

Implementation of Iwan-type Plasticity Model in AWP-ODC

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Introduction

- Strong ground motions recorded on vertical arrays indicate that site response formalism (decoupled from source and path effects) fails to reproduce empirical surface-to-borehole transfer functions in the majority of cases due to the presence of lateral heterogeneities (e.g., Thompson *et al.*, 2012)
- These observations motivated one of SCEC's research priorities and the creation of a Technical Activity Group, with the goal of understanding ground motions as the coupled response of inelastic off-fault and shallow nonlinear behavior.
- Prediction of nonlinear amplification effects for complex subsurface topography will depend on high-performance computing applications which accurately represent the stress-strain relationship of shallow crustal material (e.g., weathered rock or soils).
- One such application is the highly efficient and scalable finite difference code AWP-ODC. However, AWP previously only supported nonlinearity based on a single Drucker-Prager (or von Mises) yield surface, which may result in inaccurate prediction of ground motions in scenario simulations.
- Here, we add support for a multi-surface Iwan-type nonlinear model in AWP. The accuracy of the method is verified against reference solutions obtained with the Noah (Bonilla *et al.*, 2005, 2006) code in 1D and 2D benchmark problems.

1D Benchmark Verification

- We simulate the 1D response of the KiK-net site KSRH10, which served as a test case in the PRENOLIN code verification and validation benchmark (Regnier *et al.*, 2016, 2018).
- Plane strain conditions were specified in AWP by selecting periodic boundary conditions and defining the source as a plane wave entering at the bottom of the domain.
- Soil properties were defined following Regnier *et al.* (2015), with the reference strain for each layer derived from the provided friction angles and cohesions.
- The downhole E-W seismogram recorded during the M_w 6 earthquake of Nov 29, 2004 was used as input signal.
- Surface time series obtained with AWP are consistent with Noah's reference solution in the linear case (Fig. 3a). Time series obtained with AWP-Iwan (Fig. 3b) closely follow the reference solution obtained with Noah using the strain-space-multishear plasticity model (lai *et al.*, 1992).
- The Iwan and lai models predict significantly reduced amplification compared to the linear case. Nonlinear effects predicted with a single von Mises yield surface are less pronounced (Fig. 4).

