XXIV[th] WORLD ROAD CONGRESS
Mexico City 2011

A DYNAMICAL TIME-DOMAIN ANALYSIS FOR HEAVY WEIGHT DEFLECTOMETERS BACKACALCULATIONS

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dgac
STAC

PLAN OF THE PRESENTATION

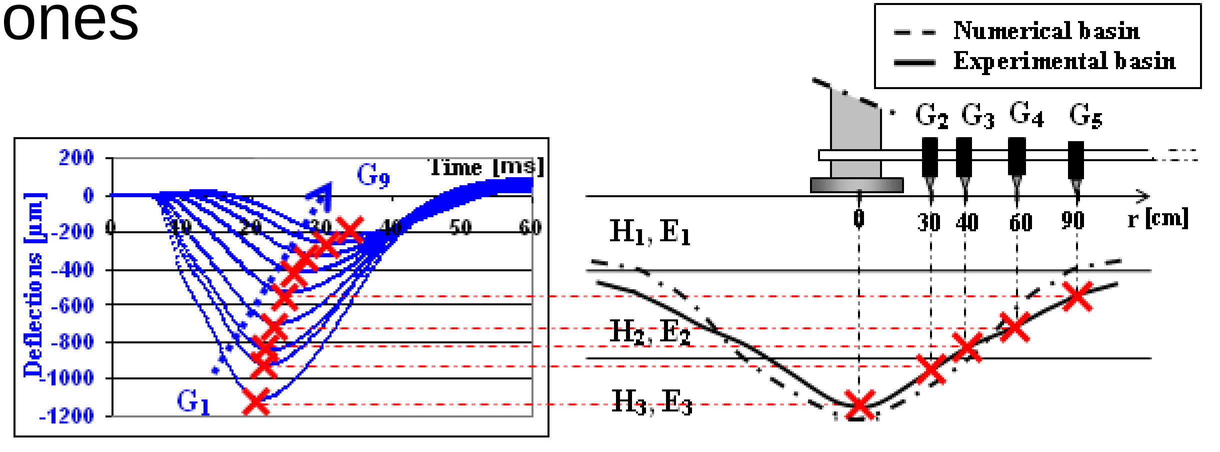
- Study framework
- Development of a dynamical mechanical modelling and associated backcalculation procedure
- Case studies and field validation
- Conclusions and perspectives

Burmister multilayered elastic model (Alizé ; BakFAA) or MET (Rosydesign)

- Calculation of deformations induced by static plate loadings

Identification performed using a « pseudo-static » basin

- Generated from maxima recorded on each of the 9 geophones



a) b)

- Minimization of the function: $f(\vec{E}) = \sum_{k=1}^{m} q_k \left(w_k\left(\vec{E}\right) - d_k\right)^2$

LIMITATIONS OF THESE USUAL METHODS

They can lead to unrealistic results, since:

- They are based on static modelling which does not correspond to the observed physical phenomenon

- The identification of mechanical parameters is performed using the pseudo-static deflection basin. This leads to use only a few part of the available information (maximal deflection for each geophone)

➡ **STAC has interested to dynamic methods**

DYNAMIC METHODS IN THE LITTERATURE

Frequency-domain methods ([Al Khoury et al., 2001]; [Grenier, 2007];…)

- Principle:

Spectral decomposition - analytical solutions - backcalculation - inverse FFT

- Weakness:

Roundtrip FFT/inverse FFT which can lead to significant errors [Chatti, 2004].

➡ **STAC chose to develop a time-domain method**

MAIN OBJECTIVES OF THE STUDY

1) **To develop a dynamical pavement modelling for HWD data**

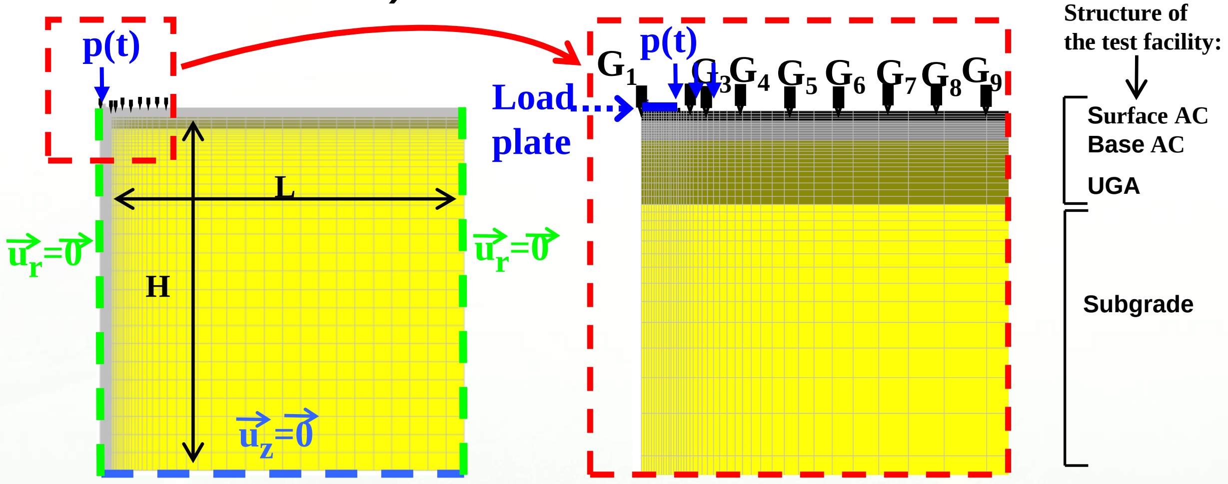
- taking into account the dynamic nature of the load, the inertia effects and damping in the pavement,
- allowing the calculation of time-related deflections imparted to the pavement.

