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SMART layers: a simple and robust alternative to PML approaches for elastodynamics

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SUMMARY

For considering elastic seismic wave propagation in large domains, efficient absorbing boundary conditions are required with numerical modelling in finite domains. Since their introduction by Bérenger, the perfectly matched layers (PML) has become the state-of-the art method because of its efficiency and ease of implementation. However, for anisotropic media, theoretical analysis and numerical experiments show that the PML method is amplifying, that is it exhibits numerical instabilities. Numerical experiments can also exhibit numerical instabilities of the PML when dealing with long time simulations even for isotropic media, especially for finite element methods in unstructured grids. Recently, a new method, called SMART layers approach, has been proposed. This method is shown to be stable even for anisotropic media. The drawback is that the SMART layers are not perfectly matched. We have implemented this new approach in a discontinuous Galerkin method and we illustrate that this method does not exhibit numerical instabilities while PML do for an isotropic elastodynamic simulation. We show that this approach is also competitive with respect to the PML method in terms of efficiency and computational cost.

Key words: Numerical solutions; Computational seismology; Wave propagation.

1 INTRODUCTION

For seismic wave propagation, we often consider the Earth as a semi-infinite medium. However, for the wavefield numerical computation, the domain of computation must be finite and as small as possible. Hence, we need to design absorbing boundary conditions (ABC) or absorbing layers at the edges of our numerical domain to avoid spurious reflections. The first-order ABC were introduced by Clayton & Engquist (1977). For planar waves perpendicular to a rectilinear edge, outgoing waves are fully absorbed. For 2-D and 3-D geometries, the waves arriving at oblique incidences are only partially absorbed and significant spurious reflections are observed at grazing angles. High-order ABC have been proposed to improve the performance of the first-order conditions. For example, Collino (1993) have proposed fractional high-order derivatives, but their implementation is not trivial, and the method is computationally intensive.

The alternative for the absorption of outgoing waves is the introduction of a layer beyond the edge where the wave is damped. In this strategy, the outgoing waves are slowly attenuated as they go deeper into the layer, while preventing any induced incoming wave. Cerjan *et al.* (1985) have introduced this strategy where a damping profile is designed inside the sponge layer with a significant efficient performance for grazing angles. Unfortunately, this technique induces also unwanted reflections between the domain of interest and the absorbing layer. A careful design of the damping profile is needed for the mitigation of these reflections, leading to rather thick layers. An improved method has been proposed by Bérenger (1994) for the Maxwell's equation as the impedance matching is perfect between the domain of interest and the absorbing layer in the continuum media: the reflection coefficient is exactly equal to zero at this interface. Unfortunately, after the domain discretization for numerical simulation, this property disappears and small reflections are generated. Even so, this approach turns out to be more efficient than any precedent strategy and since then they have been continuously developed in different domains of wave simulation.

For elastodynamics it has been used and investigated exhaustively (e.g. Chew & Liu 1996; Hastings *et al.* 1996; Collino & Tsogka 2001; Komatitsch & Tromp 2003). A successful modification to the perfectly matched layer (PML) strategy is the convolutional PML (C-PML), introduced by Komatitsch & Martin (2007), which improves the absorption at grazing angles and reduces the memory requirements. A strategy proposed to improve the stability of the PMLs is the modified PML (M-PML) method, which introduces additional absorbing terms in the directions tangential to the interface between the domain of interest and the absorbing layer. The

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Early Mesozoic Southern Mexico–Amazonian connection based on U–Pb ages from detrital zircons: The La Mora Paleo-River in the Mixteca Terrane and its paleogeographic and tectonic implications

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ABSTRACT

The La Mora Formation is the oldest Mesozoic floodplain succession in the Mixteca Terrane of Southern Mexico. The presence of Amazonian detrital zircons in the La Mora Formation and in the overlying volcanic Diquiyú Unit indicates a major fluvial system that drained the Mixteca Terrane. The La Mora Paleo-River crossed the Oaxaquia microcontinent and the Mixteca Terrane prior to the breakup of Pangea, during Late Triassic–Early Jurassic time, when the Acatlán–Oaxaquia block was part of the northwestern portion of the Amazonian craton. Detrital zircons in the La Mora Formation have ages between 3307 ± 31 and 210 ± 12 Ma, which suggest that they originated in Amazonia and Southern Mexico: 33.2% of the detrital zircons have ages that are found only in Amazonian sources; whereas 66.7% of the zircons may be associated with either the Amazonian craton, the Andean Basement, or Southern Mexico. We propose that the La Mora fluvial system drained the Amazon basin in a westward direction, with its mouth in central Pangea, and that it most likely fed the Tolimán submarine fan. The inferred location of the Acatlán–Oaxaquia tectonic block at the time of the La Mora fluvial system implies that the basement of Southern Mexico experienced a right lateral displacement of at least 2300 km with respect to South America during the Mesozoic.