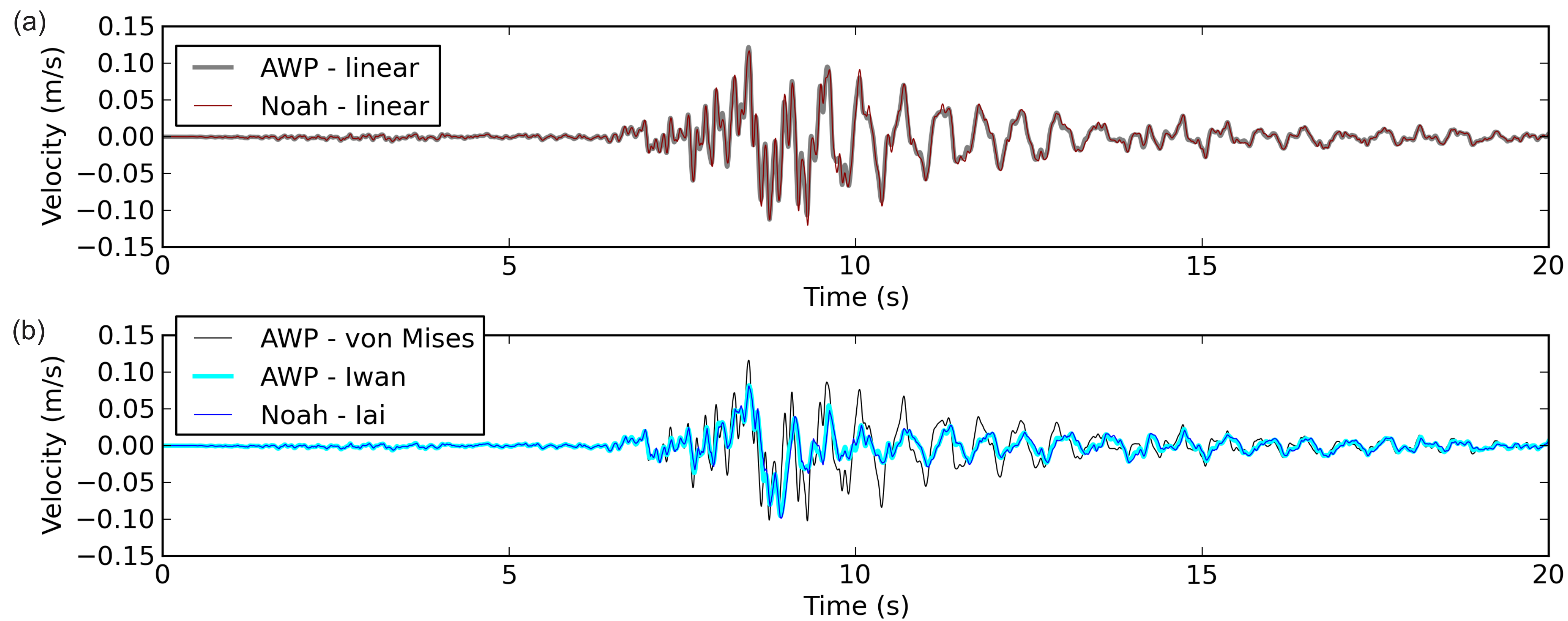
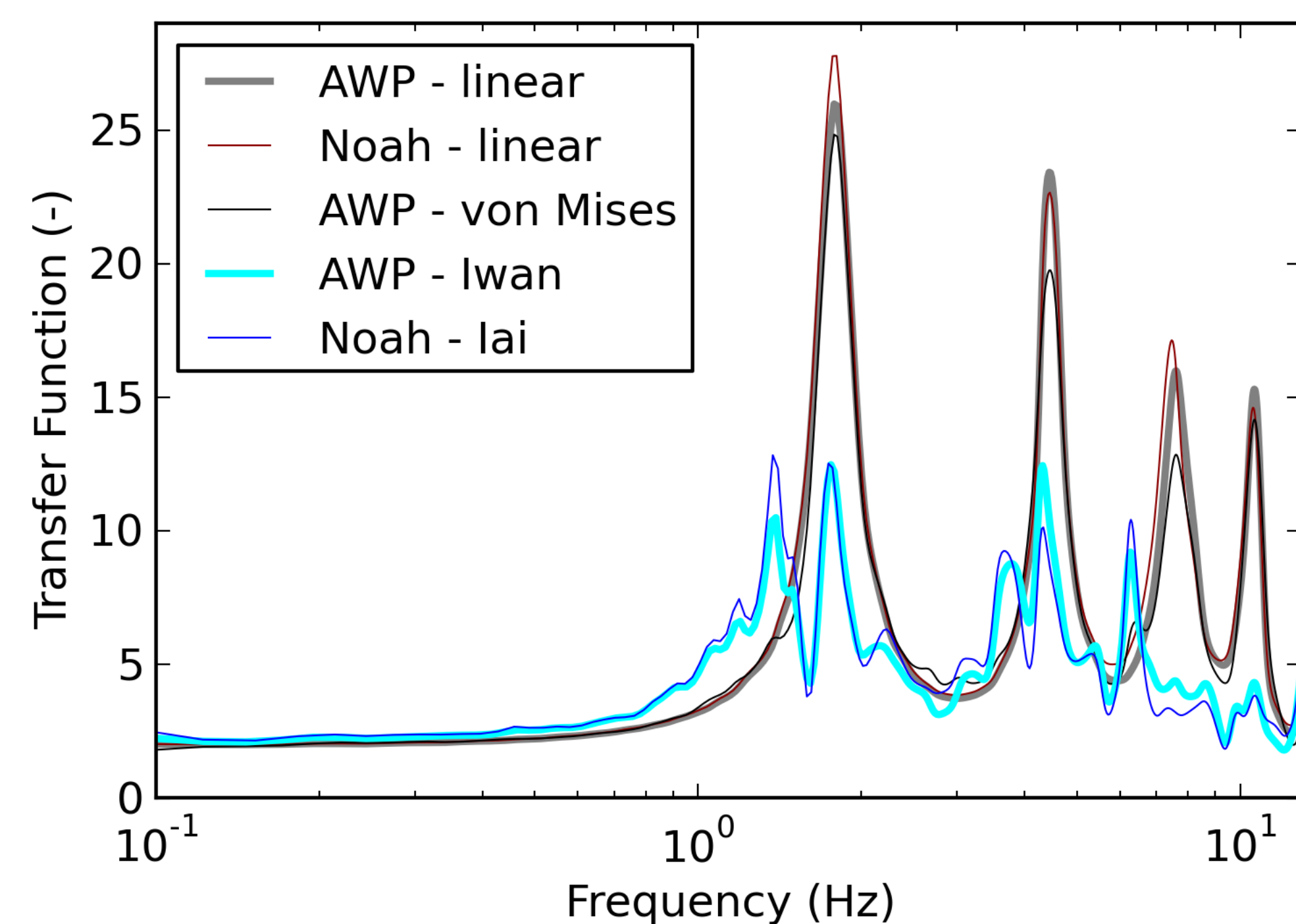