2) **To propose an associated backcalculation automated procedure**

MECHANICAL MODELLING AND ASSOCIATED BACKCALCULATION PROCEDURE

Multilayered linear elastic modelling + Rayleigh damping

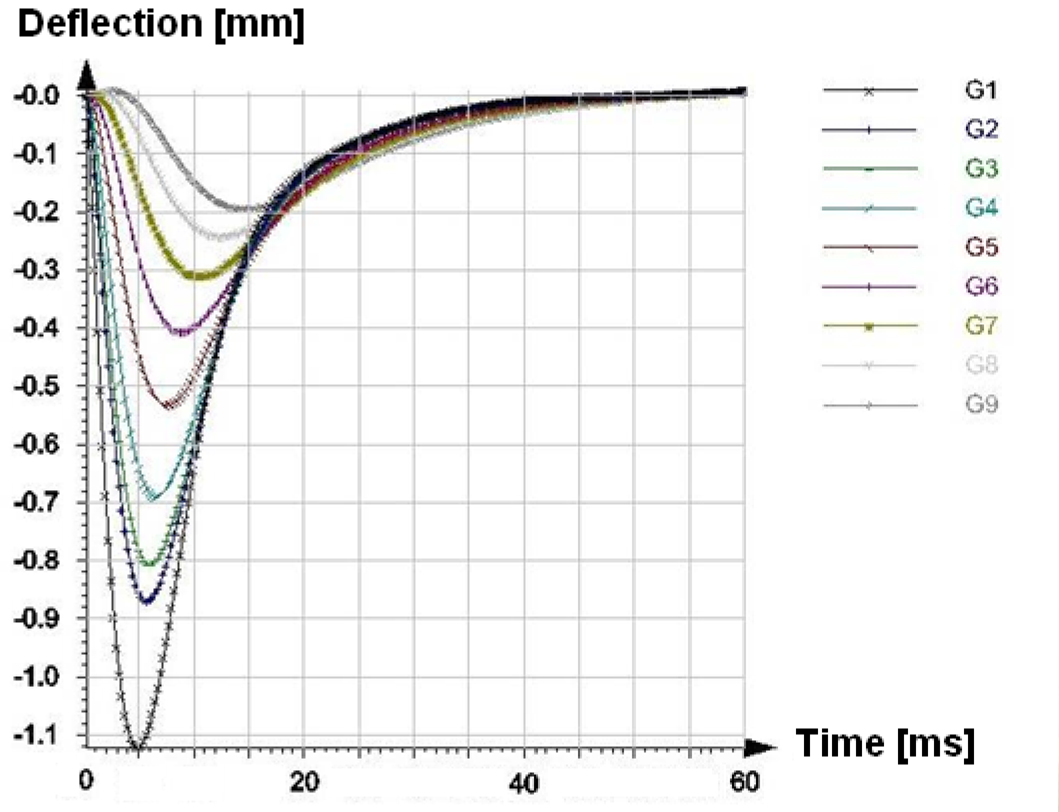
- FEM modelling (CESAR software; [Piau,1984]; [Humbert,1989])
- External action: force history (measured by force sensor integrated in HWD foot)



(Mesh optimized)

