-	5	-	-	15090	130	4%
-	-	5	-	-	15090	129	3.2%
-	-	10	-	-	11880	122	2.4%
-	-	15	-	-	9300	123	1.6%
-	-	20	-	-	6120	117	6.4%

$E_3$



► Layer effects:

Knowledge of known pavement properties (temperature), enhances soil modulus estimation



# Experimental validation

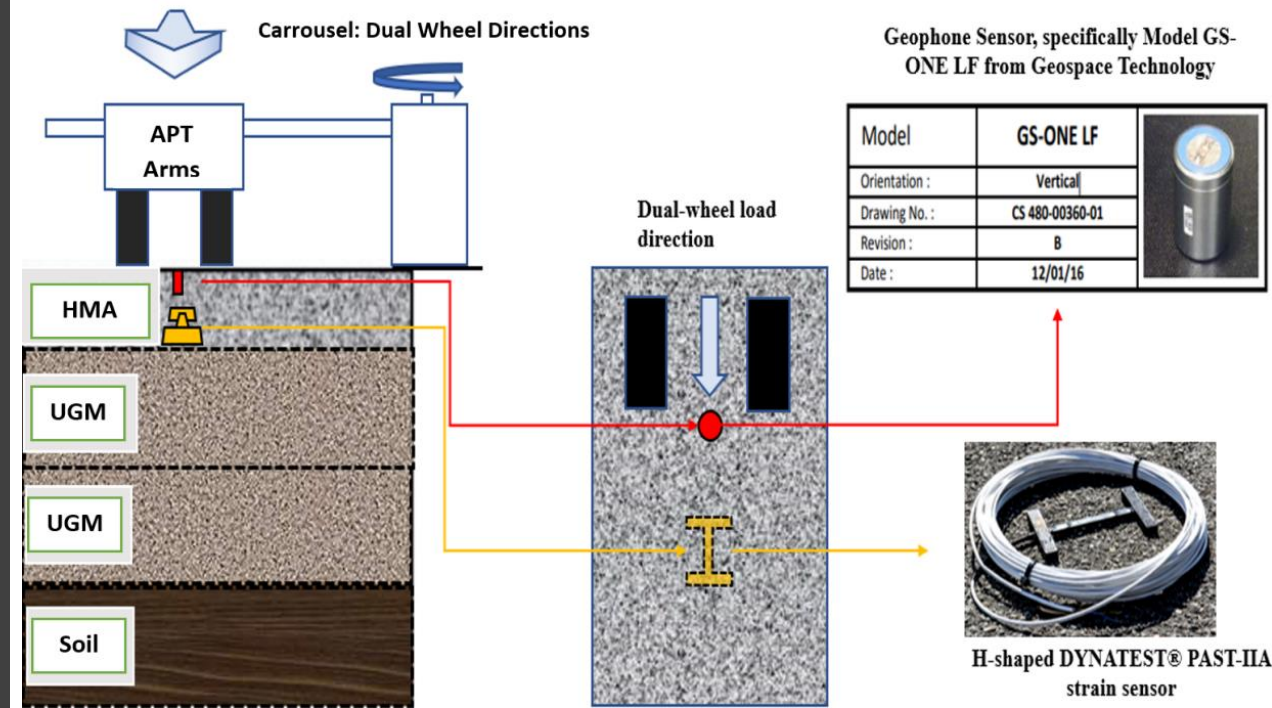
- Data acquisition & preprocessing
- Feature engineering (Global to Local)

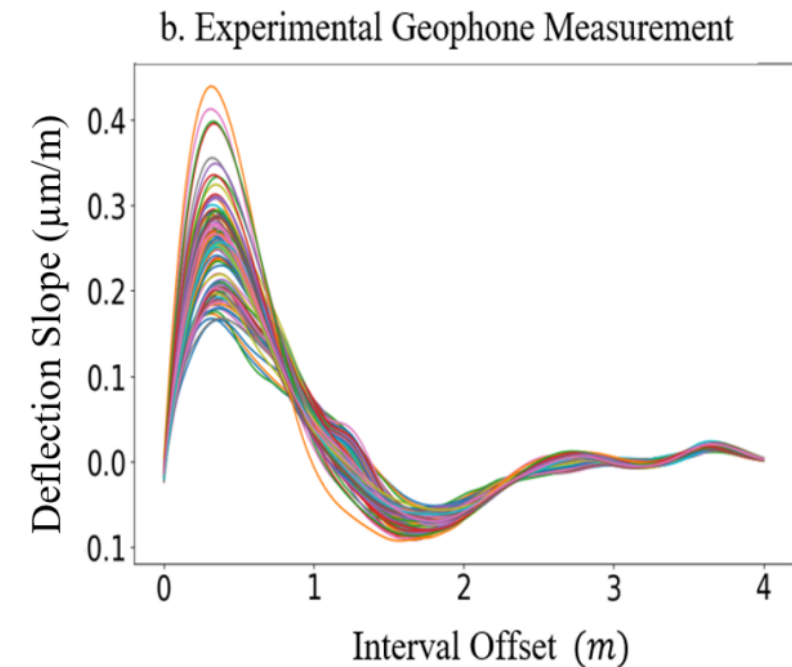
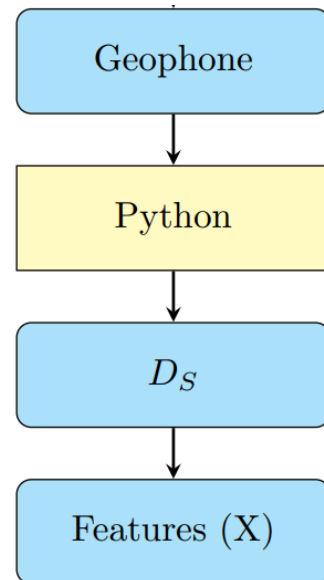
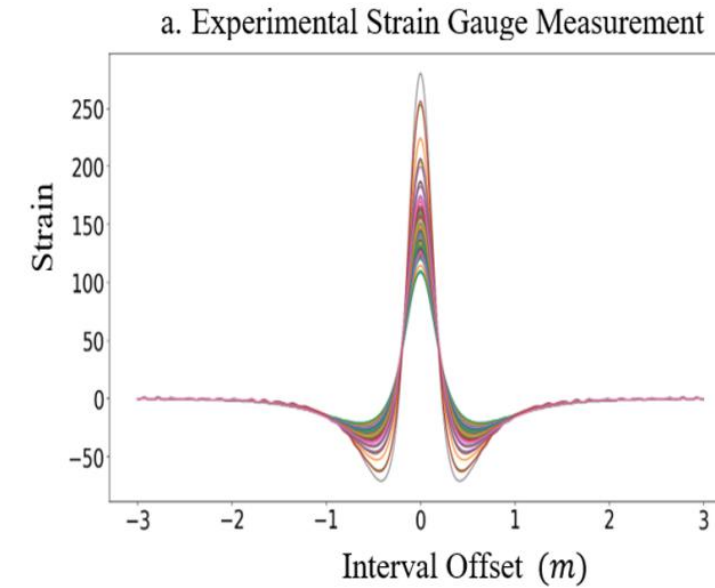
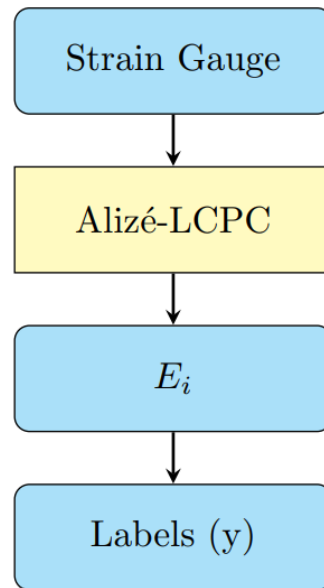


