Advanced Compaction Control for Future Quality Assurance

Wenjun Hua, Carl Wersäll, Stefan Larsson

BIG webinar, March 20, 2026

Quality acceptance (QA) of soil compaction



(Gustafsson et al., *Grundläggningsdagen 2026*)

7.2.3 Krav på bärighet

Bärlager ska för nybyggnad utföras så att krav på bärighet uppfylls enligt avsnitt 7.2.3.1 ”Krav vid nybyggnad” om ÅDTtot är ≥ 1 000 och om objektet är ≥ 5 000 m^2.

7.2.3.1 Krav vid nybyggnad

För flexibel konstruktion gäller krav enligt avsnitt 7.2.3.1.1 och för styv konstruktion gäller krav enligt avsnitt 7.2.3.1.2.

Kravet kan uppfyllas antingen med statistisk acceptanskontroll eller yttäckande packningskontroll (YPK).

7.2.3.1.2 Krav på styv konstruktion

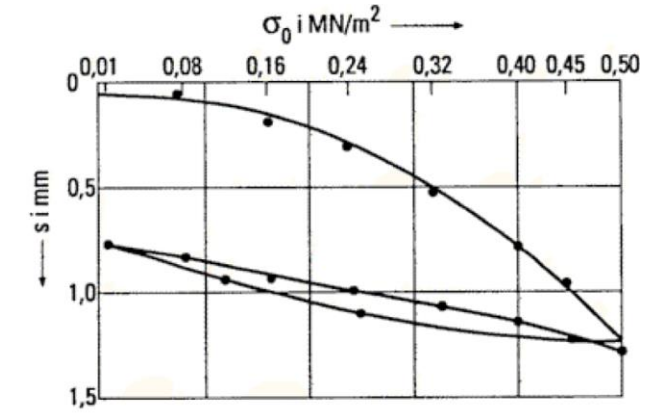
Vid nybyggnad av styv konstruktion ska krav för bärighet på bärlager uppfyllas enligt tabell 7.2.3.2.1-1 eller tabell 7.2.3.1.2-2.

Tabell 7.2.3.1.2-1 Krav på bärighet, styv konstruktion vid nybyggnad med statistisk acceptanskontroll

Acceptansintervall för styv konstruktion		
Översta obundna lagret	n = 8	$\bar{x}_{Ev2} \geq 120 + 0{,}96 \cdot s$
	n = 5	$\bar{x}_{Ev2} \geq 120 + 0{,}83 \cdot s$
	I varje enskild kontrollpunkt:	
	Om $E_{v2} \leq 120$:	$E_{v2}/E_{v1} \leq 2{,}8$
	Om $E_{v2} > 120$:	$E_{v2}/E_{v1} \leq 1 + 0{,}015\ E_{v2}$
	Antal godkända kontrollpunkter ska vara minst 7 av 8, respektive minst 4 av 5.	
	G_f om $x_i < 105$ MPa	

(TDOK2013:0530)

Repetitive static plate load test (PLT)



Figur 4. Trycksättningslinje vid packningskontroll

		Första belastning	Andra belastning
$\sigma_{1\,max}$	MN/m	0,50	0,50
a_1	mm/(MN/m²)	- 0,268	+0,610
a_2	mm/(MN/m²)	5,195	0,951
$E_v = \frac{1{,}50 \cdot r}{a_1 + a_2 \cdot \sigma_{1\,max}}$		96,6	207,3
E_{v2}/E_{v1}		2,15	

Tabell 4. Sammanställning av resultat

(TDOC 2014:0141)

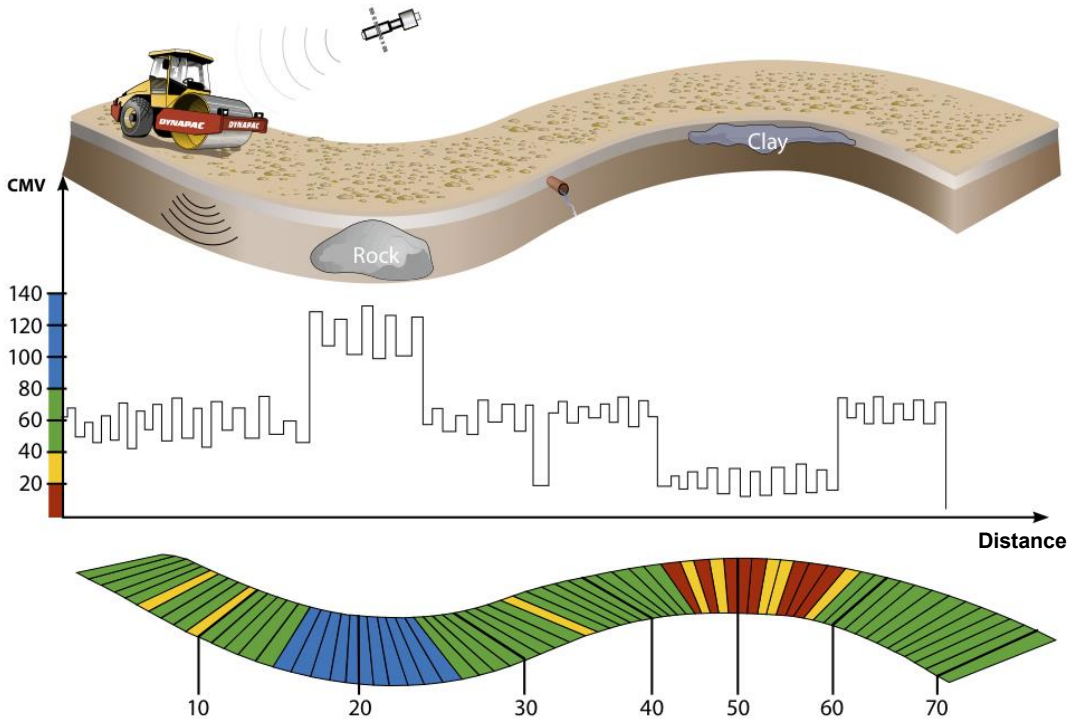


Table A.1 — Loading stages as a function of the loading plate diameter

Loading stage no.	Diameters of loading plates					
	300 mm		600 mm		762 mm	
	Load F kN	Normal stress σ_0 MN/m²	Load F kN	Normal stress σ_0 MN/m²	Load F kN	Normal stress σ_0 MN/m²
1	0,71	0,010	0,28	0,001	0,46	0,001
2	5,65	0,080	5,65	0,020	4,56	0,010
3	11,31	0,160	11,31	0,040	9,12	0,020
4	16,96	0,240	22,62	0,080	18,24	0,040
5	22,62	0,320	33,93	0,120	36,48	0,080
6	28,27	0,400	45,24	0,160	54,72	0,120
7	31,81	0,450	56,55	0,200	72,96	0,160
8	35,34	0,500	70,69	0,250	91,21	0,200

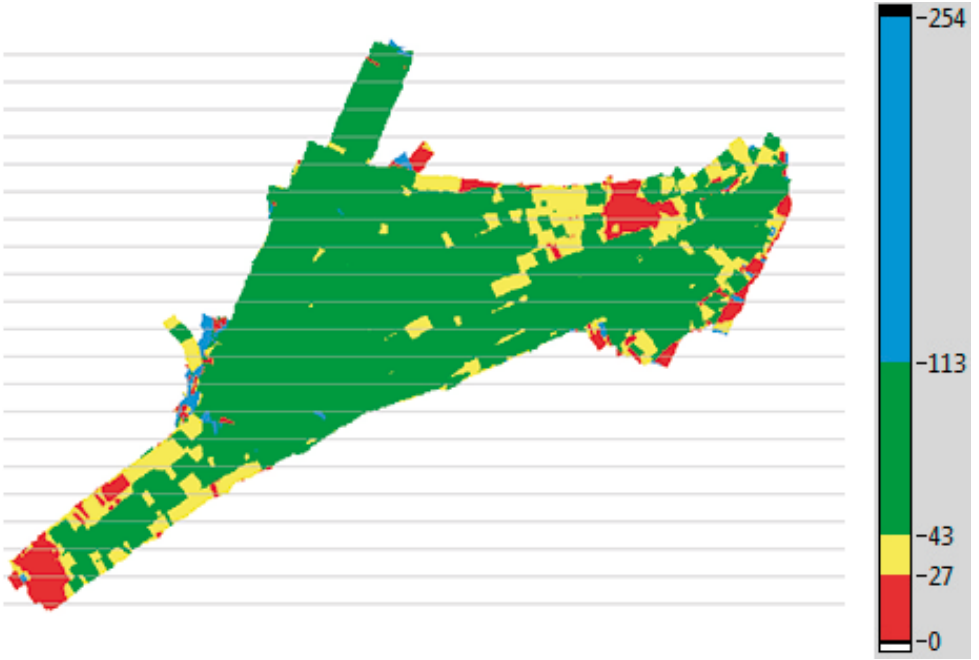
(DIN18134-2012)