Figure 3. Comparison of simulated surface velocity time series at KiK-net site KSRH10 obtained with AWP and Noah in (a) linear and (b) nonlinear case using a single von Mises yield surface, the Iwan model and the strain-space-multishear model (lai *et al.*, 1992).

Figure 4. Surface-to-borehole Fourier transfer functions obtained using AWP and Noah.



Selected References

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Multi-surface Yield Model Based on Overlay Concept

- AWP-Iwan tracks a series of von Mises yield surfaces arranged in a parallel-series configuration (Fig. 1), which in combination reproduce the behavior of a general class of material models originally conceived by Iwan (1967) and Mroz (1967).
- This overlay approach (Kaklamano *et al.*, 2015) is capable of modeling Masing unloading and reloading behavior as well as the Bauschinger effect.
- Each yield surface is characterized by its own Lamé parameters λ , μ and yield stress τ , which are computed to approximate a pre-defined backbone curve (Fig. 2).
- Stress updates are carried out separately for each yield surface. First the trial stress is computed from the Lamé parameters pertaining to each spring. Second the return map algorithm is invoked using the yield stress of the individual yield surface.
- Velocity updates are computed from the compound (overlay) stress field which is obtained by summation over the individual stress tensors.
- Because 10-20 yield surfaces must be used for accurate results, the computational demand of the overlay method is substantial. Memory requirements are also significantly increased with respect to the linear case, because the stress tensor pertaining to each yield surface must be stored.

