Research Project 3: Spectral Elements and Newmark Analysis

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This document describes the possible approaches for coupling Newmark's Formula with seismic wave propagation by a spectral element method. The final objective is the generation of earthquake-induced landslide susceptibility maps (LSM).

Additional Key Words and Phrases: Earthquake induced landslide, susceptibility maps, spectral element method, machine learning, PINN.

CONTEXT AND OVERVIEW

In this note, we will:

(1) Present weak coupling of Newmark's formula with a SEM code, to produce Newmark displacements, and finally an LSM, in 2 cases:
  (a) a simpler 2D case,
  (b) a more complete 3D case.
(2) Study strong coupling based on a PINN approach, where Newmark's formula is integrated into a machine learning model via the loss function—this could be considered as an option for Project 2.
(3) Investigate more complex physical modelling of landslides using a nonlinear, large-displacement FEM/SEM formulation.

1 RESEARCH PROJECTS

The topics for research projects will be discussed with PHIVOLCS. There are 3 tentative propositions detailed below. Note that each project relies on the contents of the training program [1, 2, 8], and the lectures, examples will need to be restudied and completed as the research progresses. The work on the projects will be divided into teams, with each team concentrating on one of them. Cross collaboration between the teams is strongly encouraged.

1.1 Project 1: EIL Inventory using ML

- Use tree-based ML on a landslide inventory to generate a detailed susceptibility map.
- Dashboards (interactive) for DRRM and risk scenario exploration.
- Use ML to update the hazard maps by integrating real-time data and continuously (re)learning from new events.
- Post Qualification (Landslide Inventory): (PE)ML can be used to validate and update the hazard maps by comparing predicted hazards with actual landslide occurrences.

1.2 Project 2: ML for Soil Parameters and FoS

- Use PEML to predict the FoS by taking into account the Newmark physics formulas.
- Perform a feature importance study on the 7 covariates (geotechnical parameters in Newmark).
- Perform a causality study, based on Shapley values, and integrate the results into the hazard/susceptibility map.
- Evaluate predictive performance of past forecasts and hazard maps.

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1.3 Project 3: SEM-Newmark Coupling for EILs

- Step 1: Simulate seismic wave propagation using SEM.
- Step 2: Predict landslide using Newmark displacement analysis.
- Step 3: Couple the above to predict Earthquake Induced Landslides. Study effects of duration of seismic events as well as peak amplitude. Evaluate risk for extreme events.

2 WEAK COUPLING OF NEWMARK-SEM

2.1 Newmark's formula

In terms of geotechnical soil and morphology parameters, the *static* factor of safety [6, 7] is,

$$\mathrm{FoS} = \underbrace{\frac{c'}{\gamma h \sin\alpha}}_{\text{cohesive}} + \underbrace{\frac{\tan\phi'}{\tan\alpha}}_{\text{frictional}} - \underbrace{\frac{m\gamma_w \tan\phi'}{\gamma\tan\alpha}}_{\text{pore pressure}}, \tag{1}$$

where

- ϕ' is the effective friction angle (from tables, lithology map)
- c' is the effective cohesion (from tables, lithology map),
- α is the slope angle (obtained from the DEM),
- γ is the material unit weight (from tables, lithology map),
- m is the proportion of slab thickness that is saturated (from rainfall data),
- γ_w is the unit weight of water, and
- h is the slope-normal thickness of the failure slab (sliding plane, empirical constant = 3.33m).

This factor is then used in the computation of the Newmark critical acceleration,

$$a_c = (\mathrm{FoS} - 1) g \sin\alpha.$$

The Newmark displacement is defined as an integral of the acceleration difference,

$$D_N = \int_{t_0}^{t_1} \int_{t_0}^{t_1} (a_s - a_c)\ \mathrm{d}t,$$

where a_s is the seismic acceleration, obtained from seismic recordings. This can be integrated directly over map units. Alternatively, one can use an empirical (regression) formula relating D_N to the Arias Intensity I_A,

$$\log I_A = M - 2\log R - 4.1,$$

where M is the Richter magnitude and R (m) the distance to the seismic source, or use

$$I_A = 0.9 t_d (\mathrm{PGA})^2,$$

where t_d is the Dobry time, itself estimated from

$$\log t_d = 0.423M - 1.83.$$

Then, the empirical formula that relates D_N (m) to I_A (m/s) and a_c is

$$\log D_N = 0.7605 \log I_A - 0.9965 \log a_c - 0.733.$$

2.2 Spectral Element Method (SEM)

Please consult the lecture notes on

- wave propagation,
- spectral finite elements.