Continuous compaction control (CCC)









Challenges & Objectives

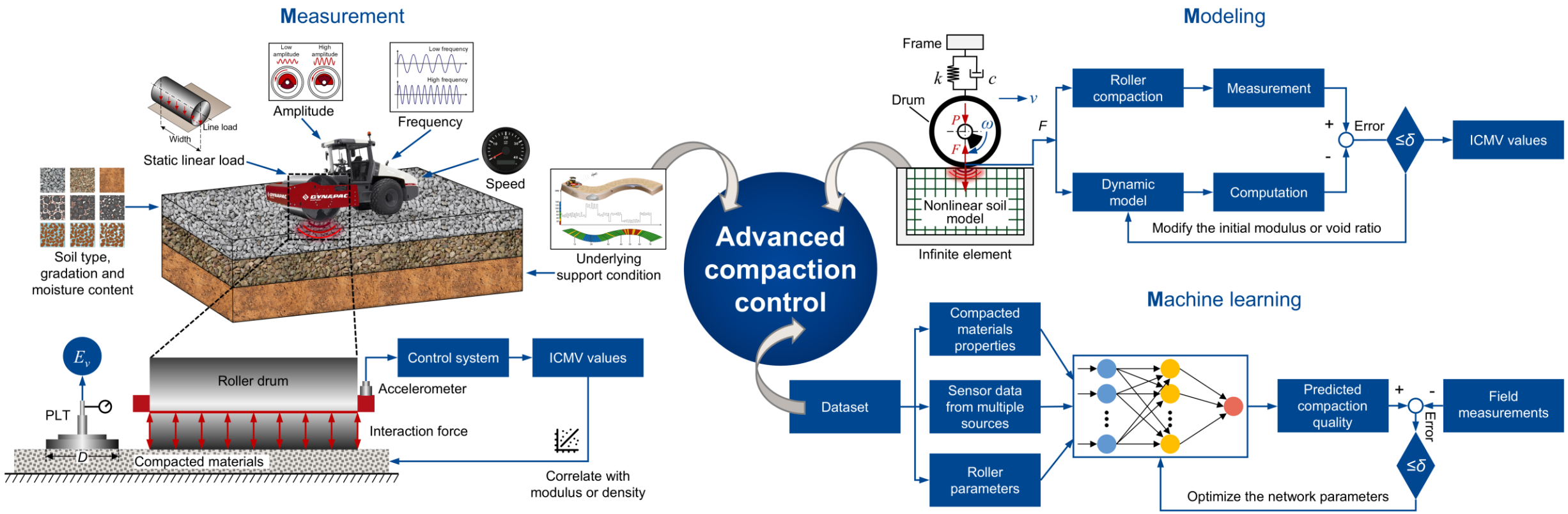
Challenges

- Current QA practice relies heavily on ineffective and uncertain spot tests.
- CCC is still not universally accepted as a standalone QA method.

Objectives

- The objective is to evaluate the influence of **plate size** and **roller type** on the correlation between compaction measurement and PLT results.
- The goal is to advance CCC technology to a level of reliability that eliminates reliance on PLT.

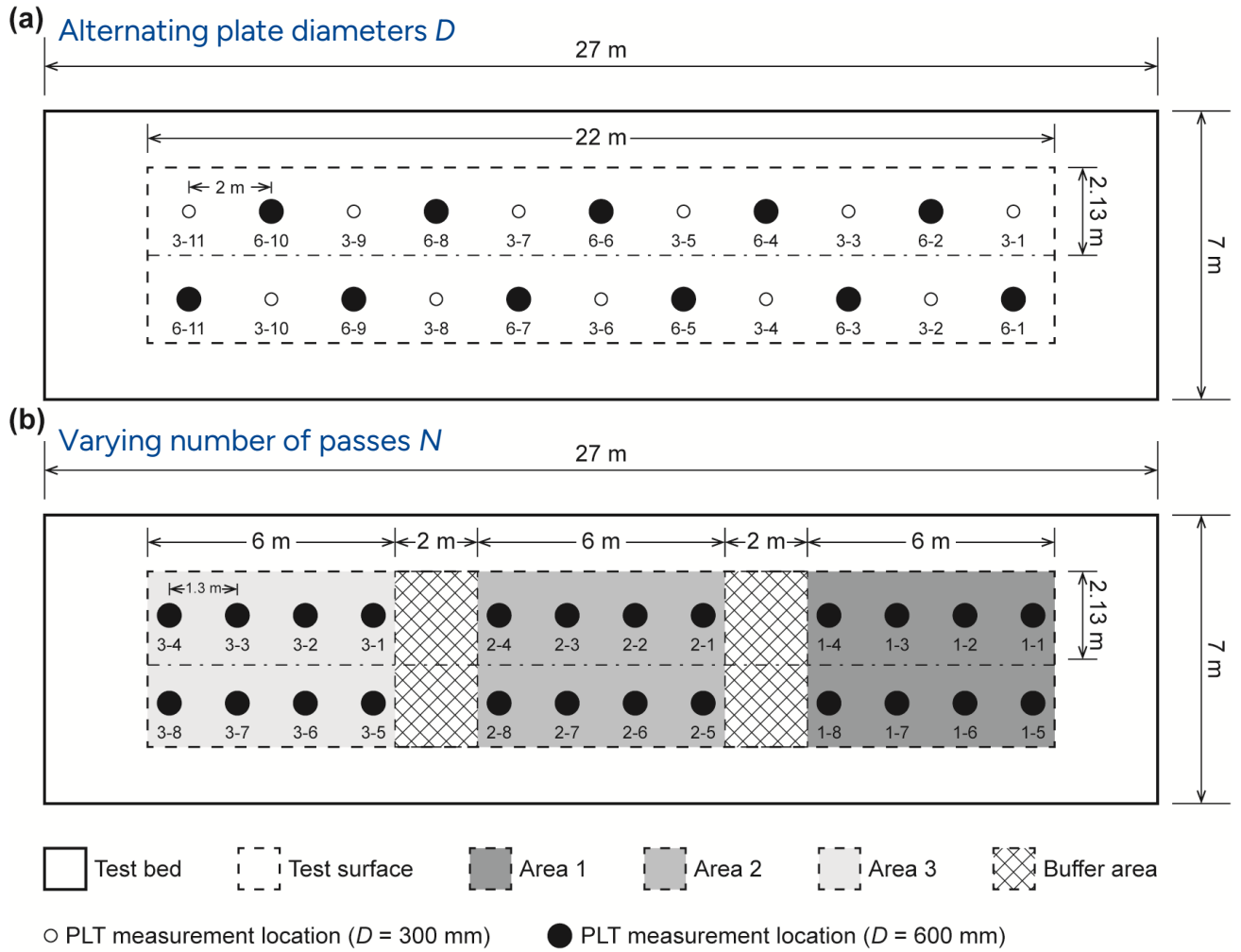
Measurement, modeling & machine learning



Full-scale compaction tests

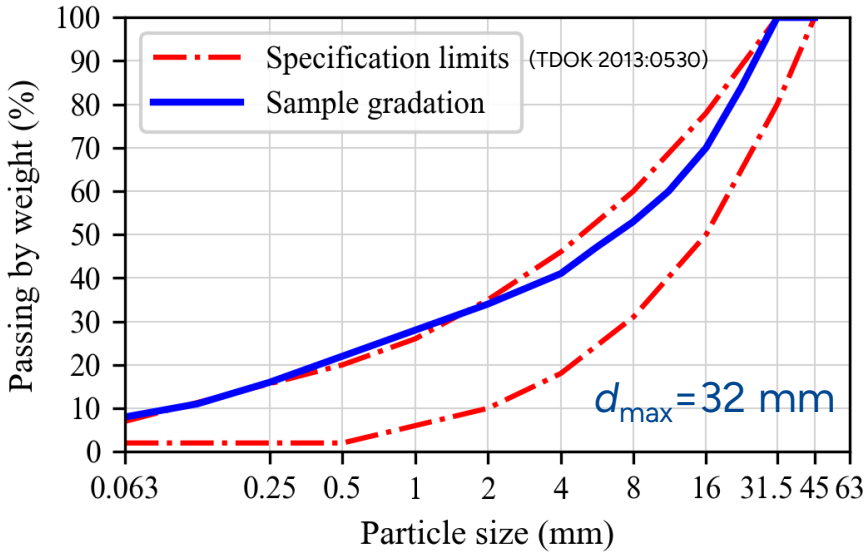






Compacted materials







Compaction & measurement equipment



(Source: Dynapac Worldwide - YouTube)