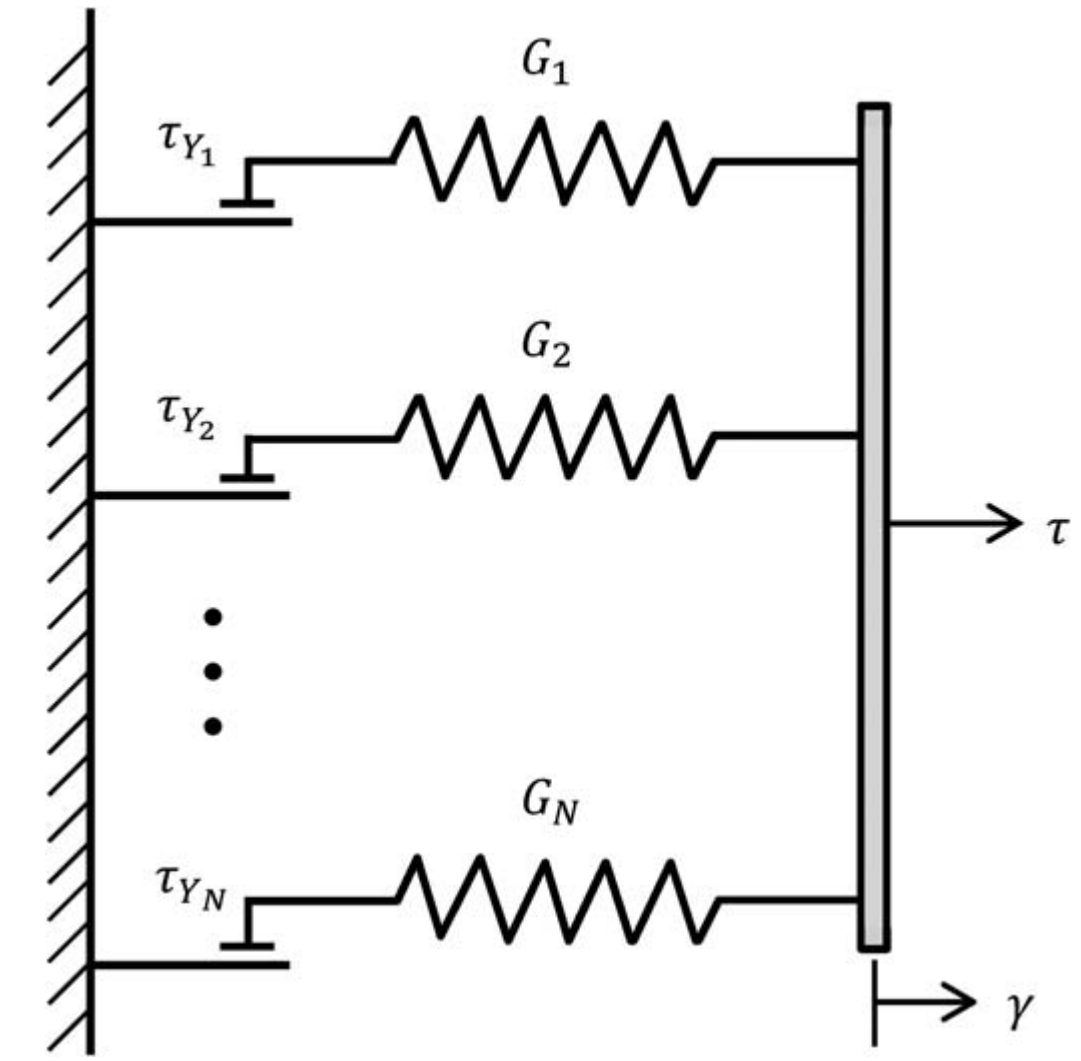


Figure 1. Parallel-series configuration of spring-slider combination in 1D Iwan model (from Kaklamano *et al.*, 2015)