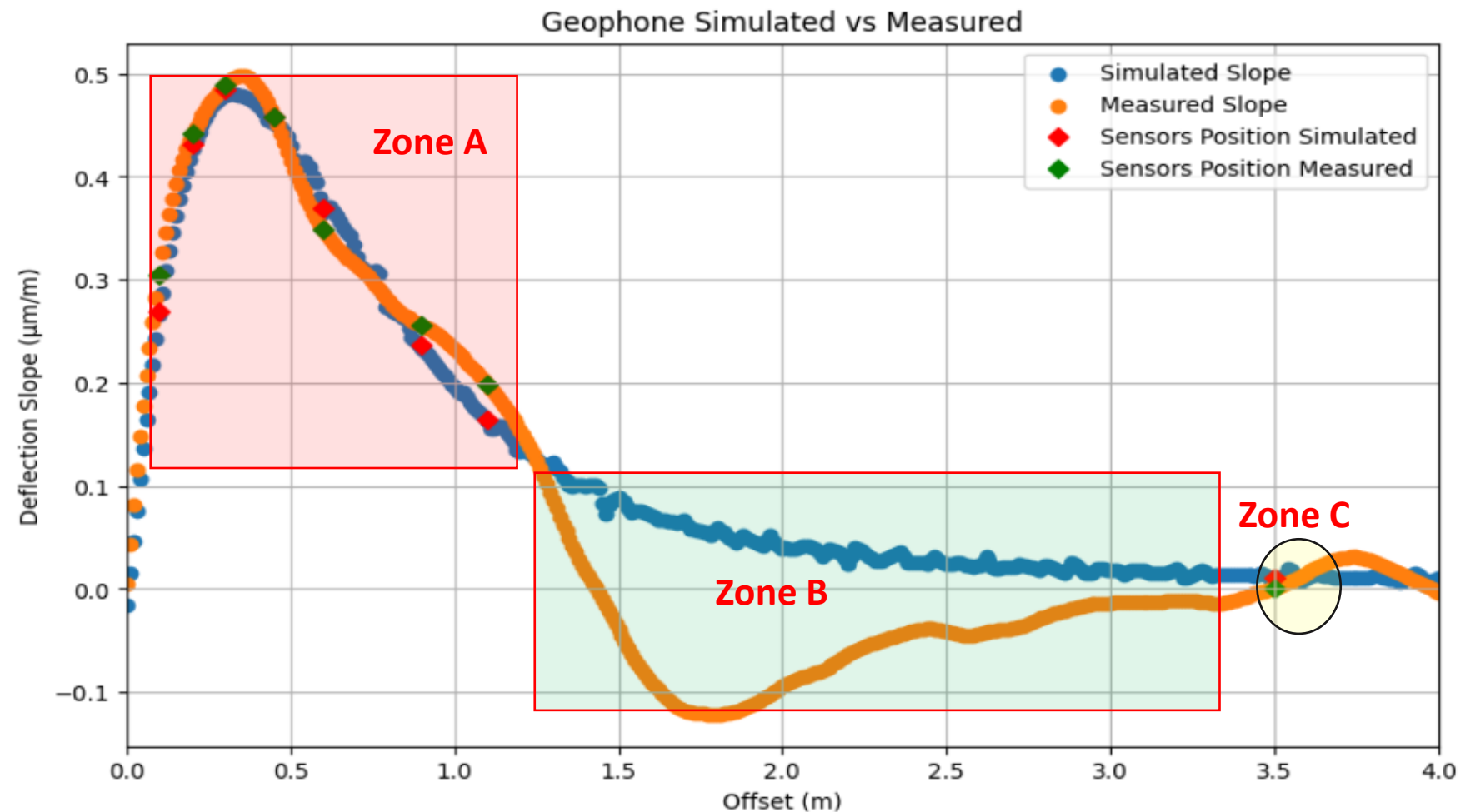
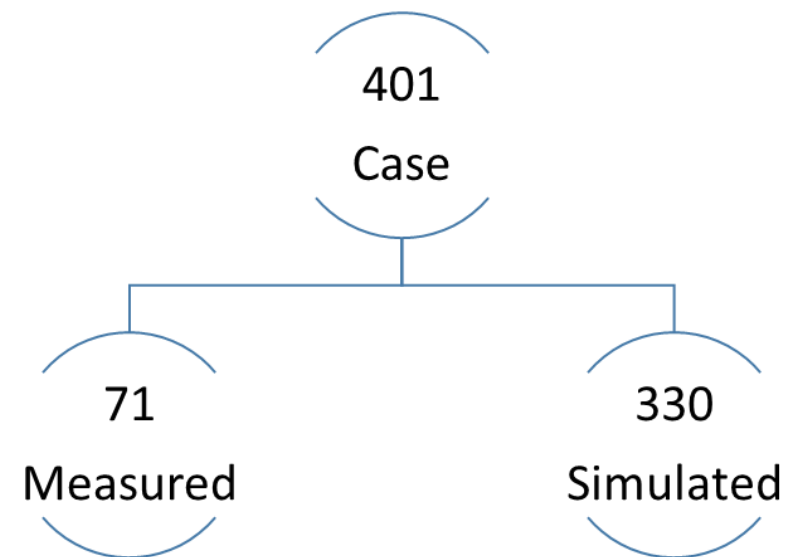
## Data Acquisition

- Location: Univ Gustave Eiffel, fatigue carousel
- Testing method: Accelerated Pavement Test (APT)
- Project: I-Street project
- Instruments: Geophone and Strain Gauge
- Purpose: Simulate real-world traffic conditions
- Bottom line: Collect fatigue data for pavement analysis