- Vibration frequency f=24 Hz
- Travel speed v=1 m/s
- High amplitude setting

Property	CA3500D	CA6500D
Drum mass (kg)	4040	5300
Frame mass (kg)	3565	8470
Operating mass (kg)	13800	21000
Drum width (m)	2.13	2.13
Drum diameter (m)	1.518	1.546
Static linear load (kg/cm)	35	65
Max. nominal amplitude (mm)	1.9	2.1
Max. vibration frequency (Hz)	31	29
Max. centrifugal force (kN)	280	360
Max. eccentric moment (kg·m)	7.31	10.31

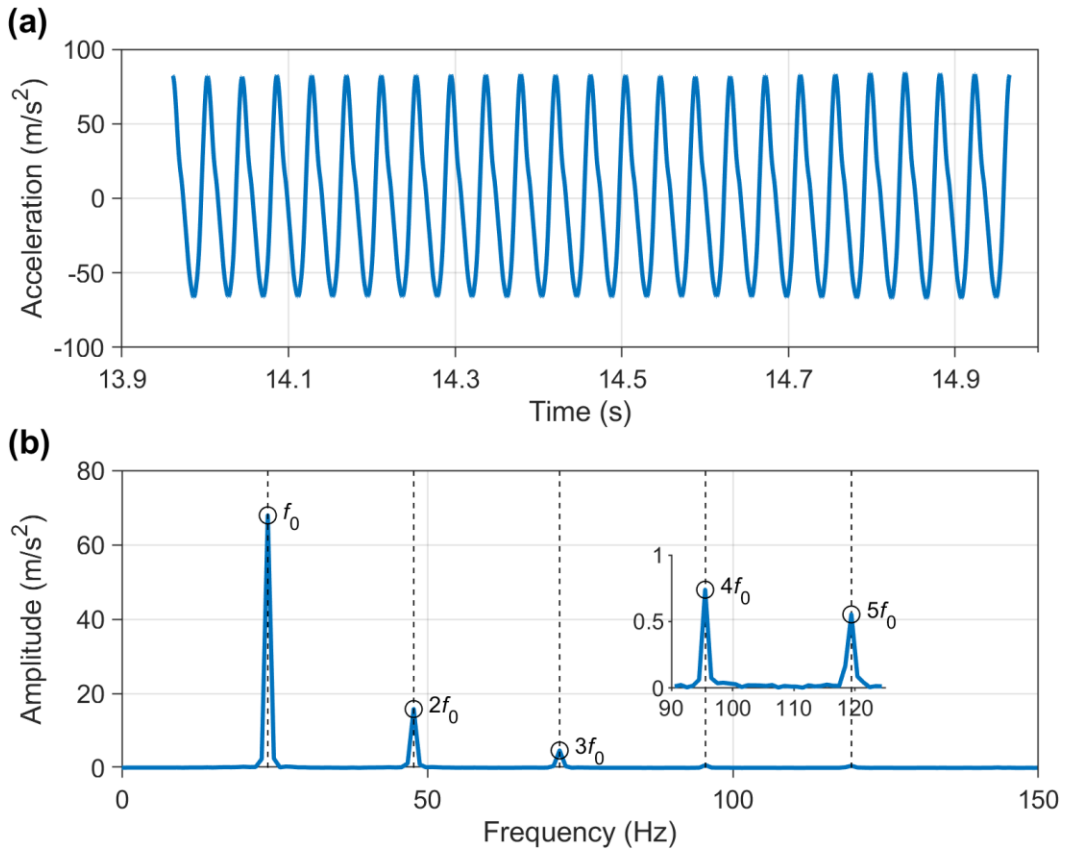
Compaction & measurement equipment





Intelligent compaction measurement value (ICMV)

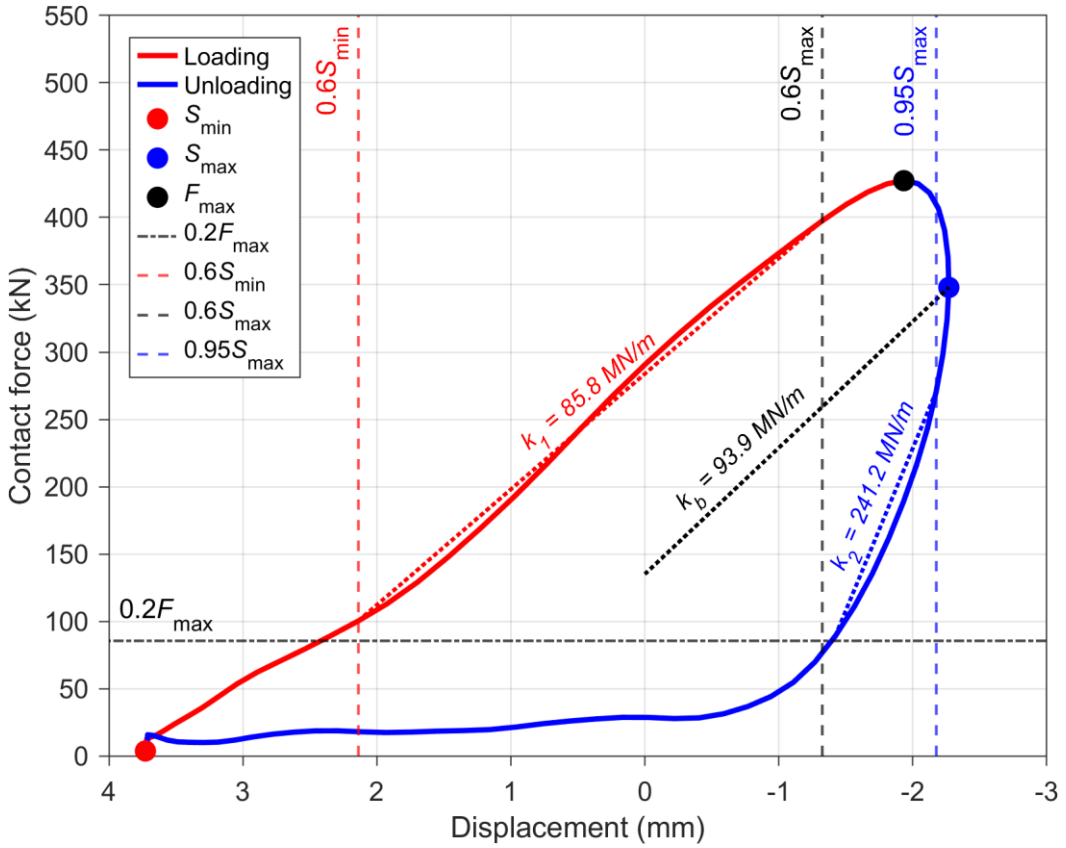
Category	Indicator	Formula	
Kinematics	CMV	$\mathrm{CMV} = C \times \frac{A_{2\omega}}{A_{\omega}}$	(1)
	AICV	$\mathrm{AICV} = C \times \frac{A_{1.5\omega}+A_{2\omega}+A_{2.5\omega}}{A_{0.5\omega}+A_{\omega}}$	(2)
	CCV	$\mathrm{CCV} = C \times \frac{A_{0.5\omega}+A_{1.5\omega}+A_{2\omega}+A_{2.5\omega}+A_{3\omega}}{A_{0.5\omega}+A_{\omega}}$	(3)
	THD	$\mathrm{THD} = C \times \frac{\sqrt{A_{2\omega}^2+A_{3\omega}^2+\cdots+A_{6\omega}^2}}{A_{\omega}}$	(4)
	F_t	$F_t = \frac{F_s}{(m_d+m_f)g} \cdot \frac{A_{1.5\omega}+A_{2\omega}+A_{2.5\omega}+A_{3\omega}+A_{3.5\omega}+A_{4\omega}}{A_{0.5\omega}+A_{\omega}}$	(5)
	CF	$\mathrm{CF} = \frac{a_p}{a_{rms}} = \frac{\max\{\lvert a_i \rvert\}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i^2}}$	(6)
Mechanics	k_s	$k_s = \Omega^2 \left(m_d + \frac{m_0 e_0 \cos\varphi}{z_d}\right)$	(7)
	E_{vib}	$z_d = \frac{1-v^2}{E_{vib}} \cdot \frac{F_s}{L} \cdot \frac{1}{\pi} \cdot \left(1 + 2ln\frac{4L}{b}\right)$	(8-a)
		$b = \sqrt{\frac{16}{\pi} \cdot \frac{R(1-v^2)}{E_{vib}} \cdot \frac{F_s}{L}}$	(8-b)
Energy	CEV	$H(\omega,t) = \mathrm{Real}\sum_{i=1}^{n} a_i(t) e^{j\int \omega_i(t)dt}$	(9-a)
		$h(\omega) = \int_0^T H(\omega,t)\,dt$	(9-b)
		$\mathrm{CEV} = \sum_{i=1}^{n} h(\omega_i)$	(9-c)
	DMV	$\mathrm{DMV} = \pi\omega_0^3 \sum_{i=1}^{n} \frac{A_i^2}{\omega_i^3}$	(10)
	OMEGA	$\mathrm{OMEGA} = \oint_{2T} \left(m_d \ddot{z}_d + (m_d + m_f)g - m_0 e_0 \Omega^2)\dot{z}_d\,dt\right.$	(11)
	E	$\mathrm{E} = 2A\left(W + \frac{\pi F_s}{4} \cdot \frac{fN}{LhV}\right)$	(12)