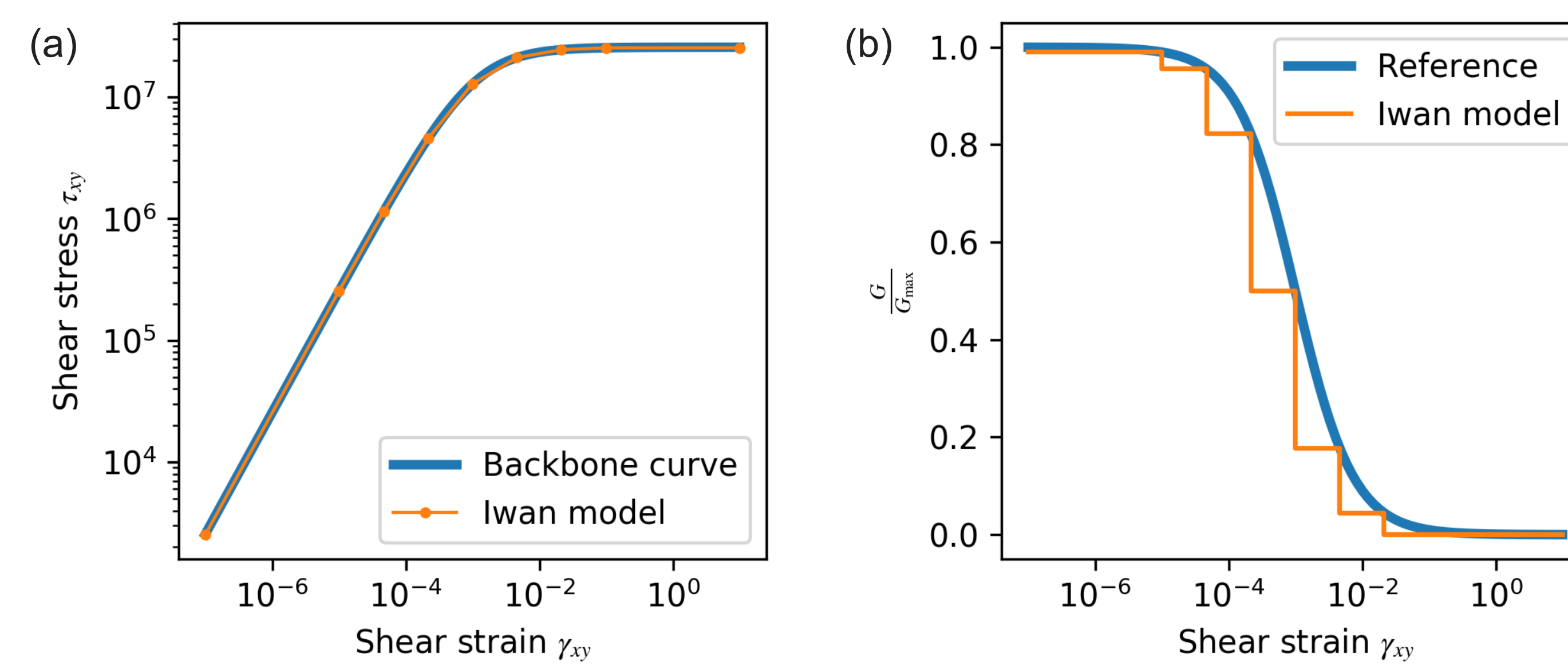


Figure 2. (a) Backbone curve showing shear stress as function of shear strain for a hyperbolic model with a reference strain of $\gamma_r = 10^{-3}$ and the Iwan model using 7 spring-slider combinations. (b) Shear modulus reduction curve in the reference solution and approximated by the Iwan model.

2D Benchmark Verification

- We verified AWP-Iwan for the 2D case by carrying out a P-SV simulation and computing a reference solution using Noah2D.
- The source is defined as a vertically incident, plane wave composed of a Ricker wavelet with a central frequency of 2 Hz in the transverse (perpendicular to valley axis) direction.
- The structure consists of a generic sediment-filled valley characterized by a sloping and sine-shaped sediment-bedrock interface and a strong velocity contrast (Fig. 5b).
- The horizontal discretization Δh was set to 2 m in AWP-Iwan and to 1 m in Noah2D.
- Time series obtained with AWP and Noah2D are very similar in shape and amplitude (Fig. 2a). In both codes, peak velocities in the valley center are reduced from 38 cm/s in the linear case (not shown) to ~20 cm/s in the nonlinear case; in addition, the nonlinearity greatly reduces the duration of the shaking.

