Modeling of 1D wave propagation in nonlinear soils using the elasto-plastic Iwan model by four numerical schemes

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1. Context and objectives

The international project ***PRENOLIN*** *i*s focused on verification and validation of numerical codes for ground motion simulations including nonlinear soil rheologies. In this particular study, we present implementations of the elasto-plastic Iwan model (Iwan, 1967) into numerical schemes based on finite-difference, finite element, spectral element and discontinuous Galerkin methods, and results based on test numerical simulations.

We study the amplification of ground motion in a soft layer with nonlinear behavior overlying a half-space with linear behavior. We assume a vertically incident plane SH wave with source-time function given by a Gabor wavelet. We include different amplitude levels and frequency ranges. Special attention is given to the hysteresis loops and the reversal points in the stress-strain plane, and their effects on the computed seismograms and corresponding transfer functions.

We compare key aspects of the individual numerical schemes and methods, and their advantages and disadvantages.

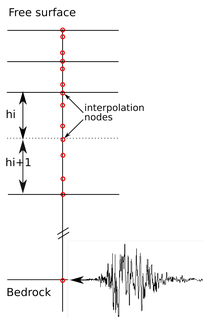
2. Numerical test : 1D soil column

Equation of motion $\rho \frac{\partial v}{\partial t} = \frac{\partial \sigma}{\partial x}$

$\sigma = G(\epsilon)\,\epsilon = \mathrm{Iwan}(\epsilon)$

where v velocity, ϵ strain, σ stress, ρ the density, and G the shear modulus

- Iwan elasto-plastic model
- Total stress analysis (no pore pressure build up)
- No viscoelastic attenuation (all hysteretic)
- No « damping control » → *Masing* rules
- Homogeneous layer over elastic half space
- SH input motion : Gabor wavelet (fc = 3.75 Hz)
- Rigid or elastic boundary conditions at the bottom



H (m)	Vs (m/s)
20	300
∞	1000

→ f0= 3.75 Hz

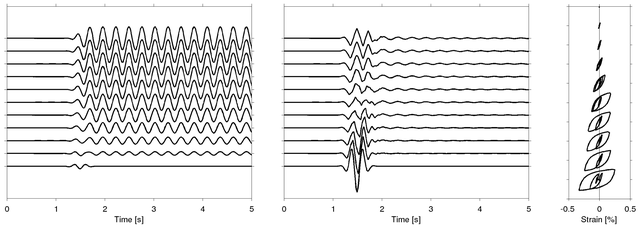


Figure 1. Model of the soil column with the input motion applied at the basement node.

Figure 2. Velocity seismograms at each depth (Z=0m on top, Z=20 m at the bottom). Input motion 1 g Peak Ground Accerelation. Left : example of a linear elastic simulation (rigid base), Center : non-linear simulation (rigid base), and Right : stress-strain curves at different depths (Z=1 m to Z = 19 m)

3. Iwan (series-parallel) model

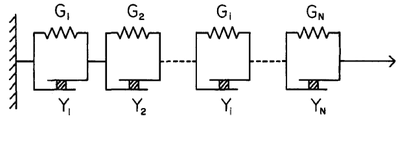


Figure 3. Model used for constitutve relation. It consists of simple elastic springs with constants Gi and Coulomb friction elements with yield stresses Yi (modified from Joyner and Chen, 1975)

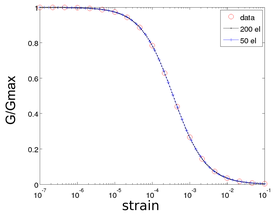


Figure 4. Shear modulus degradation curve interpolated by different number of Iwan elements