2.3 The global workflow for Newmark-SEM coupling

The coupling, as presented in [10], is weak in the sense that we use the Newmark formula to compute the critical acceleration, a_c, which is then fed into the SEM that provides the seismic acceleration, a_s, which is then used to obtain the Newmark displacement, D_N. In Figures 1 and 2 we present a description that shows all the important parameters.

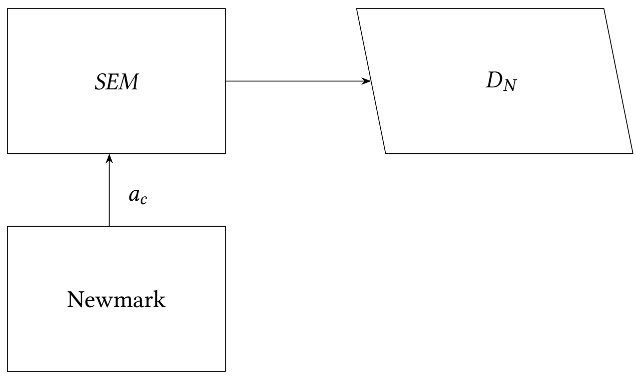

Fig. 1. Weak coupling between Newmark and SEM

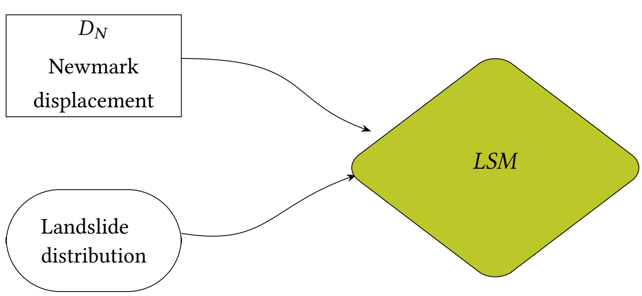

Fig. 2. Generation of the final Landslide Susceptibility Map (LSM)

3 STRONG COUPLING OF NEWMARK'S FORMULA USING A PINN APPROACH

The PINN approach is described in the lecture notes [1, 2]. This project proposal could be a part of Project 2, bit it could equally well be considered as being an option for Project 1. In additional to Newmark's formula, it is possible to integrate models of seismic wave propagation (SEM) into the PINN loss function, to ensure that the seismic acceleration itself respects physical laws.

Recall that the PINN loss function is a sum of terms

$$\mathcal{L}_{\text{PINN}} = \mathcal{L}_{\text{data}} + \mathcal{L}_{\Phi_1} + \cdots + \mathcal{L}_{\Phi_m},$$

where $\Phi_1, \ldots, \Phi_m$ are terms representing the physical losses, and are obtained by including physical formulas, differential equations, and boundary conditions. The term $\mathcal{L}_{\text{data}}$ is one of the standard machine learning loss functions—RMSE (least-squares) or cross entropy. Note that this is, in principle, a straightforward generalization of standard ML methods (RF, SVM, NN, etc.), but in reality requires a lot of tuning, and potentially a very long computation time.

In [9], the Newmark formula is included as a physical constraint for a neural network based machine learning method. Their formulation is very nice, and could serve as an example for application to PHIVOLCS data.

4 OTHER POSSIBLE RESEARCH DIRECTIONS

To go (much) further, one can consider:

- time-dependent, early-warning systems for “smart cities/regions”,
- nonlinear, large-displacment FEM modelling of EILs.

THINGS TO DO

- Carefully consider the *feasibility* of 3D spectral element simulations that require a 3D model of the zones of interest, including:
  - topography
  - geology
  - fault locations
  - seismic sources.
- Reproduce the very recent results of [9] on Philippine data, but this requires a digital model of the region (see previous point). Examine the feature importance and try to determine which features are really necessary to obtain reasonable accuracy.
- Use the approach of [9] on an academic, half-space problem, then a 3-layer problem as was done with SPEFEM3D in the Wave Propagation exercises of the training.
- Question: should one go all the way to D_N or stop before, at E, as in done actually at PHIVOLCS? This is a central question since it conditions the trustworthiness of the target variable for the ML training.

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