TYPICAL RESULTS

Time-related surface deflections



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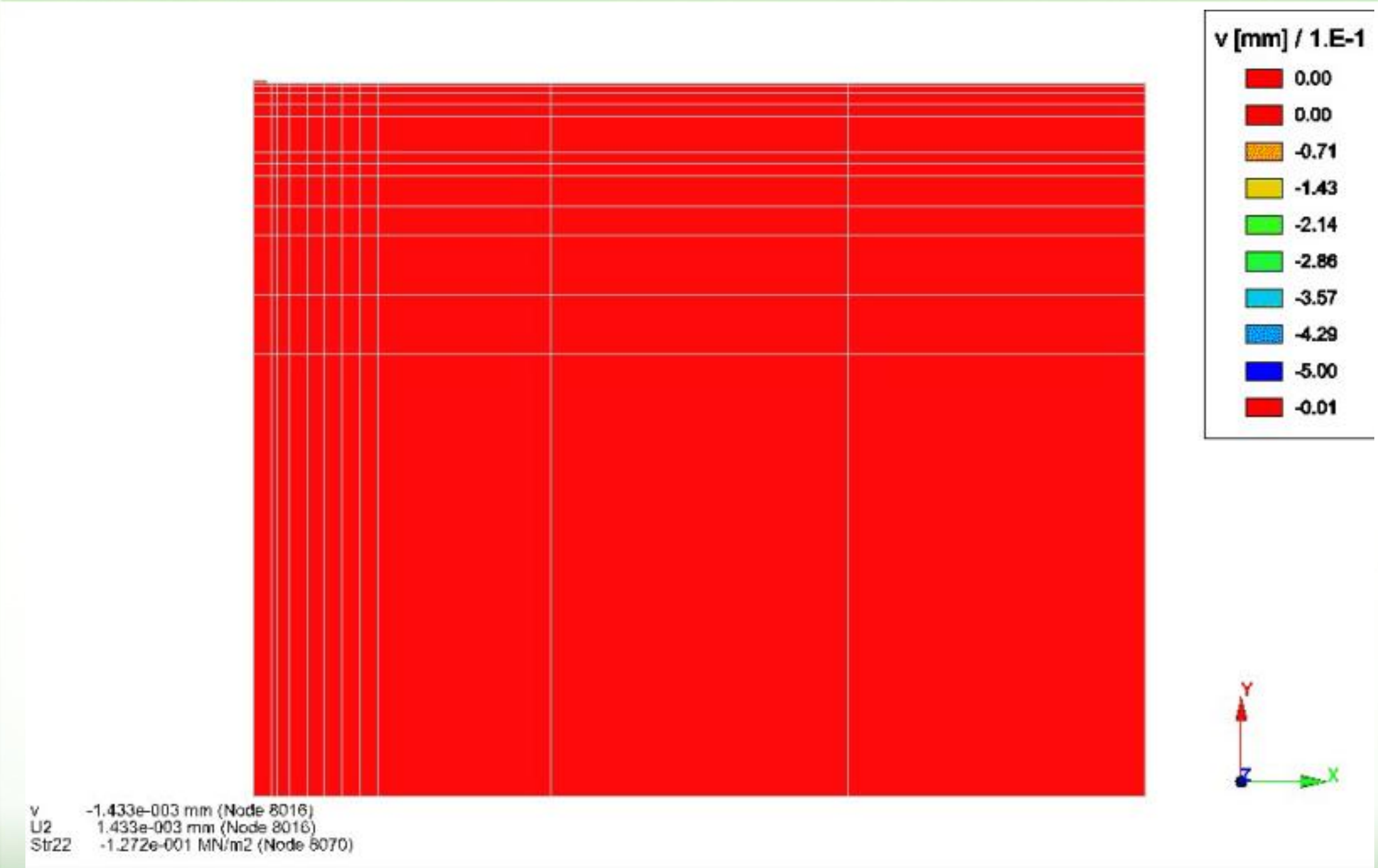


PARAMETERS

Known parameters

- Thicknesses (including depth to bedrock) + densities supposed to be known
- Poisson's ratio assumed

Parameters to be backcalculated

- Pseudo-static method: Young's moduli
- Dynamic methods: Young's moduli + damping

GAUSS NEWTON ALGORITHM

Problem: Finding $\min_{\vec{E} \in \Re_+^{n+1}} f_t(\vec{E}) = \sum_{st=st\min}^{st\max} \sum_{k=1}^{m} q_k \left(w_k\left(\vec{E}, st\right) - d_k(st)\right)^2$

Iterative process:

1) Initialization: choice of a seed moduli set: $\vec{E}^0$

2) Resolution at Nth step: $S^N \cdot d\vec{E}^N = \vec{R}^N$

with $S_{ij}^N = \sum_{st=st\min}^{st\max} \sum_{k=1}^{m} q_k \frac{\partial w_k}{\partial E_i} \frac{\partial w_k}{\partial E_j}$ and $\vec{R}_j^N = -\sum_{st=st\min}^{st\max} \sum_{k=1}^{m} q_k \left(w_k\left(\vec{E}^N, t\right) - d_k(t)\right) \times \frac{\partial w_k}{\partial E_j}$

In practice $\frac{\partial w_k}{\partial E_j} \approx \frac{w_k\left(E_1^{N-1},........, E_j^{N-1} + \Delta E_j^N,........, E_{n+1}^{N-1}\right) - w_k\left(E_1^{N-1},........, E_j^{N-1},........, E_{n+1}^{N-1}\right)}{\Delta E_j^N}$

3) Updating parameters $\vec{E}^N = \vec{E}^{N-1} + d\vec{E}^N$

4) Stopping of the process when $\left\| f_t(\vec{E}_N) \right\| \le e_0$ or $N \ge N_0$

CHOICE OF A TARGET ERROR (e_0)

Has relied on coupled results from repeatability and sensitivity study

$$U^2(f_t) = \sum_{k=1}^{m}\left(\sum_{st=st\min}^{st\max}\lambda_{k,st}^2 U^2(d_{k,st})\right) + \sum_{k=1}^{m}\left(\sum_{st=st\min}^{st\max}\lambda'^2_{k,st} U^2(w_{k,st})\right)$$

It is assumed that $w_k \approx d_k$

$U^2(d_k)$: obtained from repeatability study results

$$U^2(w_k) = \sum_{i=1}^{n}\sum_{st=st\min}^{st\max} S_{i,k,st}^2 U^2(\rho_i) + \sum_{i=1}^{n}\sum_{st=st\min}^{st\max} S'^2_{i,k,st} U^2(v_i) + \sum_{i=1}^{n}\sum_{st=st\min}^{st\max} S''^2_{i,k,st} U^2(t_i) + \sum_{st=st\min}^{st\max} S'''^2_{k,st} U^2(bd) + \sum_{st=st\min}^{st\max} S''''^2_{k,st} U^2(x_k)$$