Vertical drum acceleration in: (a) time and (b) frequency domains

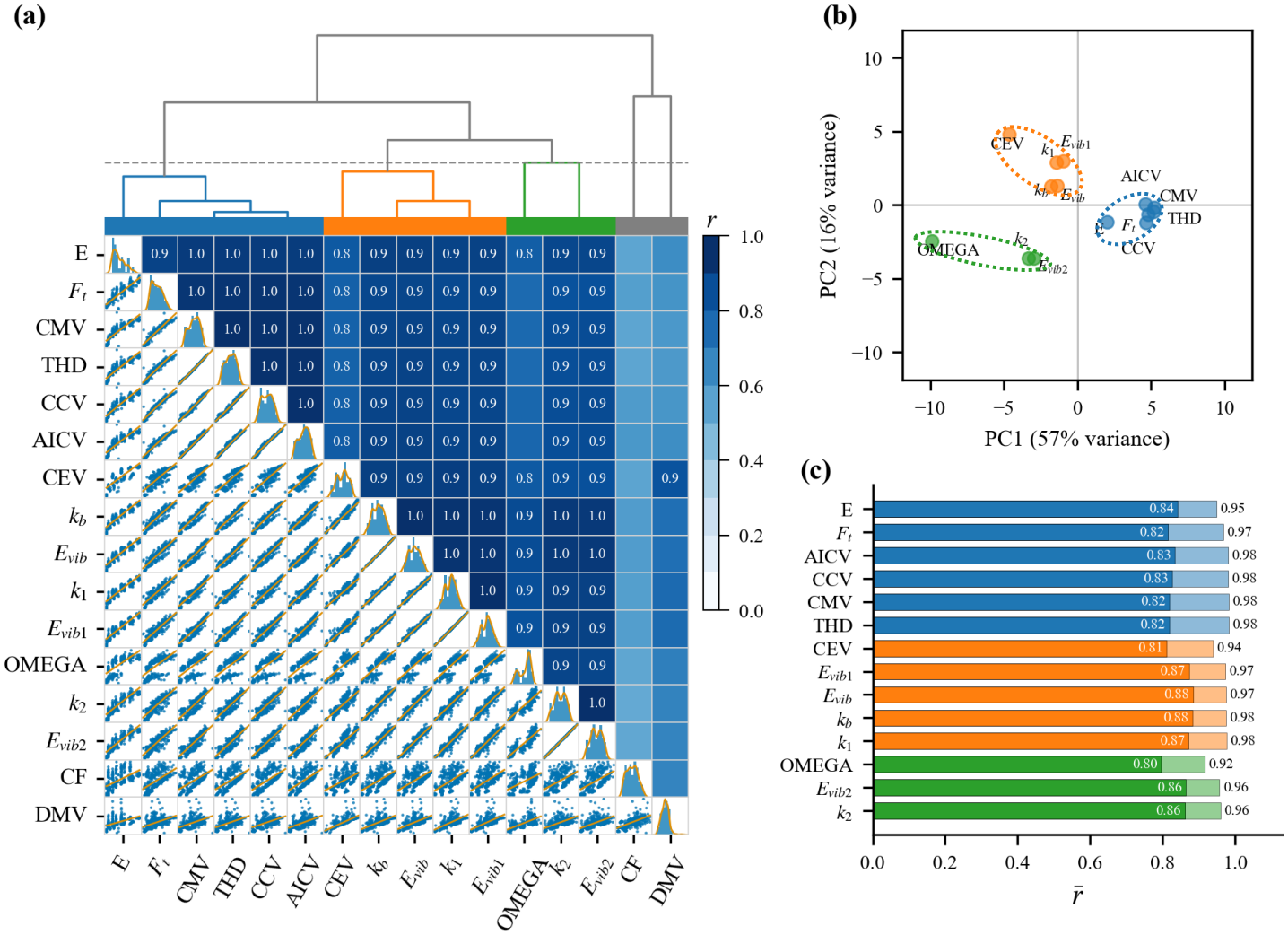
Intelligent compaction measurement value (ICMV)

Category	Indicator	Formula	
Kinematics	CMV	$\mathrm{CMV} = C \times \frac{A_{2\omega}}{A_{\omega}}$	(1)
	AICV	$\mathrm{AICV} = C \times \frac{A_{1.5\omega}+A_{2\omega}+A_{2.5\omega}}{A_{0.5\omega}+A_{\omega}}$	(2)
	CCV	$\mathrm{CCV} = C \times \frac{A_{0.5\omega}+A_{1.5\omega}+A_{2\omega}+A_{2.5\omega}+A_{3\omega}}{A_{0.5\omega}+A_{\omega}}$	(3)
	THD	$\mathrm{THD} = C \times \frac{\sqrt{A_{2\omega}^2+A_{3\omega}^2+\cdots+A_{6\omega}^2}}{A_{\omega}}$	(4)
	F_t	$F_t = \frac{F_s}{(m_d+m_f)g} \cdot \frac{A_{1.5\omega}+A_{2\omega}+A_{2.5\omega}+A_{3\omega}+A_{3.5\omega}+A_{4\omega}}{A_{0.5\omega}+A_{\omega}}$	(5)
	CF	$\mathrm{CF} = \frac{a_p}{a_{rms}} = \frac{\max\{\lvert a_i \rvert\}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i^2}}$	(6)
Mechanics	k_s	$k_s = \Omega^2 \left(m_d + \frac{m_0 e_0 \cos\varphi}{z_d}\right)$	(7)
	E_{vib}	$z_d = \frac{1-v^2}{E_{vib}} \cdot \frac{F_s}{L} \cdot \frac{1}{\pi} \cdot \left(1 + 2ln\frac{4L}{b}\right)$	(8-a)
		$b = \sqrt{\frac{16}{\pi} \cdot \frac{R(1-v^2)}{E_{vib}} \cdot \frac{F_s}{L}}$	(8-b)
Energy	CEV	$H(\omega,t) = \mathrm{Real}\sum_{i=1}^{n} a_i(t) e^{j\int \omega_i(t)dt}$	(9-a)
		$h(\omega) = \int_0^T H(\omega,t)\,dt$	(9-b)
		$\mathrm{CEV} = \sum_{i=1}^{n} h(\omega_i)$	(9-c)
	DMV	$\mathrm{DMV} = \pi\omega_0^3 \sum_{i=1}^{n} \frac{A_i^2}{\omega_i^3}$	(10)
	OMEGA	$\mathrm{OMEGA} = \oint_{2T} \left(m_d \ddot{z}_d + (m_d + m_f)g - m_0 e_0 \Omega^2)\dot{z}_d\,dt$	(11)
	E	$\mathrm{E} = 2A\left(W + \frac{\pi F_s}{4} \cdot \frac{fN}{LhV}\right)$	(12)