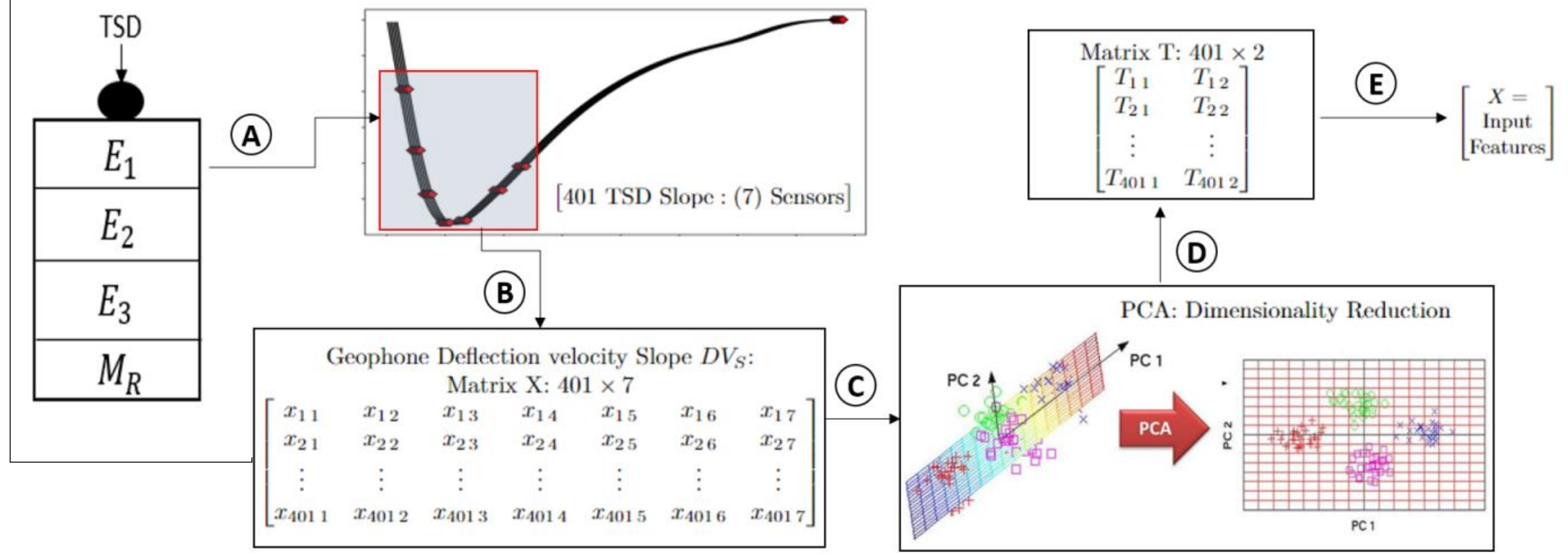
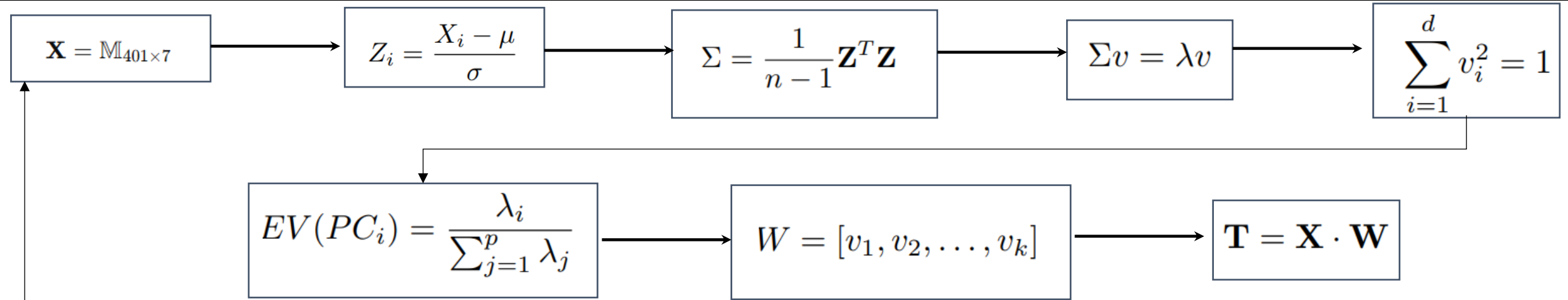
$L_i$	$h$ (m)	Material	$E_i$ (MPa)	$\nu$	Interface	(°C)
1	0.10	HMA	2000 - 10000	0.35	(1) bound	5 - 35
2	0.05	UGM	126	0.35	(1) bound	5 - 35
3	0.25	UGM	126	0.35	(1) bound	5 - 35
4	$\infty$	$M_R$	104	0.35	(1) bound	5 - 35