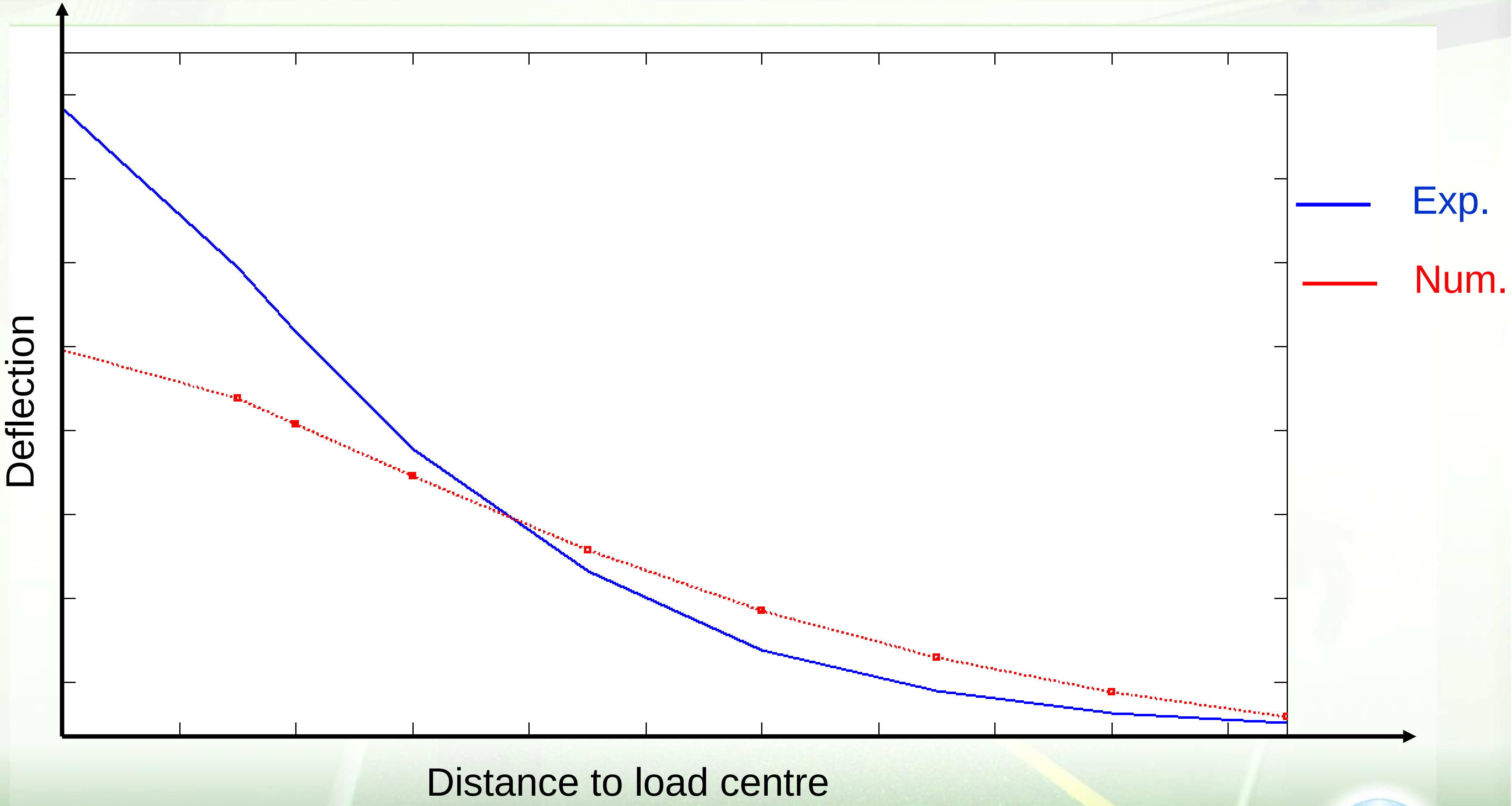
Also allowed to evaluate precisions attainable on backcalculated parameters

A NUMERICAL TOOL: THE PREDIWARE SOFTWARE
(PAVEMENT RATIONAL EVALUATION USING DEFLECTIONS INDUCED BY FALLING WEIGHTS FOR AIRFIELD AND ROAD ENGINEERS)