Ground contact force–drum displacement curve

Interrelationships among ICMVs



Cluster 1
Harmonic-based
CMV, AICV, CCV, THD, F_t, E

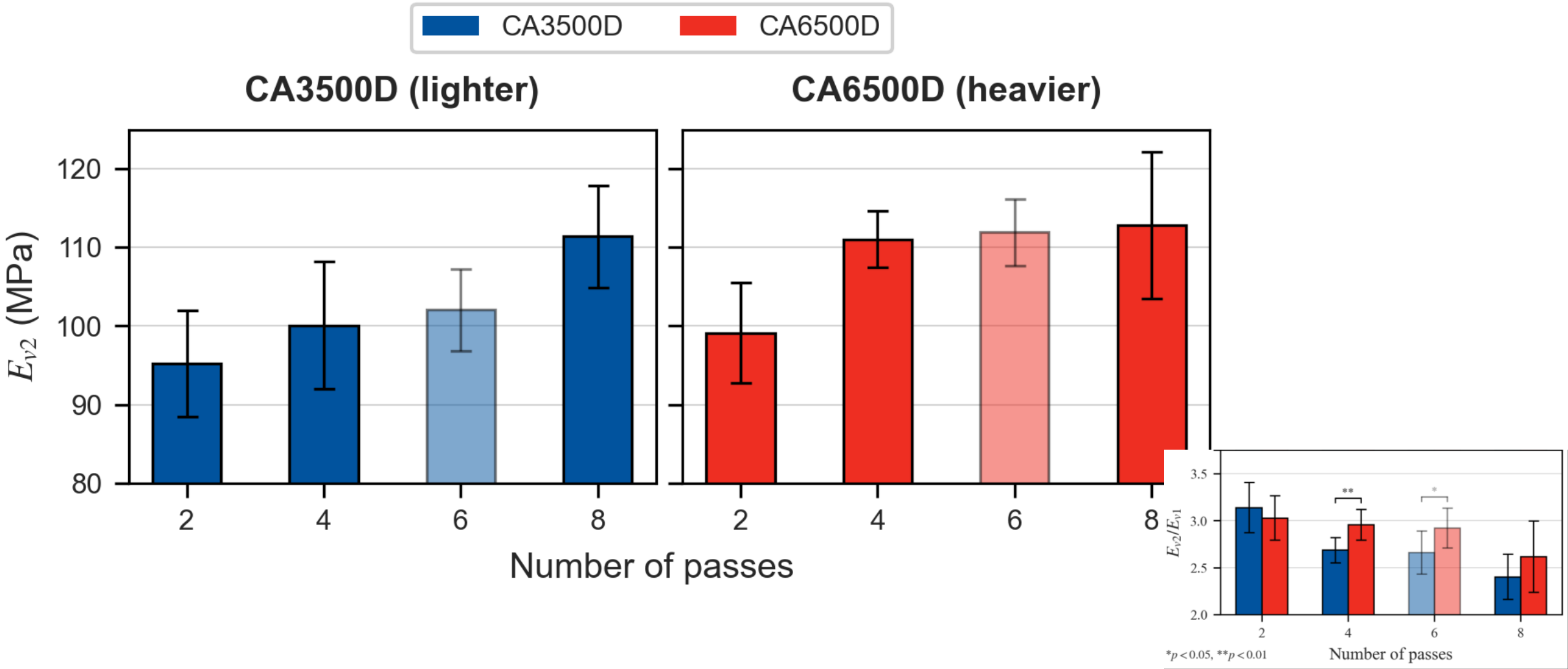
Cluster 2
Loading-related
k_1, E_{vib1}, k, E_{vib}, CEV

Cluster 3
Unloading-related
k_2, E_{vib2}, OMEGA

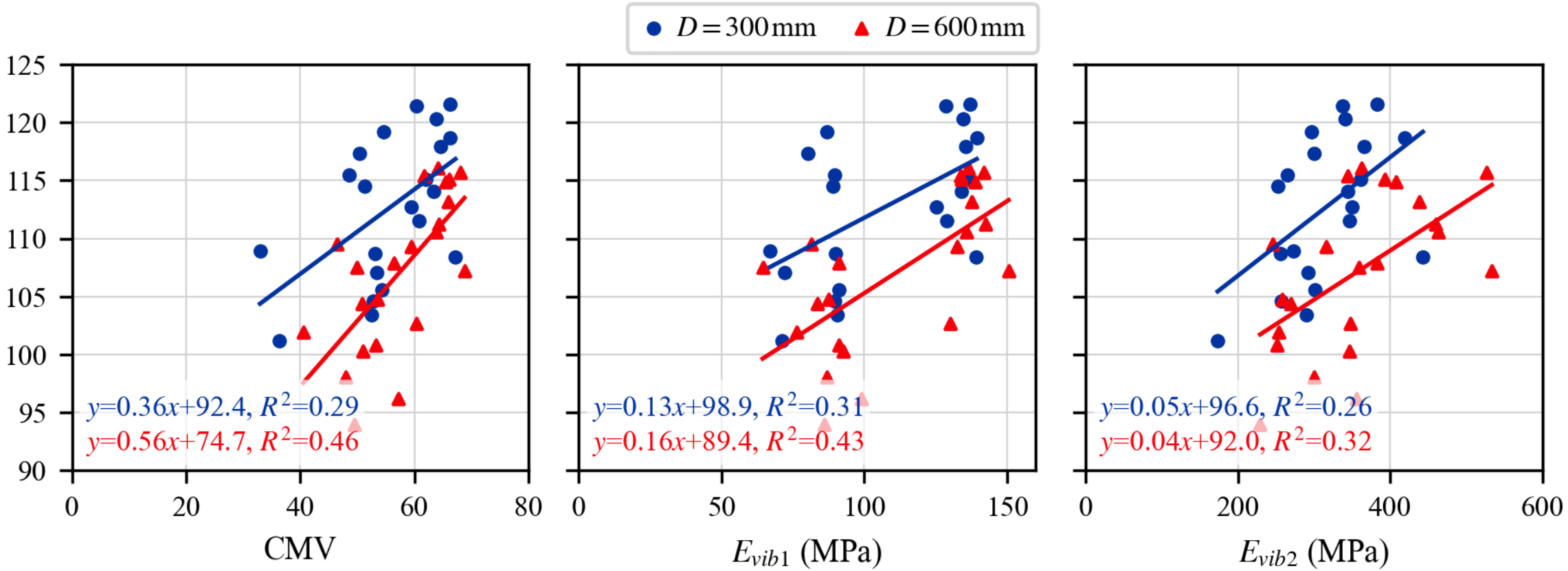
Influence of plate diameter on PLT results

Metric	D (mm)	E_{v1} (MPa)		E_{v2} (MPa)		E_{v2}/E_{v1} (–)	
		CA3500D	CA6500D	CA3500D	CA6500D	CA3500D	CA6500D
Mean	300	39.3	38.8	109.6	117.7	2.8	3.0
	600	38.7	38.5	102.1	111.9	2.7	2.9
CV	300	8%	6%	6%	6%	7%	4%
	600	13%	8%	5%	4%	9%	7%