4. Results

Three levels of input motion : PGA 0.01 g, 0.1 g and 1 g

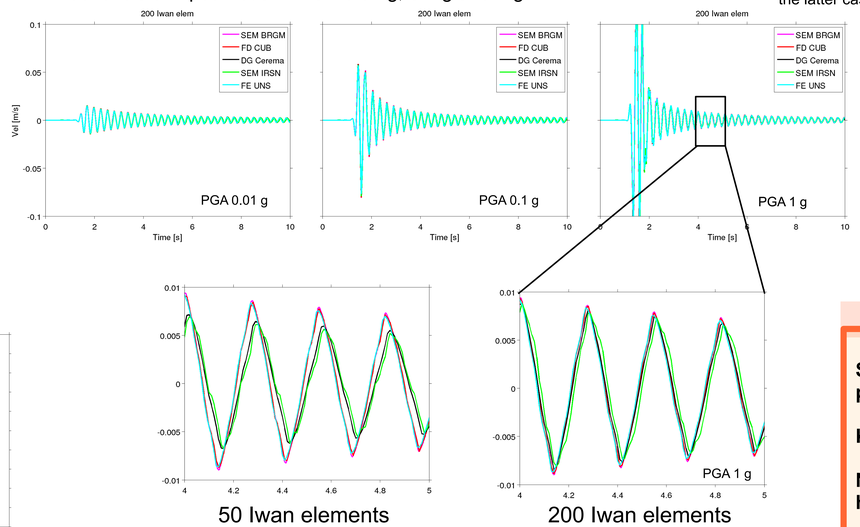
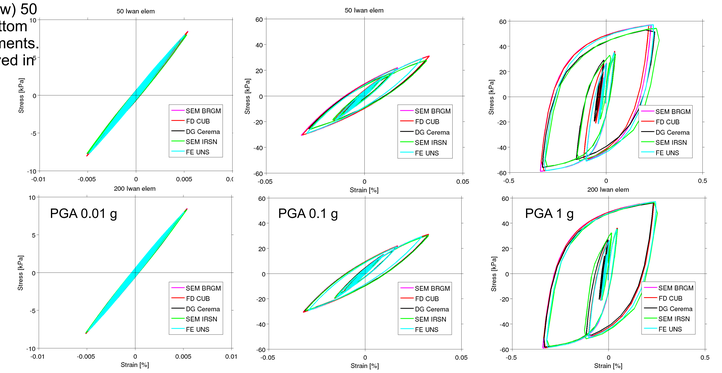


Figure 5. Comparison of velocity seismograms at Z=0 m for three different input motion levels. (bottom) Detail between 4 s and 5 s for the highest input acceleration (PGA 1g), where we can see the improvement in the convergence when the number of Iwan elements is increased from 50 to 200 elements.

Team	Method	Scheme	Spatial grid	Spatial sampling	Eq. of motion	Rheology for nonlinear
A. Richterova CUB	FD	(2,4) displacement-velocity-stress	uniform Cartesian staggered grid	minimum 6 grid spacings per minimum wavelength at any time	strong form	original Iwan elastoplastic
F. De Martin BRGM	SFEM	Legendre 4th to nth - order polynomial Gauss-Lobatto-Legendre integration	unstructured Cartesian grid	minimum 5 grid spacings per minimum wavelength at any time	weak form	hyperbolic model with extended Masing rules
D Mercerat CEREMA	discontinuous Galerkin FEM	Lagrangian interpolation in space (any order) / upwind fluxes / 4th order explicit Runge-Kutta for time integration	any FEM grid	minimum 5 interpolation points per minimum wavelength at any time	weak form	original Iwan elastoplastic
Santisi d'Avila M.P. UNICE	FEM	Gauss for spatial integration, Newmark for time integration	3 nodes line FE, 3 dof per node	minimum 10 nodes per shear wavelength possibility to reduce vs until 70%	weak form	3D Iwan elastoplastic
Elif Oral IRSN-IFSTTAR	SFEM	Legendre 4th to nth - order polynomial Gauss-Lobatto-Legendre integration	unstructured Cartesian grid	minimum 5 grid spacings per minimum wavelength at any time	weak form	original Iwan elastoplastic

Summary table with the five different codes participating in the comparison.

Figure 6. Stress-strain curves at Z=19m for : (top row) 50 Iwan elements (bottom row) 200 Iwan elements. The fiting is improved in the latter case.



5. Conclusions

Satisfactory fit between different numerical methods modeling non-linear wave propagation with Iwan elasto-plastic model

Key parameter : number of Iwan elements to interpolate the shear modulus decay

Next step: implementation of damping control (i.e. no Masing rules for hysteresis loops)

If you are interested in validation of these codes with real data (KikNet sites) please attend the presentation 15-526 on Thurdsday, 3:45 pm, Ballroom G :
PRENOLIN project: a benchmark on numerical simulation of 1D nonlinear site effect : Validation on real sites*, by Bard P-Y *et al.