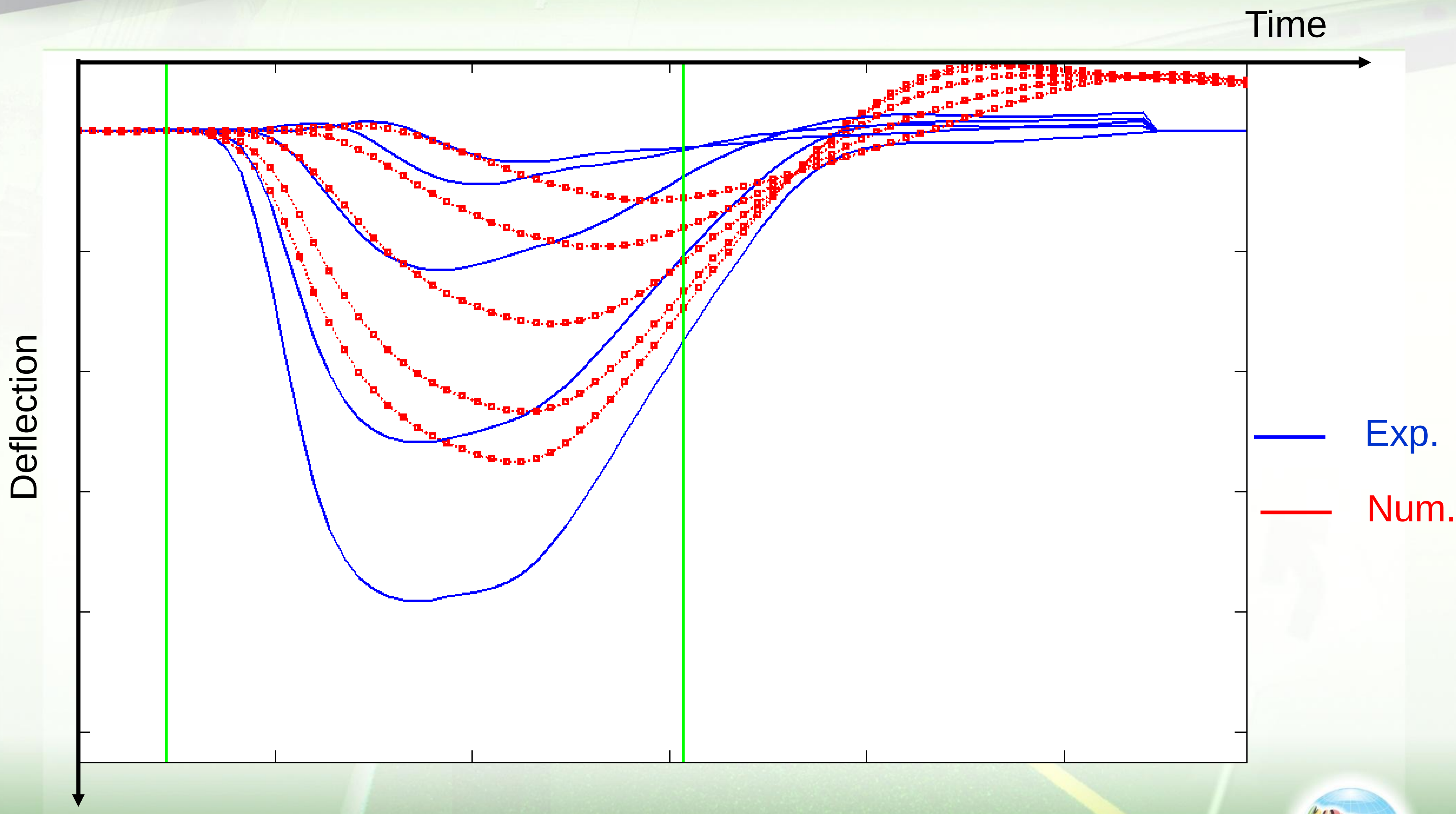
Provides the possibility to:

- Automating the creation of a mesh and the associated CESAR data file
  - ➢ Accounting for aforementioned optimization rules
- Performing direct calculations for a given structure
  - ➢ Static or dynamic (applied force modelling) calculation
  - ➢ Surface deflections and/or critical strains
- Performing backcalculations
  - ➢ Pseudo-static or dynamic method
  - ➢ Dynamic case: with fixed or backcalculated damping

PREDIWARE: PSEUDO-STATIC FITTING



PREDIWARE: DYNAMIC FITTING



PREDIWARE – NUMERICAL VALIDATION

1) Direct calculation

Comparison between Alizé and PREDIWARE (static case) without plate

- Using a selected common structure and a reference parameters set
- Comparison of surface deflections and strains

Geophone	G1	G2	G3	G4	G5	G6	G7	G8	G9
Alizé LCPC	258	220	203	169	122	86	58	38	24
PREDIWARE (Static without plate)	258	220	203	168	122	86	58	38	24

Considered stress	σ_{XX} (Bottom of AC)	σ_{ZZ} (Bottom of AC)	σ_{XX} (Top of UGA)	σ_{ZZ} (Top of UGA)	σ_{XX} (Top of S)	σ_{ZZ} (Top of S)
Alizé LCPC	-1.166	0.05	0.003	0.05	0.001	0.028
PREDIWARE Static without plate	-1.159	0.048	0.0033	0.050	0.0014	0.0281

2) Backcalculation (test on simulated data set)

- Using:
  - a selected common structure
  - a reference parameters set
  - 9 random parameters sets (in a "physically reasonable" range)
- Creation of a simulated data set (using reference parameters set)
- Comparison between backcalculated parameters with reference data set
- Same work performed in both pseudo-static and dynamic cases