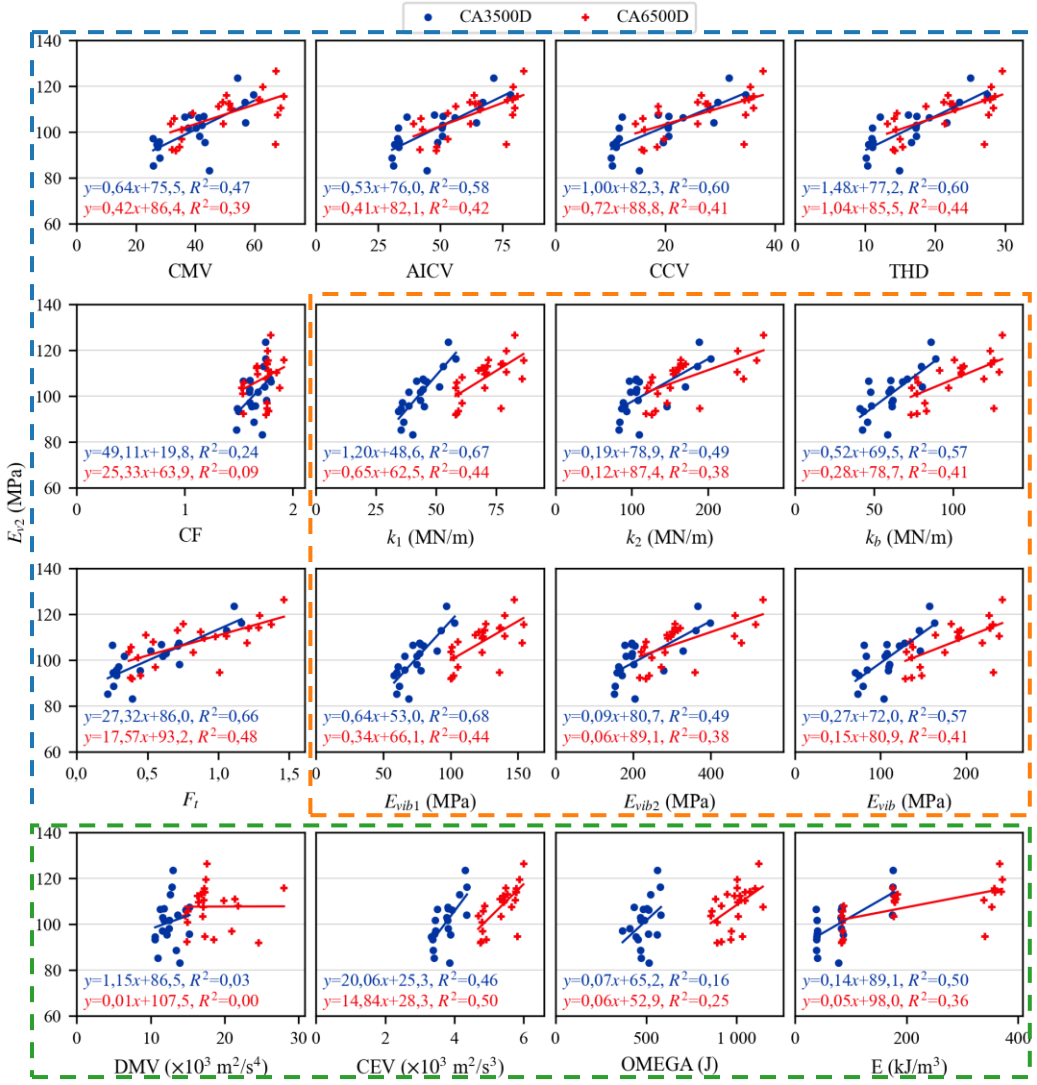
Influence of roller type & number of passes on E_{v2}

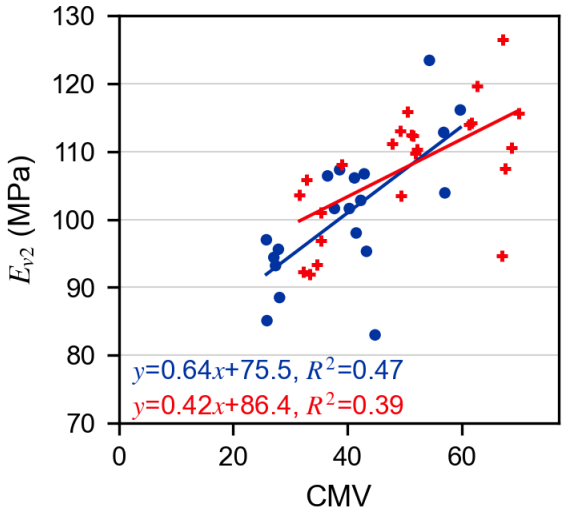


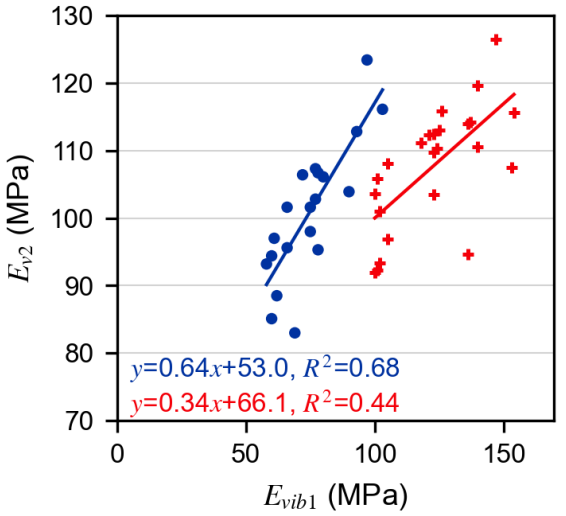
Influence of plate diameter on ICMV-E_{v2} correlations

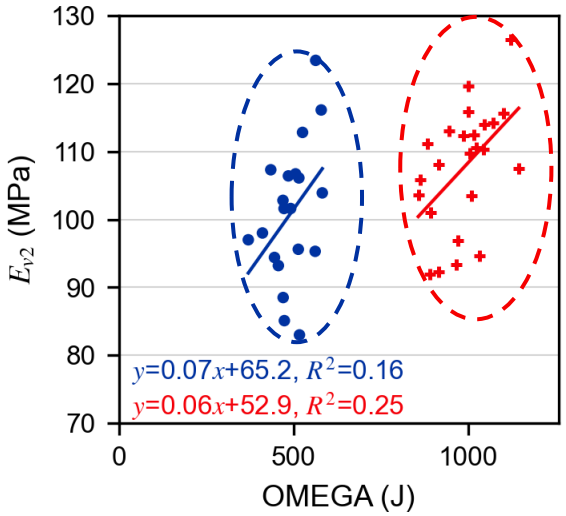


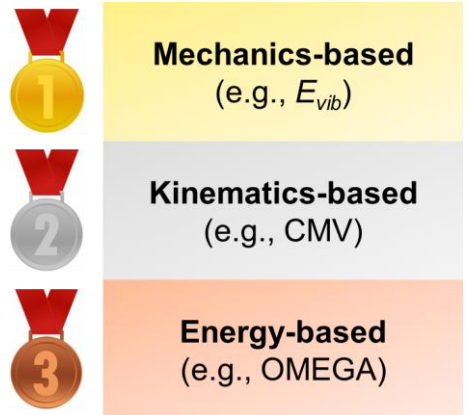
Influence of roller type on ICMV-E_{v2} correlations