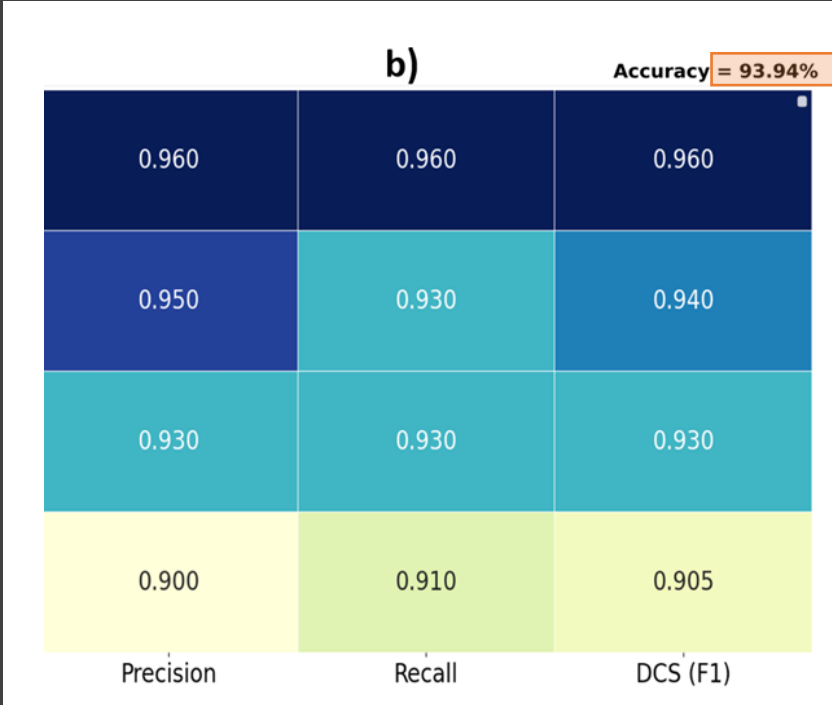
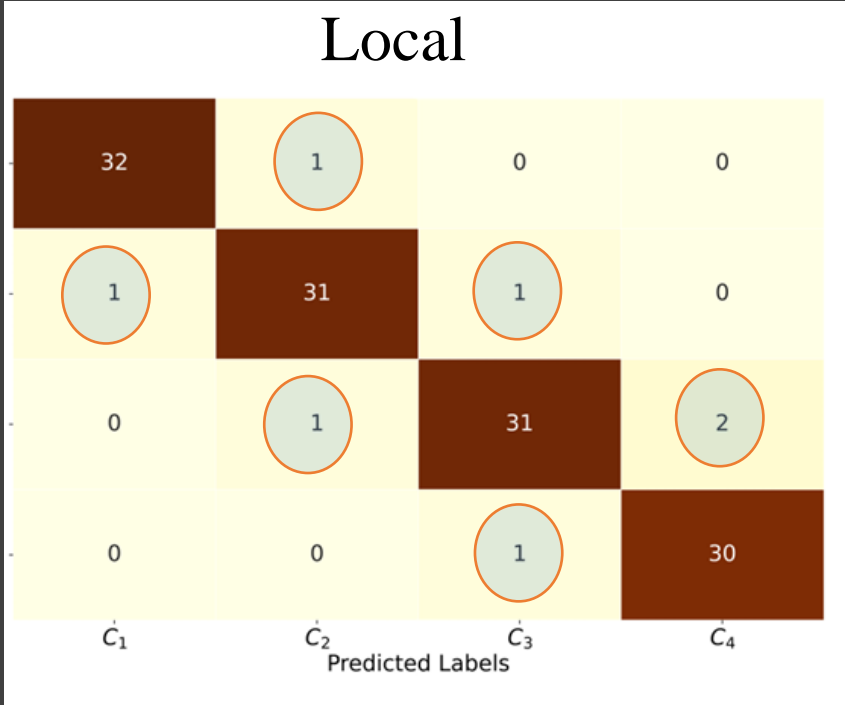
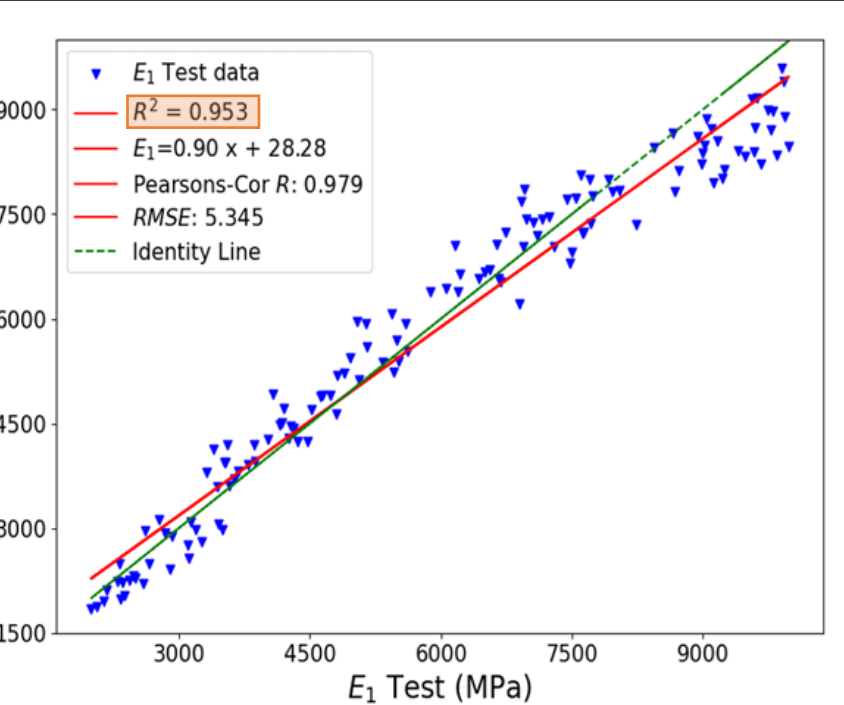
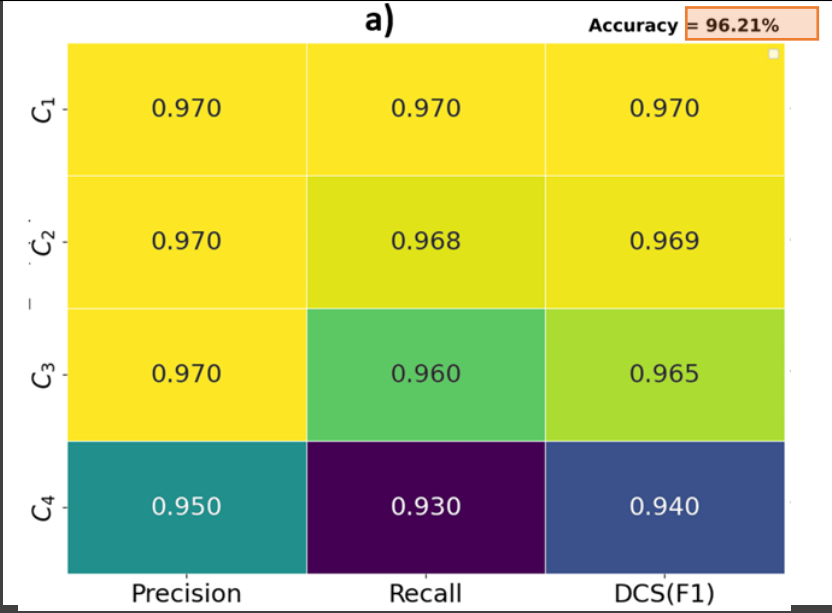
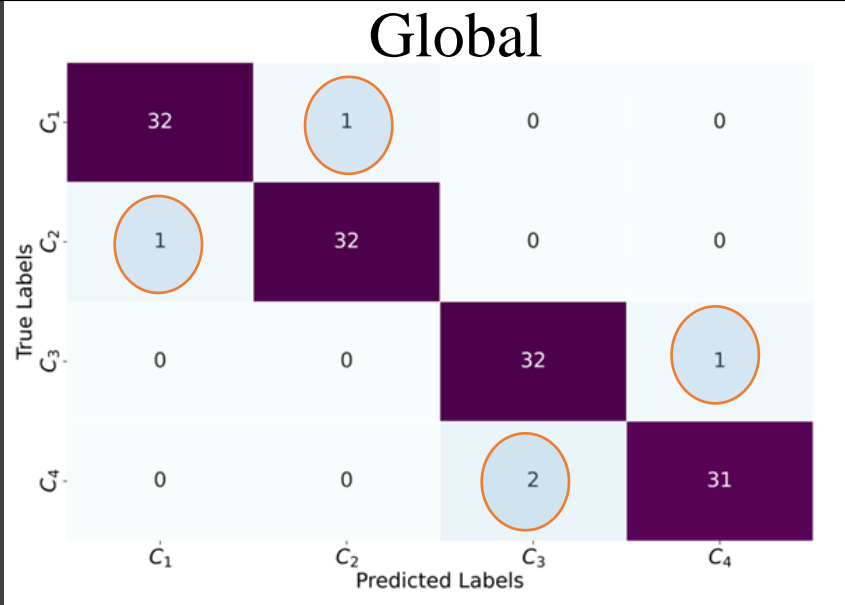
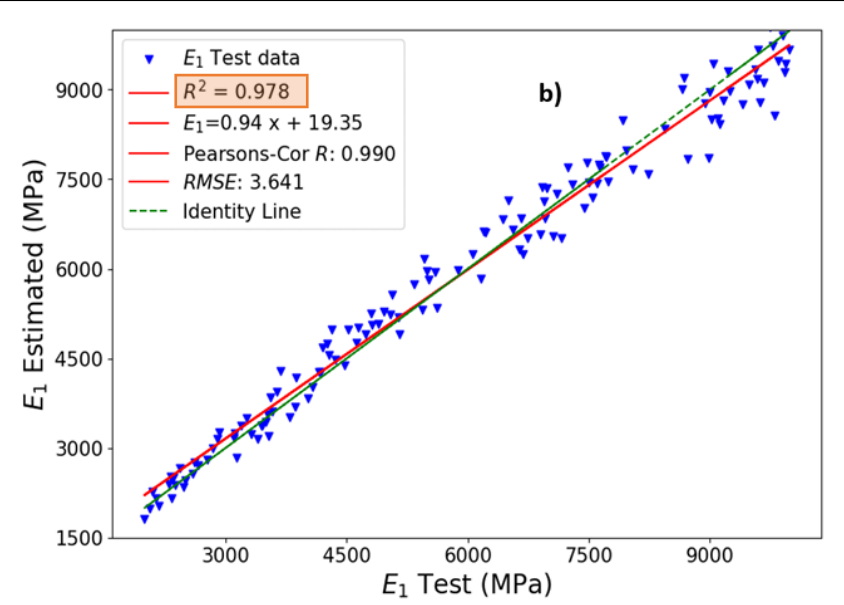