1. Introduction

The Mixteca Terrane of Southern Mexico had an enigmatic history in the Early Mesozoic. The earliest Mesozoic geological record previously reported refers to a clastic continental succession of the Middle Jurassic (Morán-Zenteno et al., 1993; Campos-Madrigal et al., 2013). The content of the Triassic detrital zircons in the La Mora Formation exposed in the Ayuquila Basin located northwest of Huajuapan allows two inferences to be made (Silva-Romo et al., 2011): A) the continental record in the Mixteca Terrane extends back in time prior to the breakup of Pangea; B) the Mixteca Terrane was probably drained by the La Mora Paleo-River, whose floodplain facies are described in Section 2.1. During the Late Triassic, the northwestern sector of Pangea was drained by large fluvial systems, such as the Lena Paleo-River, the Taymir Paleo-River, and the Trans-Laurentian Paleo-River, that have been identified on the basis of detrital zircon analyses (Miller et al., 2013) (Fig. 1). The largest fluvial systems of the Late Triassic, with drainage towards the Paleo-Pacific, have been identified in the central sector of the western margin of Pangea (Fig. 2). For example, a river–estuarine system represented by the Barranca and Antimonio formations flowed in the region of Sonora (González-León et al., 2009), and probably drained the Laurentian lands. The Alamar fluvial system identified in central Mexico (Dickinson and Gehrels, 2009; Barboza-Gudiño et al., 2010) likely fed the Potosí submarine fan (Silva-Romo, 1993; Centeno-García and Silva Romo, 1997; Silva-Romo et al., 2000; Centeno-García, 2005). According to Barboza-Gudiño et al. (2010), the Alamar fluvial system drained landmasses such as the Grenvillian Oaxaquia microcontinent, and Pan-African landmasses such as the Yucatán block and southeastern Texas. The Alamar Paleo-River formed within the framework of the crustal extension that resulted from the fragmentation of Pangea and the formation of the Gulf of Mexico (Barboza-Gudiño et al., 2010).

Based on the analysis of detrital zircons contained in siliciclastic units, the stratigraphic knowledge and paleogeographic affinity for Central and Southern Mexico have been refined. For example, in the Chilar Complex exposed in Central Mexico, an age associated with the Late Triassic has been recognized (Dávila-Alcocer et al., 2009), and Proterozoic detrital zircons that likely originated from the Río Negro-Juruena

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The DRASTIC-Sg model: an extension to the DRASTIC approach for mapping groundwater vulnerability in aquifers subject to differential land subsidence, with application to Mexico City

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Abstract Mexico City relies on groundwater for most of its domestic supply. Over the years, intensive pumping has led to significant drawdowns and, subsequently, to severe land subsidence. Tensile cracks have also developed or reactivated as a result. All such processes cause damage to urban infrastructure, increasing the risk of spills and favoring contaminant propagation into the aquifer. The effects of ground deformation are frequently ignored in groundwater vulnerability studies, but can be relevant in subsiding cities. This report presents an extension to the DRASTIC methodology, named DRASTIC-Sg, which focuses on evaluating groundwater vulnerability in urban aquifers affected by differential subsidence. A subsidence parameter is developed to represent the ground deformation gradient (Sg), and then used to depict areas where damage risk to urban infrastructure is higher due to fracture propagation. Space-geodetic SqueeSAR data and global positioning system (GPS) validation were used to evaluate subsidence rates and gradients, integrating hydrogeological and geomechanical variables into a GIS environment. Results show that classic DRASTIC approaches may underestimate groundwater vulnerability in settings such as the one at hand. Hence, it is concluded that the Sg parameter is a welcome contribution to develop reliable vulnerability assessments in subsiding basins.

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Introduction

The Mexico City Metropolitan Area (MCMA), located within the southwestern sector of the Basin of Mexico (Fig. 1), is home to about 21 million people (INEGI 2010). Mexico City is one of the world's largest megacities and depends mostly on groundwater as its main source of domestic supply. Providing water to an ever-growing population poses a major management challenge. Currently, water consumption in the basin amounts to 61.6 m^3/s, out of which 66 % are supplied by wells. Most of the extractions take place from a regional complex of Quaternary-Tertiary alluvial, pyroclastic and fractured aquifers, overlain by a compressible lacustrine aquitard.