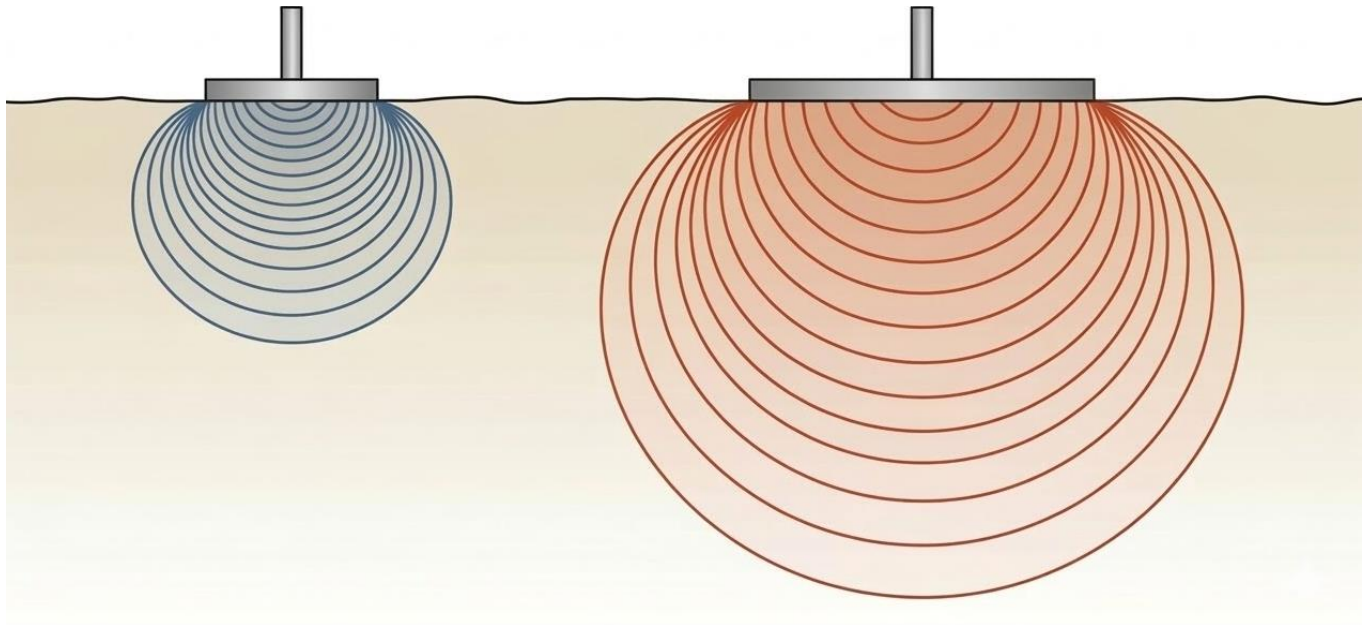






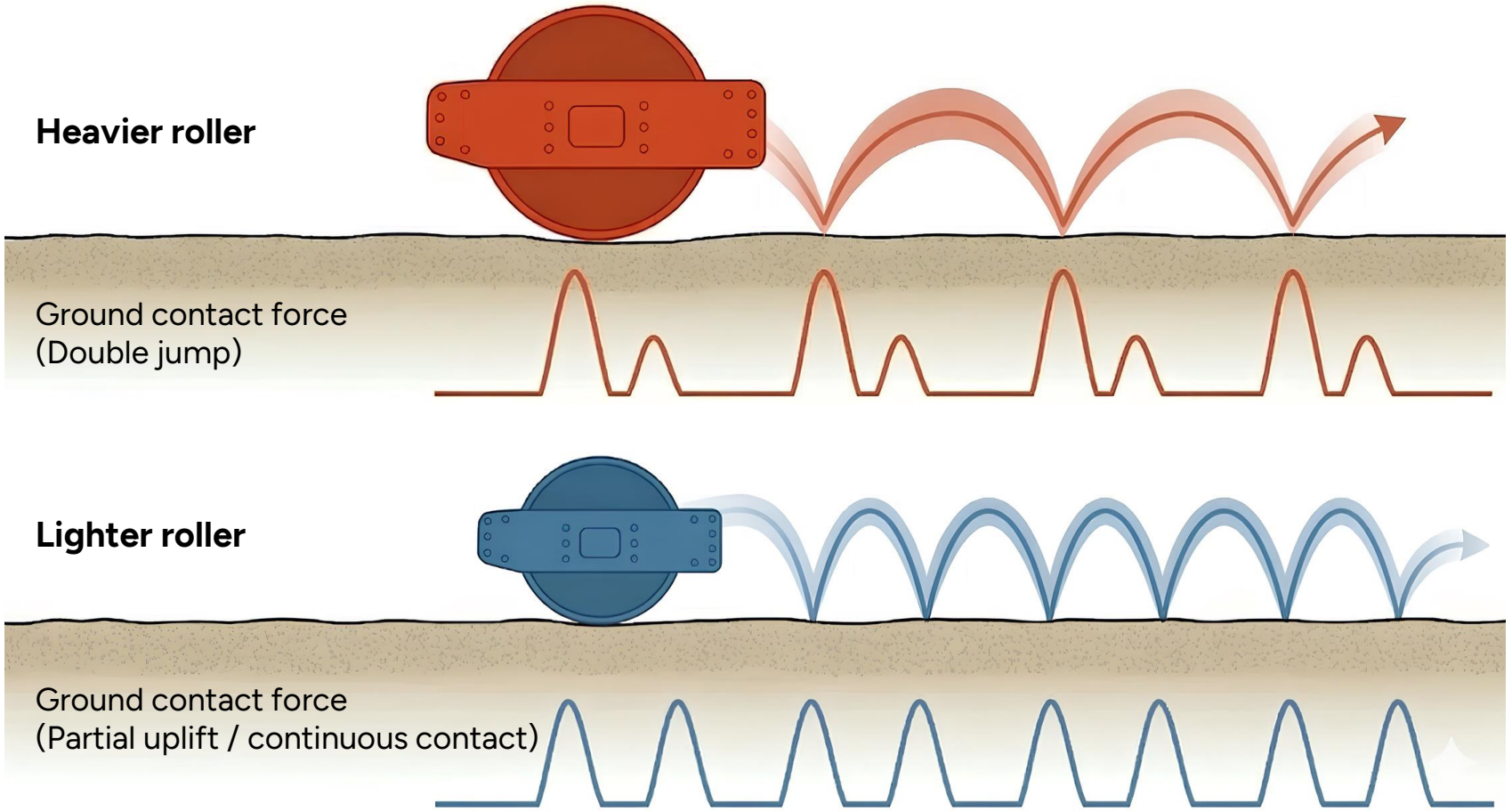


The larger plate provides improved correlations



The larger plate mobilizes a deeper influence zone that better matches the roller’s effective measurement depth.

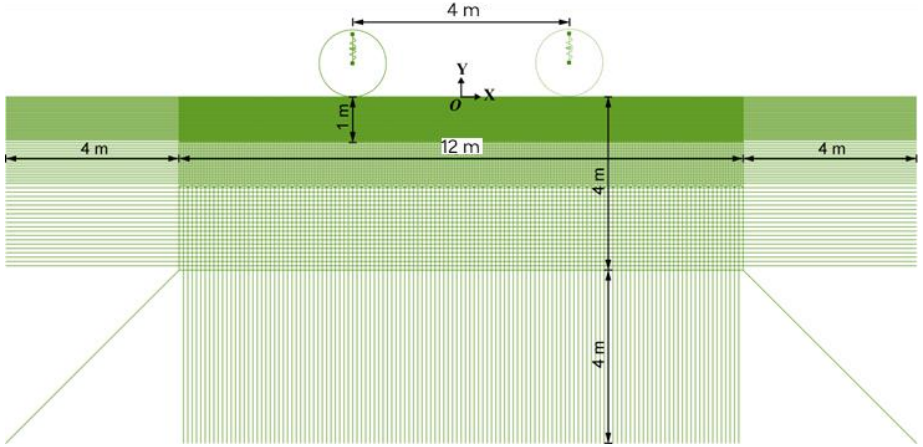
The lighter roller produces better correlations

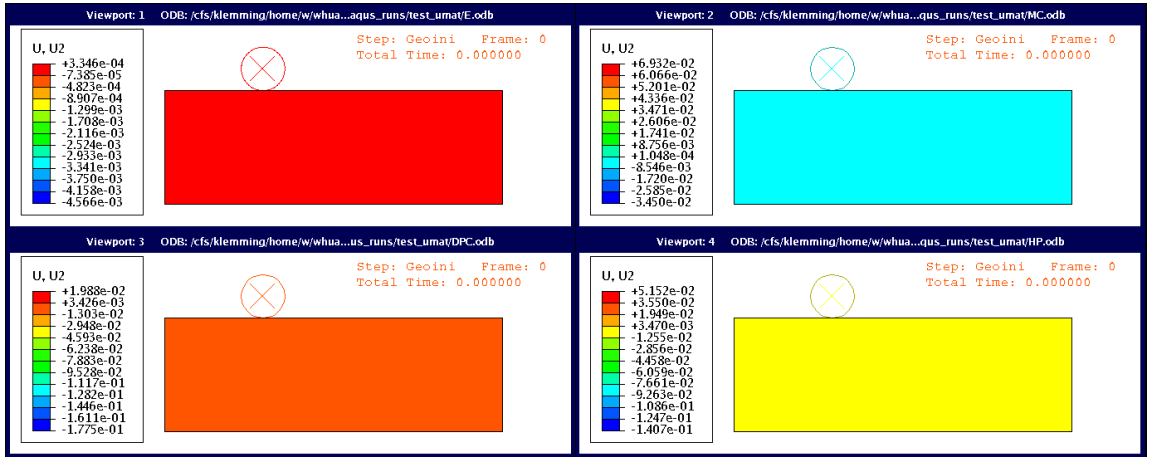


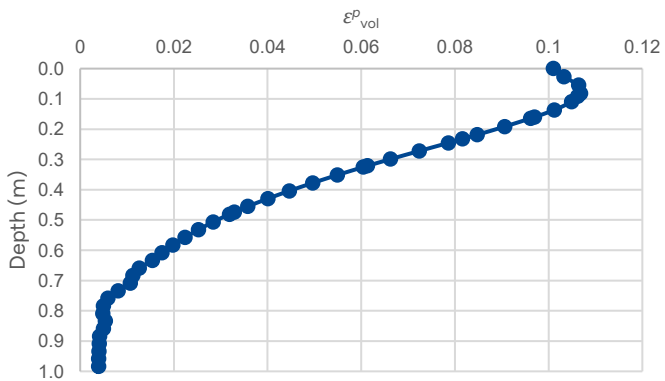
Implications for CCC-based QA workflows

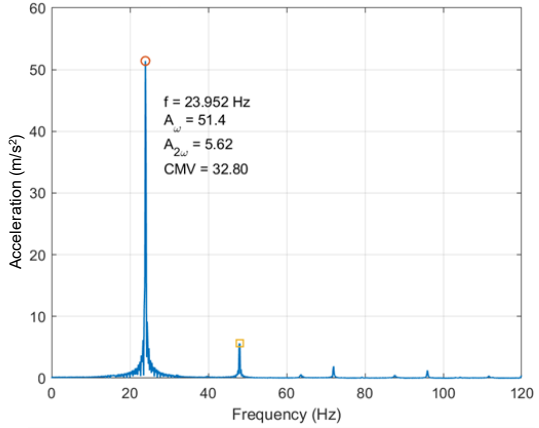
Decision	Recommendation	Why
Plate size	Use 600 mm PLT for calibration	Better correlation with ICMVs
Primary indicator	Use E_{vib}	Strongest physical and statistical link
Secondary indicator	Add one harmonic-based metric (e.g., CMV)	Easy implementation
Roller strategy	Calibrate per roller model	Strong machine dependency observed
Pass strategy	Avoid excessive passes	Marginal stiffness gain; variability may increase