	Seed moduli sets					Backcalculated moduli sets (Stat)					Backcalculated moduli sets (Dyn)				
	AC1	AC2	UGA	G	S	AC1	AC2	UGA	G	S	AC1	AC2	UGA	G	S
Ref	4700	9000	200	150	120	4700	9000	200	150	120	4700	9000	200	150	120
SMS2	4476	10957	241	342	138	4657	9211	192	157	119	4665	9088	200.04	150.04	120.02
SMS3	6572	13368	275	260	108	4677	9115	196	154	119	4938	8464	199.31	149.81	119.82
SMS4	5054	10463	281	234	74	4654	9229	191	158	119	4747	8889	199.90	149.95	119.96
SMS5	2741	6691	255	205	38	4640	9292	189	160	118	4755	8871	199.87	149.94	119.96
SMS6	2645	13635	193	211	49	4837	8467	216	138	120	4762	8843	200.01	149.93	119.95
SMS7	2014	8236	280	192	79	4681	9080	197	152	120	4545	9383	200.43	150.18	120.11
SMS8	4843	4356	338	204	145	5154	7416	250	116	120	4849	8621	200.23	149.85	119.86
SMS9	3443	7908	256	237	82	4682	9083	197	153	120	4688	9033	199.99	150.02	120.01
SMS10	6332	8877	160	182	41	4672	9148	194	156	119	4723	8944	199.97	149.97	119.98
Mean	4055	8291	258	226	93	4742	8880	203	149	121	4736	8914	200	150	120
Std Dev	1450	3120	43	53	38	165	589	19	14	3	105	251	0	0	0
Var	35.8%	37.6%	16.7%	23.6%	40.8%	3.5%	6.7%	9.5%	9.3%	2.9%	2.2%	2.8%	0.1%	0.1%	0.1%

Validation means

1) Laboratory testing

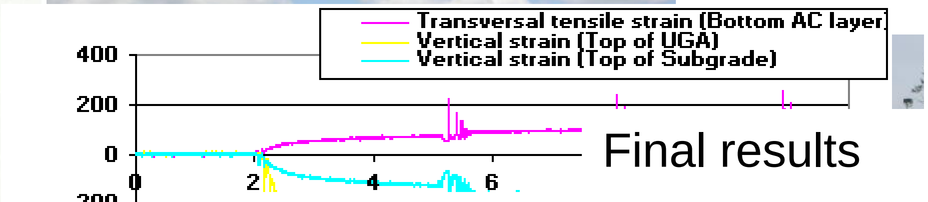
- Asphalt materials: complex moduli tests $|E^*| = \sqrt{E_1^2 + E_2^2}$; $\xi = Q^{-1} = \frac{1}{2} \times \frac{E_2}{E_1}$
  - Subgrade and untreated materials: resonant column tests [ASTM]

1) Gage measurements: feasability study on the LCPC's ALT facility

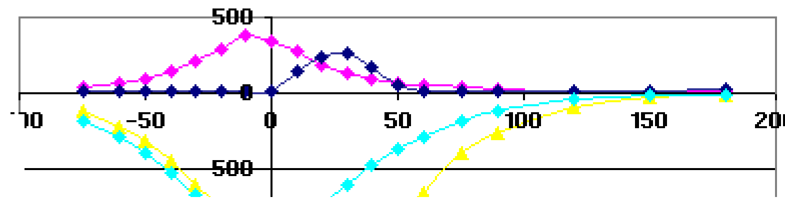
- Development of a specific experimental protocol (which can be extended to the study every instrumented test facilities)