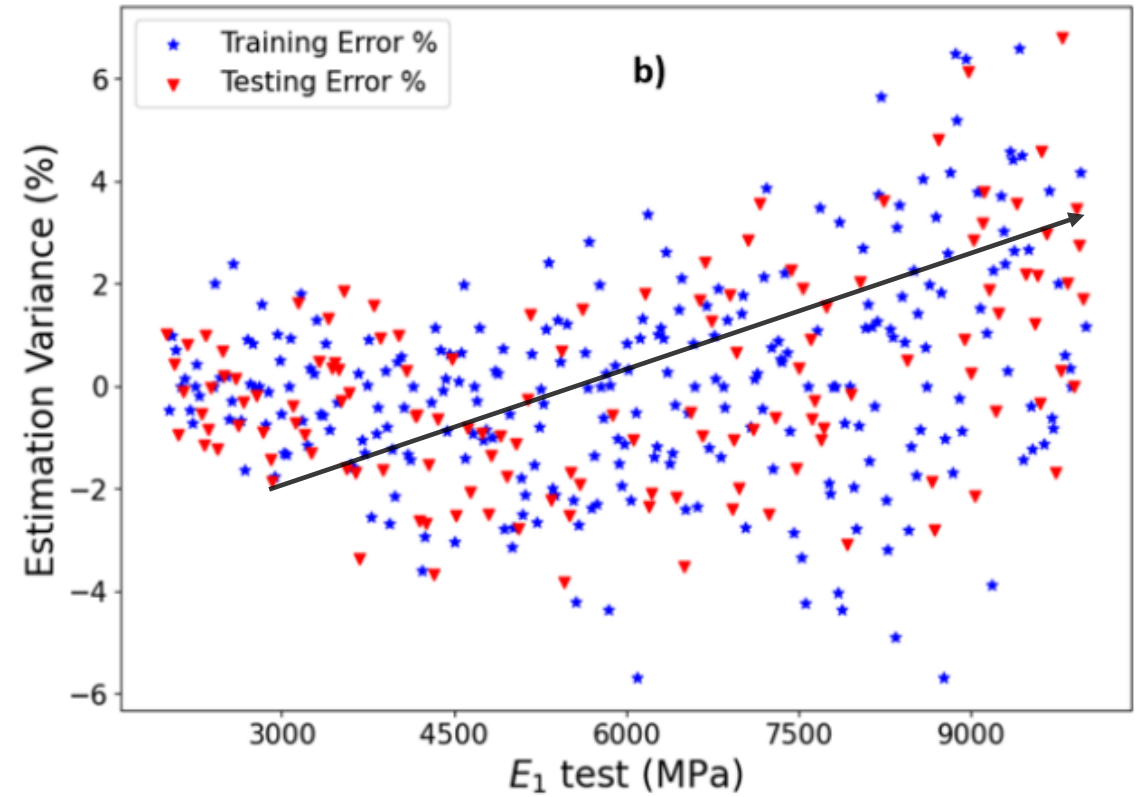
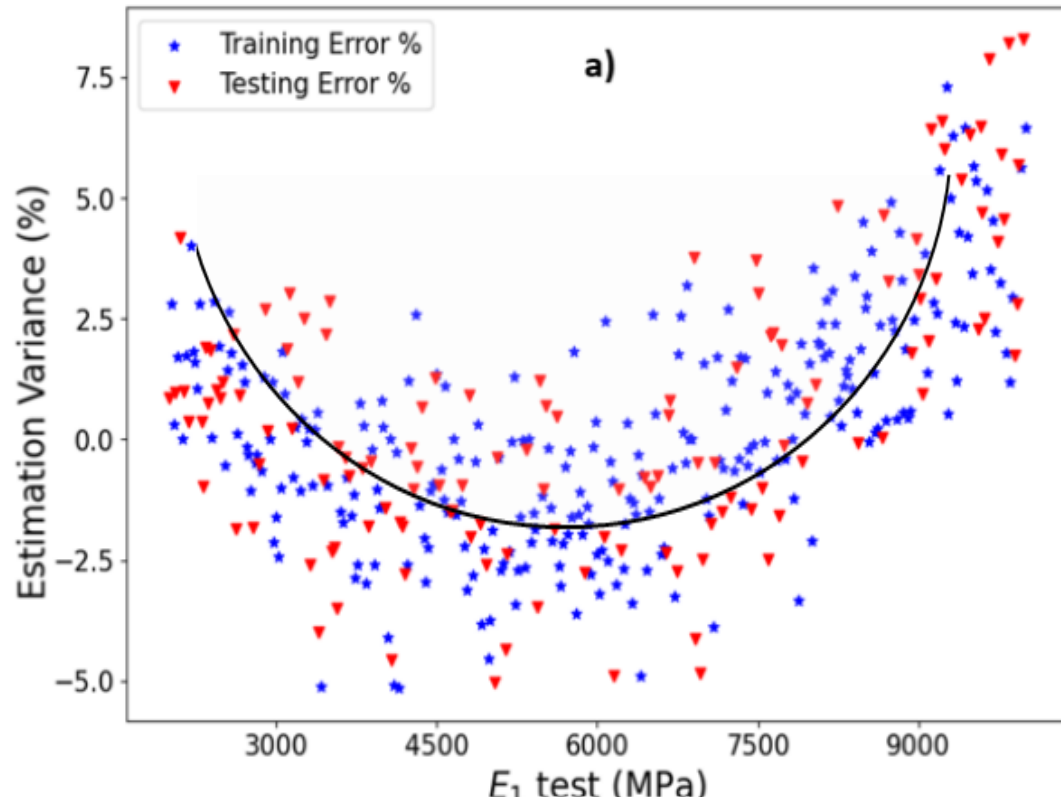


$$\lim_{\text{slope} \rightarrow \infty} \frac{1}{\text{slope}} = 0$$





Variance analysis a) Local b) Global



Factor	Local (PCA)	Global
Accuracy	Slightly ↓	↑
Data Efficiency	↑ (faster processing)	↓ (computation-intensive)
Generalizability (limited data)	Potentially ↑	Potentially ↓
Strength	Balancing accuracy and efficiency	Mitigate uncertainty

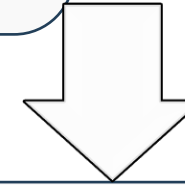
# Conclusion

- Challenges and limitations
- Perspective (future Work)
- Valorization & outreach



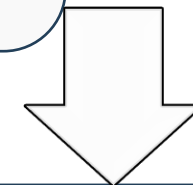
► **Numerical Forward Model :**

SCI, MLI, LLI, and are key pavement indices, incorporating other sensors with proportional significance is essential for a more accurate structural assessment



► **Numerical Inverse problem :**

- I. ML effectively estimates soil modulus from the deflection slope
- II. Noise impacts measurement accuracy, necessitating noise reduction techniques
- III. Incorporating temperature thermal model leads to enhancing modulus estimation



► **Experimental validation :**

- I. Experimental approach validates the accuracy and reliability of the numerical model
- II. Local approach balances accuracy, while offering computational efficiency

## Research limitations and challenges

- Limited labeled data for supervised learning
- Applicability across diverse environments (Generalizability)

## Future work :

- Validate with real TSDDs measurement data
- Explore TSD applications for concrete and composite pavements
- Vertical temperature analysis and thermal modeling
- Integrate TSD and Ground Penetrating Radar (GPR) data for (Thickness, Interface...)

# General conclusion

Conclusion	Limitation	Perspective	Valorization
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## Journal articles



## International conferences



11th Young Researchers Seminar  
May 15-17, 2023 – Lisbon, Portugal



## Scientific outreach (vulgarization)



## Career perspective



R&D Project Manager

## National conferences



## Research visits



## LIST OF PUBLICATIONS

- [1] A. Abdelmuhsen et al. “ML-based Model for Numerical Pavement Elastic Modulus Estimation Using TSD Deflection Slope Data”. In: *Discover Applied Sciences* (2024). DOI: SubmissionID:1dcf31a2-54f4-4780-820c-4174ec74bdde. URL: <https://submission.springernature.com>.
- [2] A. Abdelmuhsen et al. “On the variants of SVM method for the estimation of soil elastic modulus from TSD model: Numerical parametric study”. In: *Transportation Engineering* 13 (2023), p. 100187. ISSN: 2666-691X. DOI: <https://doi.org/10.1016/j.treng.2023.100187>. URL: <https://www.sciencedirect.com/science/article/pii/S2666691X23000271>.
- [3] Abdelgader Abdelmuhsen et al. “Database Construction based upon Numerical Modelling of Pavement Deflection Behaviour under the Traffic Speed Deflectometer”. In: *25e Congrès Français de Mécanique*. 2022.
- [4] Abdelgader Abdelmuhsen et al. “Machine Learning-based modelling for numerical evaluation of the traffic speed deflectometer performance”. In: *YRS2023-11th Young Researchers Seminar*. Zenodo. 2023.
- [5] Abdelgader Abdelmuhsen et al. “ML-Based Model for the Estimation of the Pavement Elastic Modulus via Deflection”. In: *Transport Research Arena (TRA)*. 2024.
- [6] Abdelgader Abdelmuhsen et al. *Numerical modeling of pavement deflection behavior under The Traffic Speed Deflectometer*. Version V1. 2024. DOI: 10.57745/QNUCI6. URL: <https://doi.org/10.57745/QNUCI6>.