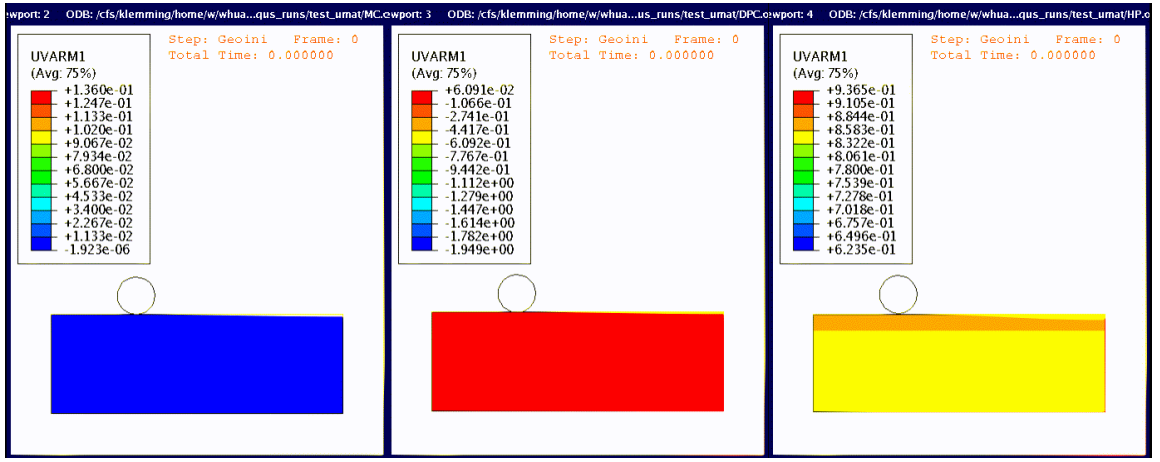
Coupled multibody and finite element simulations



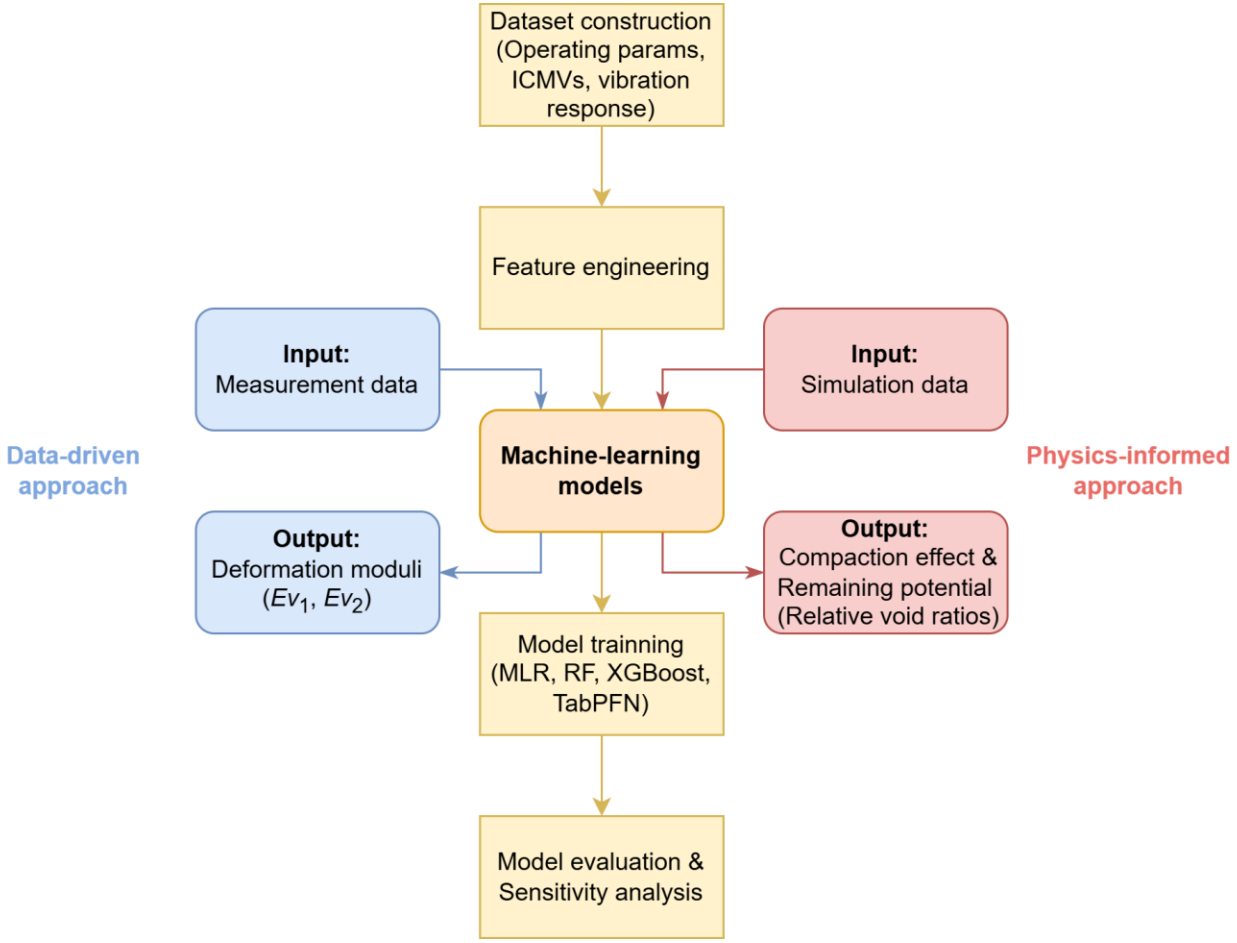








Machine-learning-based surrogate models





Future work

- To develop **a stiffness-based ICMV** that better represents ground stiffness and is less sensitive to compaction parameters. This ICMV is expected to be universally applicable across diverse soil conditions and roller characteristics.

- To investigate the influence of compaction parameters (e.g., vibration amplitude, frequency, and travel speed) on measurements through further full-scale compaction tests, and thereby identify **optimal proof-rolling settings** that maximize correlation with PLT.

- To establish a synthetic dataset through high-fidelity coupled multibody-finite element simulations of vibratory compaction, and then propose **a machine-learning model** based on the generated dataset to estimate both the achieved compaction effect and the remaining compaction potential.

References

- Hua, W. (2026) Towards reliable vibratory compaction control: Integrating full-scale testing and advanced finite element analysis. Licentiate thesis (manuscript).
- Hua, W., Wersäll, C., & Larsson, S. Correlating continuous compaction measurement to plate load tests for quality assurance. Submitted to *Transportation Geotechnics*.
- Hua, W., Wersäll, C., & Larsson, S. Nonlinear vibration response of the roller-soil interaction system using finite element analysis with hypoplasticity. Manuscript to be submitted to *Computers and Geotechnics*.
- Hua, W., Wersäll, C., & Larsson, S. (2025) Packningskontroll för framtiden – Modern teknik istället för långsamma försök. *Bygg & Teknik* Nr. 1/25: 10-12.
- Hua, W., Wersäll, C., Persson, A. & Larsson, S. (2026) Mot tillförlitlig yttäckande packningskontroll – lärdomar från fullskaleförsök. Presentation och artikel på *Grundläggningsdagen 12 mars 2026*. Stockholmsmässan, Älvsjö, SGF – Svenska Geotekniska Föreningen. 12 sidor.
- SBUF Projekt 14198 Slutrapport. Utvecklad packningskontroll för framtidens kvalitetssäkring – Etapp 1.


KTH
VETENSKAP
OCH KONST