EXPERIMENTAL PROTOCOL

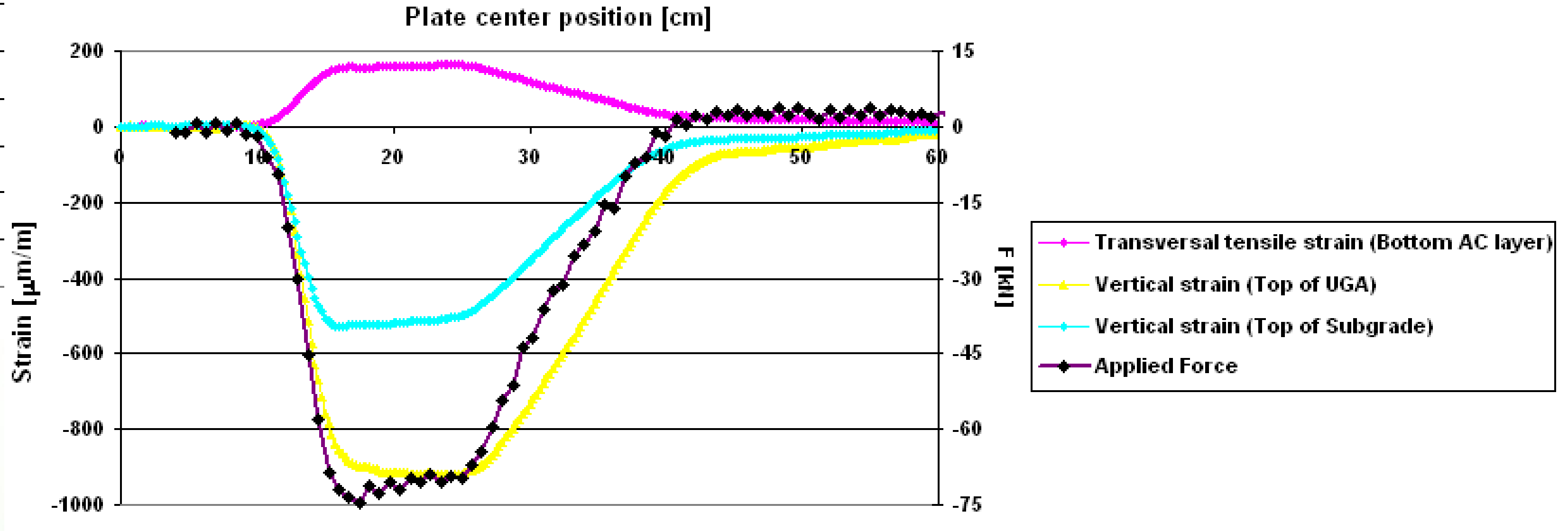
Typical results

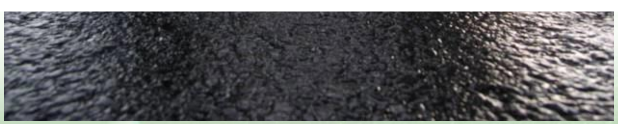


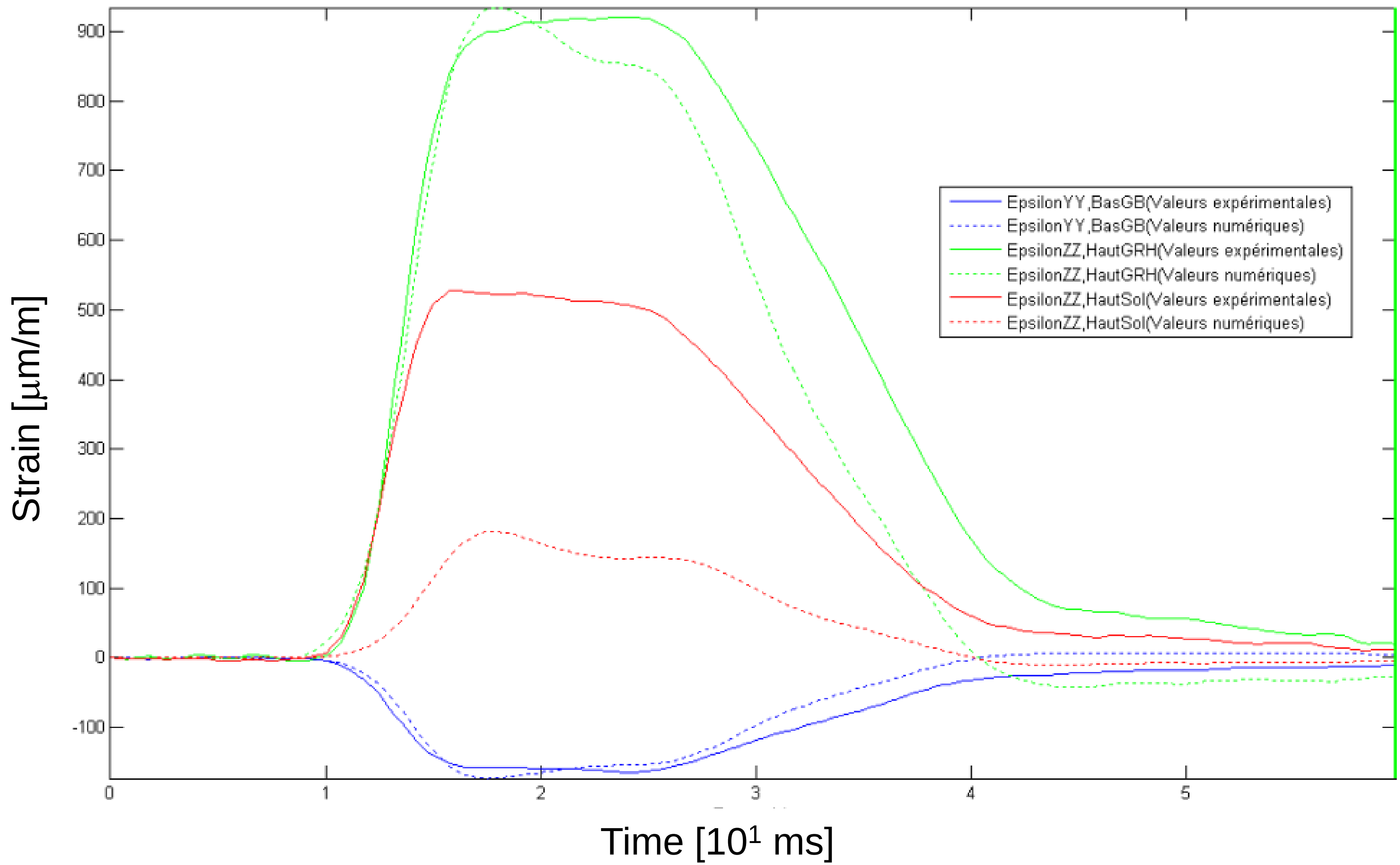
Sensors pre-localization



Final results







Strain [µm/m]
Time [10¹ ms]
900
800
700
600
500
400
300
200
100
0
-100
0
1
2
3
4
5
EpsilonYY,BasGB(Valeurs expérimentales)
EpsilonYY,BasGB(Valeurs numériques)
EpsilonZZ,HautGRH(Valeurs expérimentales)
EpsilonZZ,HautGRH(Valeurs numériques)
EpsilonZZ,HautSol(Valeurs expérimentales)
EpsilonZZ,HautSol(Valeurs numériques)

Dynamic method provides:

- More robust than the pseudo-static method
- Better for deep layers than the pseudo-static method

For Both methods:

- Important discrepancy between backcalculated and expected values for asphalt layers
- Potential explanations:

1) Viscoelastic behaviour not taken into account
2) Damping modelling to be improved
3) Layer bonding ?