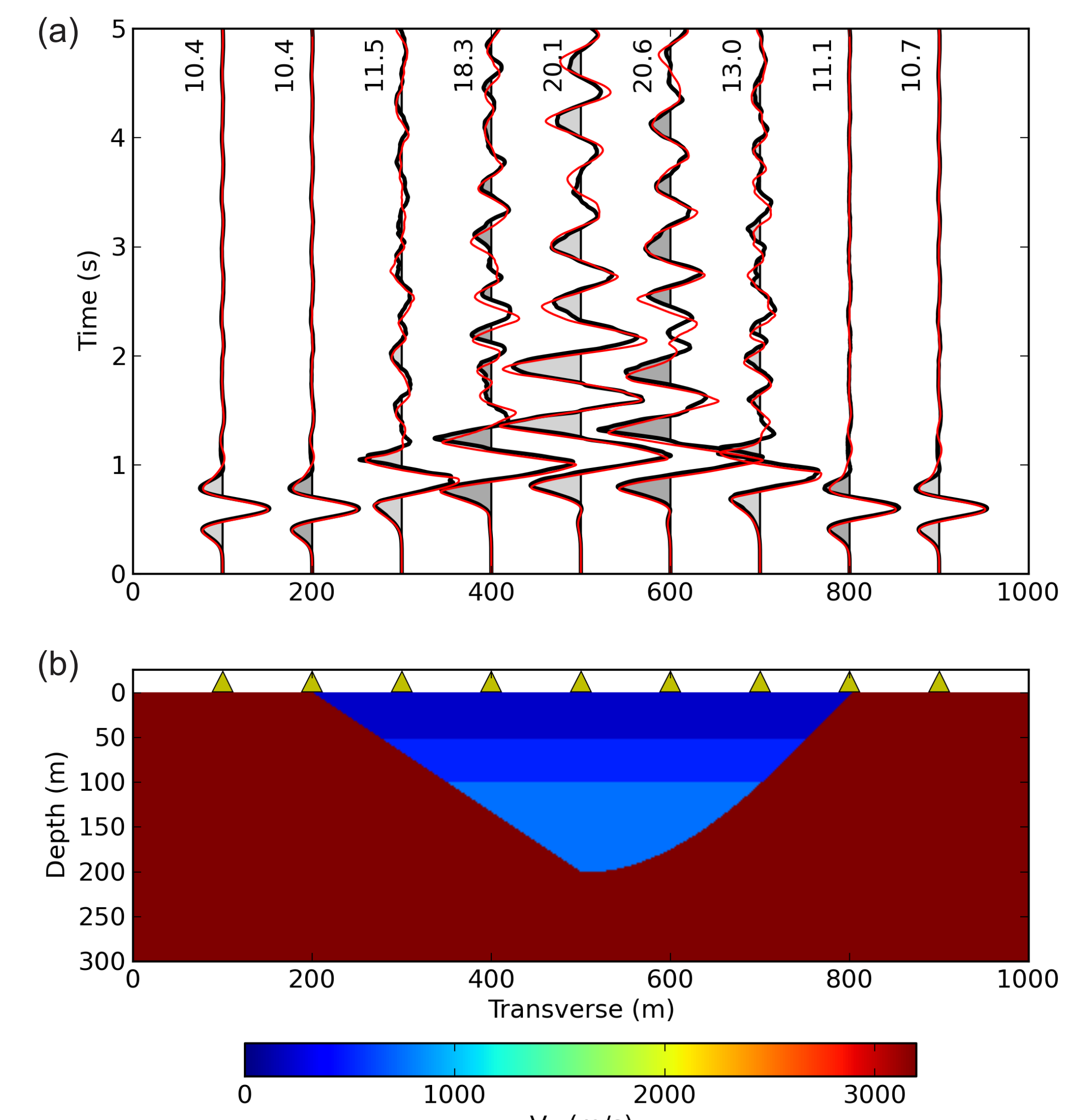


Figure 5. Comparison of transverse velocity time series obtained from 2D nonlinear P-SV wave propagation inside a sediment-filled valley. (a) Black semi-filled wiggles show the solution obtained with AWP-Iwan; the reference solution calculated by Noah2D is plotted in red. (b) Cross-section through valley with shear-velocity and location of plotted stations.

Summary and Outlook

- Time series obtained using AWP-Iwan agree well with reference solutions calculated with the Noah code in the selected 1D and 2D benchmarks.
- Because Noah has been verified against other nonlinear codes and validated against observations (e.g., Regnier *et al.*, 2016, 2018), this implies that the implementation of the Iwan model is working correctly in AWP.
- Benchmark results shown here were obtained using 20 yield surfaces, although we found acceptable solutions using 10-15 yield surfaces, as already noted by Kaklamano *et al.* (2015).
- The code still needs to be optimized for improved efficiency, as the compute and memory overhead associated with tracking several yield surfaces is currently very large.
- The prototype of AWP-Iwan was built on top of the CPU version of AWP due to the simpler programming model. The Iwan model will also be implemented in the highly efficient GPU version of AWP, which supports discontinuous finite different meshes for faster time-to-solution.

Acknowledgments

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