# Annex

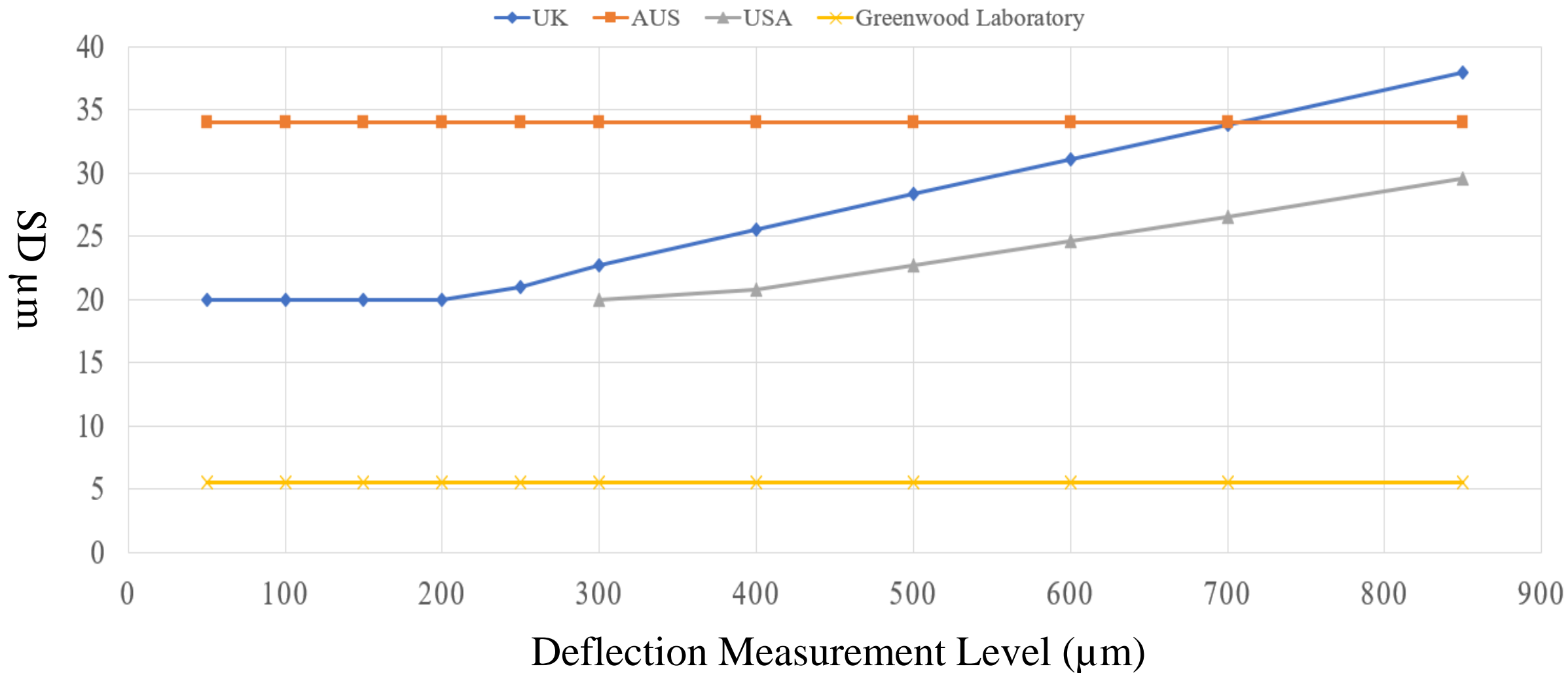
- Repeatability test (Noise level)
- Geophone Signal Processing
- Principle Components Analysis