Conclusions

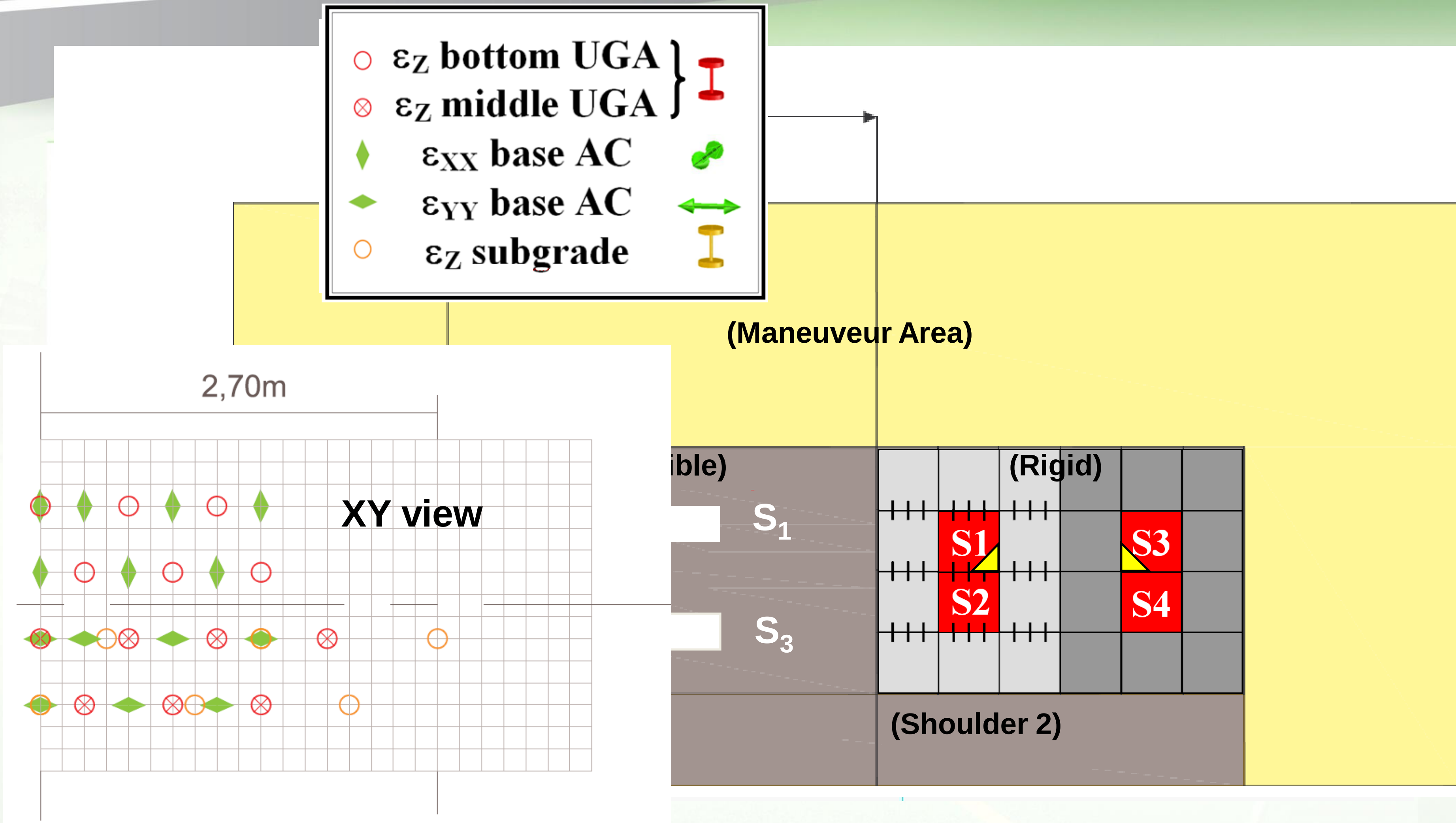
- **A dynamical model has been developed**
- **Associated backcalculation**
- **A numerical tool has been created to automate calculations**

- **First backcalculation results are promising**
- **Nevertheless discrepancies with expected results for asphalt layers**
- **Next steps of work:**
  - Improvements of the model (viscoelasticity/damping/bonding)
  - The STAC's test facility will be a priviledged validation tool

Wide-scale validation tool: the STAC's instrumented test facility

Strains sensors

- ε_z **(Subgrade and UGA)**
- ε_{xx} **and** ε_{yy}**(bottom of asphalt layer)**



εZ bottom UGA
εZ middle UGA
εXX base AC
εYY base AC
εZ subgrade
(Maneuveur Area)
2,70m
XY view
ible)
(Rigid)
S1
S3
S1
S2
S3
S4
(Shoulder 2)

STAC'S INSTRUMENTED TEST FACILITY

1) **A validation tool of mechanical modelling**
   - To date: fitting of the model relies only on surface deflections.
   - With the test facility : strain values are available at different critical levels in the structure.

2) **A priviledged site for F/HWD (or other apparatus) crossed tests**

3) **An in-situ calibration site of material**
   - Deflection history measured thanks to deep anchors
   - Force history measured thanks to test bench

Thank you for attention…

…and for further information:

Michaël BROUTIN PhD thesis:

« Assessment of flexible airfield pavements using Heavy Weight Deflectometers; Development of a FEM dynamical time-domain analysis for the backcalculation of structural properties » ; June 2010

http://www.stac.aviation-civile.gouv.fr/chaussee/ausc_hwd.php