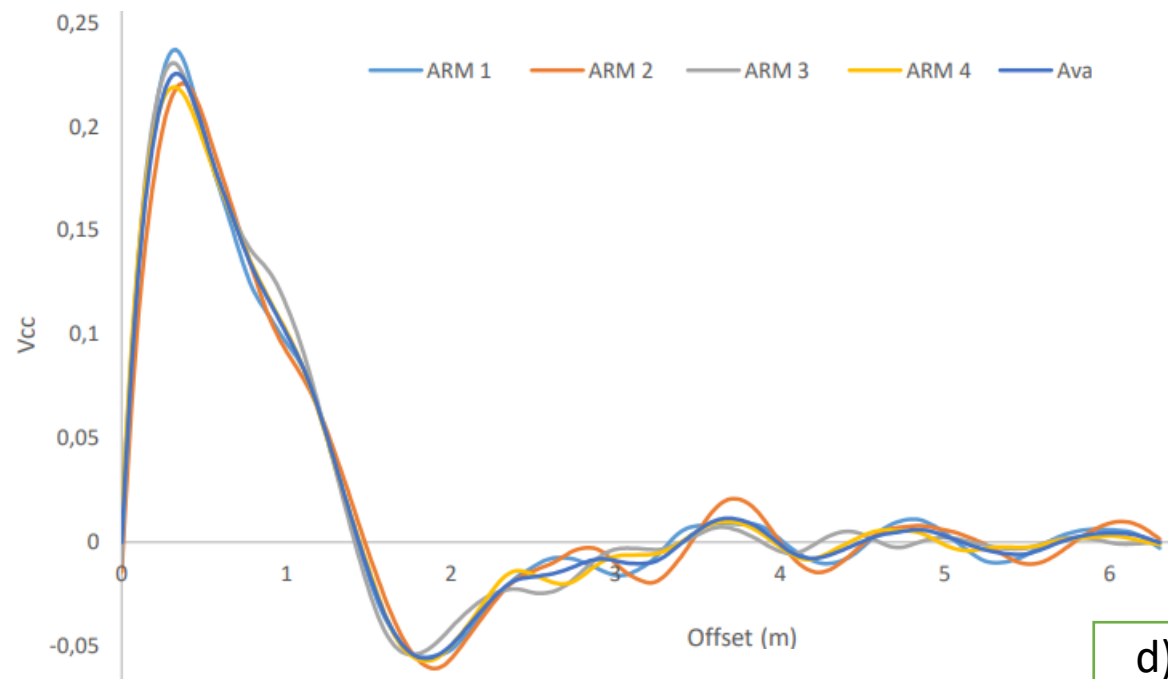
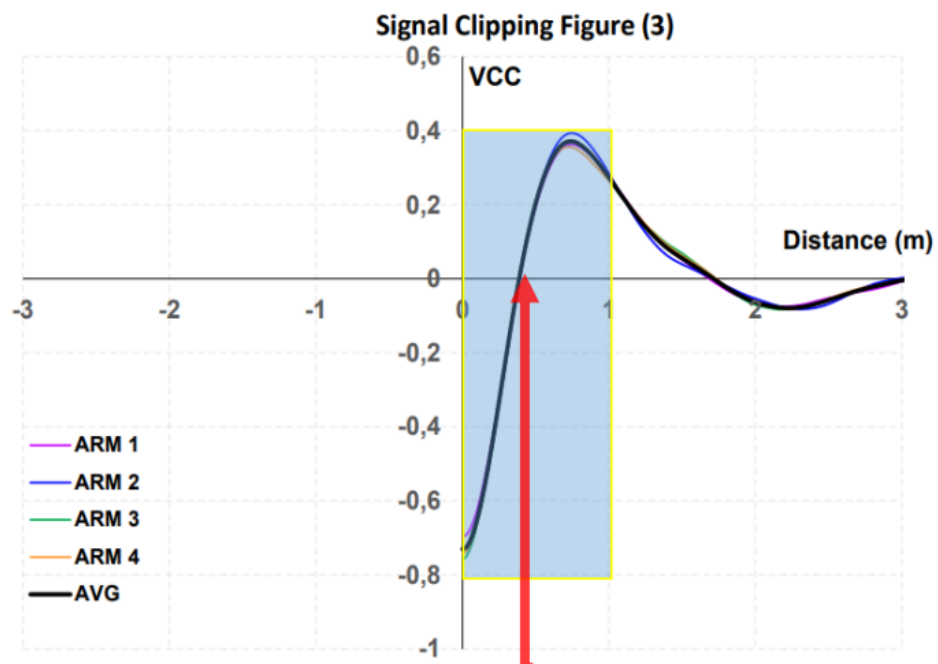
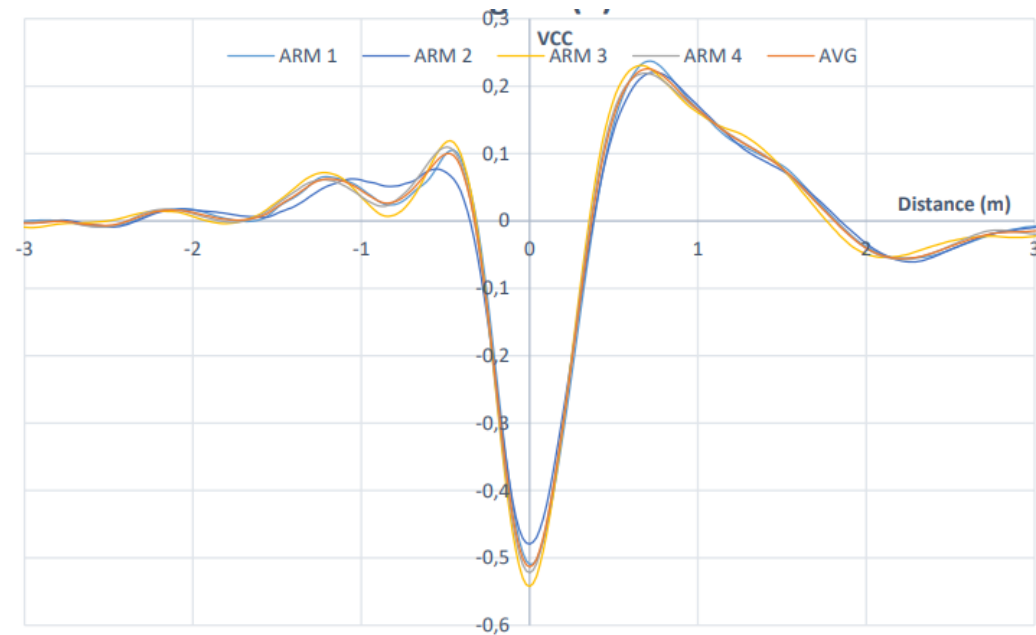
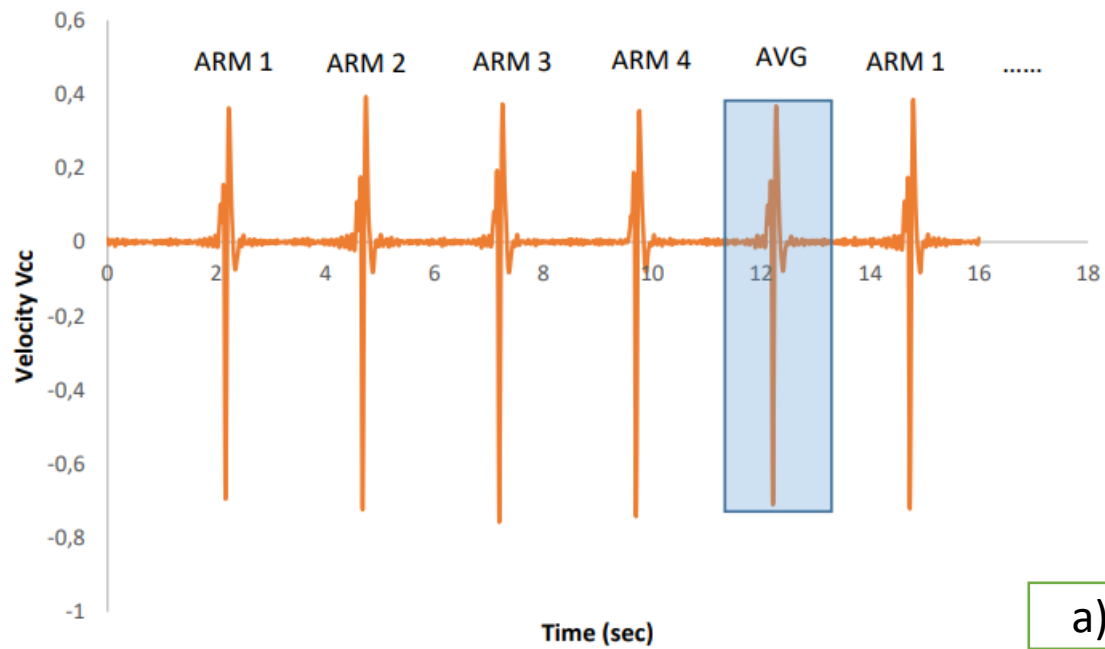
$$\text{SNR} = 10 \log_{10}(\text{SD})^2$$

$$20 \cdot \log_{10}(5.5) \approx 20 \cdot 0.740$$

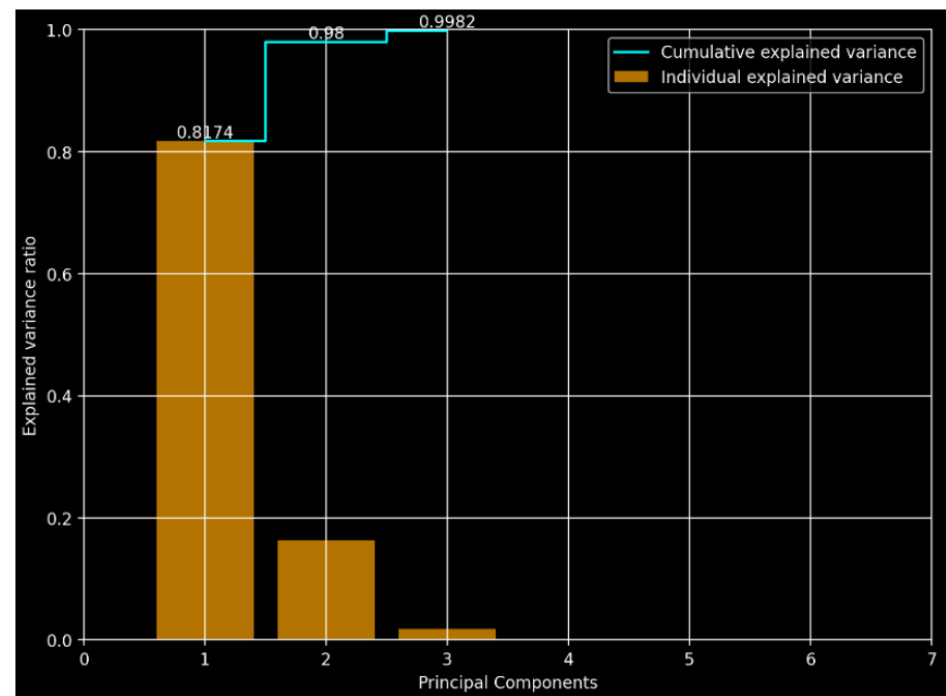
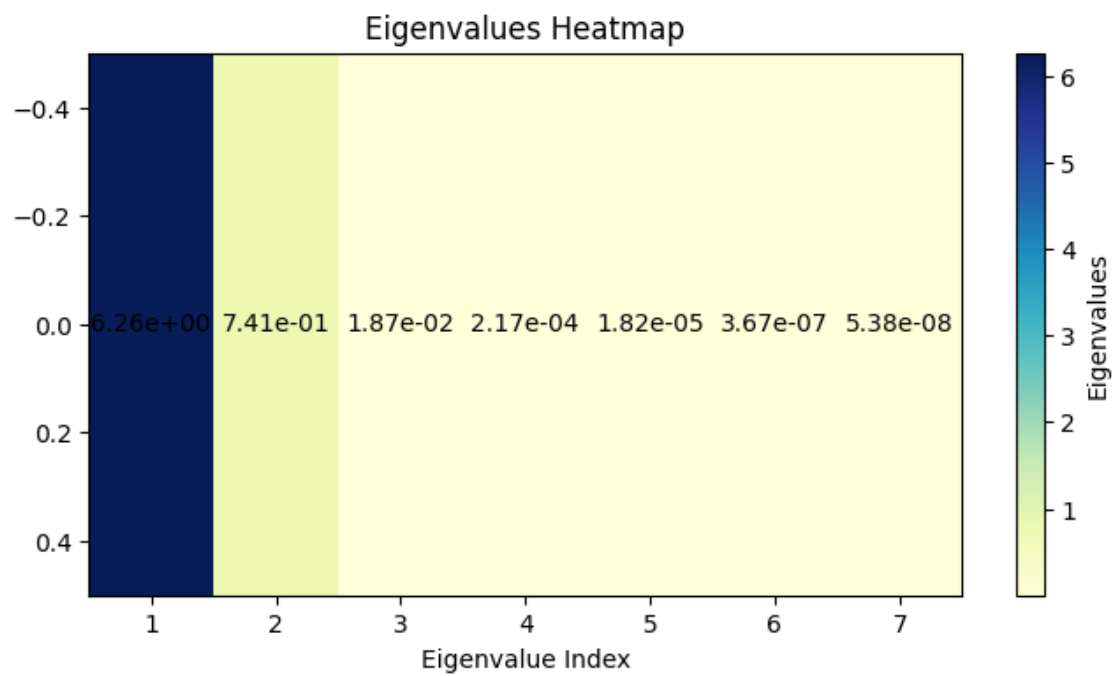
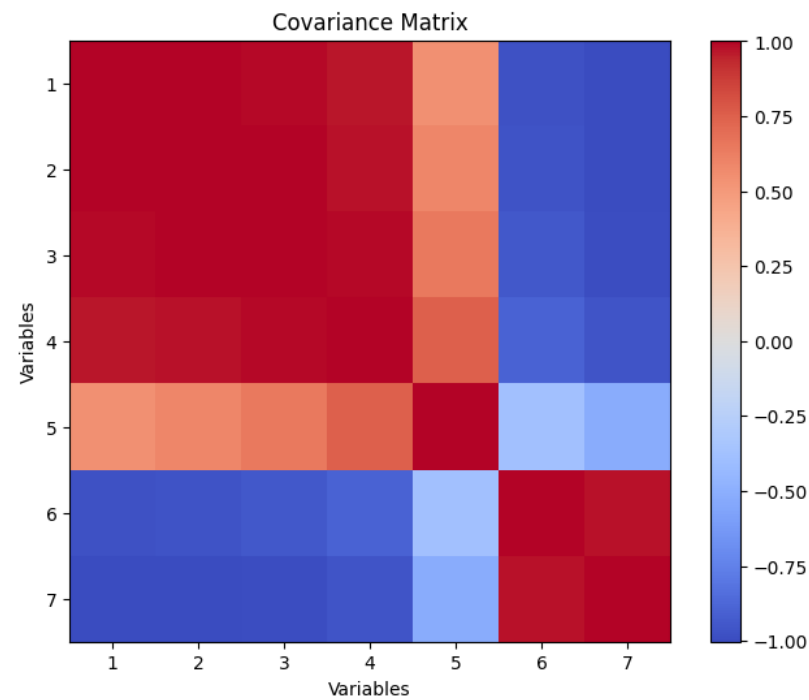
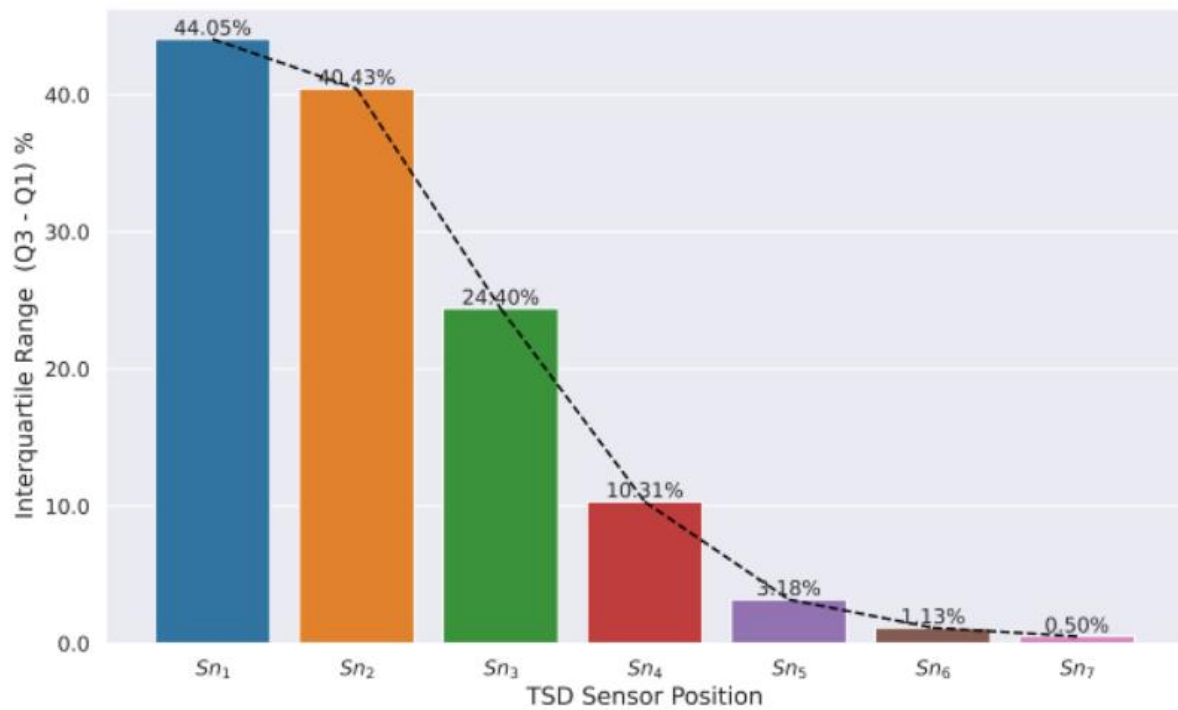
$$\approx 14.80 \approx 15 \text{ dB}$$

AWGN









# References

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2. J.-M. Simonin, V. Le Boursicaud, and P. Horny, “Correction of deflection bowls measured by rolling devices using simple shape function,” *Transportation Engineering*, vol. 3, p. 100050, 2021.
3. S. Katicha, G. Flintsch, and B. Diefenderfer, “Ten years of traffic speed deflectometer research in the United States: A review,” *Transportation research record*, vol. 2676, no. 12, pp. 152–165, 2022.
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5. Y. LeCun, Y. Bengio, and G. Hinton, “Deep learning,” *nature*, vol. 521, no. 7553, pp. 436–444, 2015.
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7. Horak, Emile. (2008). Benchmarking the structural condition of flexible pavements with deflection bowl parameters. *Journal of the South African Institution of Civil Engineers*. 50.



Thank you  
for your attention