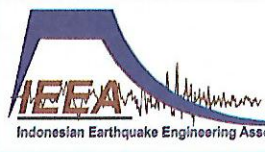




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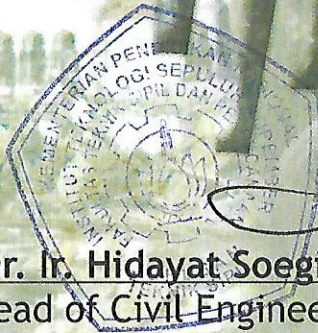
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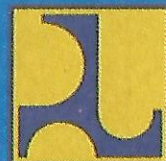
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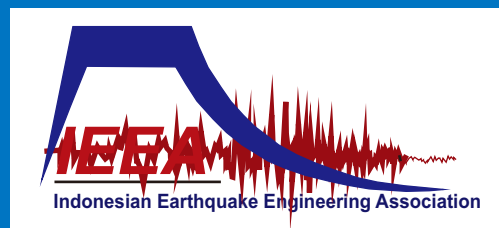


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# ICEEDM

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# LIST OF CONTENT

<b>PREFACE</b>	i
<b>WELCOMING SPEECH FROM ITS PRESIDENT</b>	iii
 <b>KEYNOTE AND INVITED SPEAKERS</b>	
Seismic Isolation for Housing, Schools and Hospitals in The Urban Environment <i>James M. Kelly and Dimitrios Konstantinidis</i>	1
The Role of IAEE in A Seismically Perilous World <i>Polat Gülkan</i>	11
Background, Historical Development, and Key Role of Lateral Steel in Enhancing Ductility of RC Members <i>P. Suprobo, Tavio, B. Suswanto, and D. Iranata</i>	17
Cumulative Ductility Under Earthquake Loads <i>Adang Surahman</i>	31
Lessons for Building Safety Evaluation Systems from The 2010 Canterbury Earthquake and Aftershocks <i>C. W. K. Hyland and S. Wijanto</i>	45
Experimental Study and Evaluation on The Seismic Behavior of Coupling Beams <i>E. Lim, C.H. Cheng, and S.J. Hwang</i>	55
Some Methods to Develop Seismic Vulnerability Functions for Loss Modeling <i>Keith Porter</i>	67
The Role of Earthquake Vulnerability Research in Risk Mitigation <i>Mark Edwards</i>	69

Tehran Seismic Risk and New Hazard-Compatible Urban Planning and School Safety Program <i>Mohsen Ghafory-Ashtiany</i>	85
A Practice-Oriented Method for Nonlinear Seismic Analysis of Building Structures <i>P. Fajfar and M. Kreslin</i>	101
Some Recent Efforts in Earthquake Hazard and Risk Analyses for Disaster Risk Reduction in Indonesia <i>I Wayan Sengara, Masyhur Irsyam, Indra D. Sidi, Widiadnyana Merati, Krishna S. Pribadi, Made Suarjana, Mark Edwards</i>	113
Retrofitting of St. Leo Chapel in Padang, Damaged by The September 30, 2009 West Sumatra Earthquake <i>Teddy Boen and Lenny</i>	131
Response of Singapore Buildings to A Giant Earthquake in Sumatra <i>Tso-Chien Pan, Kusnowidjaja Megawati, and Key Seng Goh</i>	143
<b>A. Case Histories in Earthquake Engineering Design and Construction</b>	
Assessment of Reinforced Concrete Bridge Under Earthquake Resistance Design Considering Corrosion Effect <i>A.B.Delima, Y-C. Ou, IGP. Raka</i>	A-1
<b>Synthetic Ground Motion Compatible With SNI-02-1726-2002</b> <i>Paulus Karta Wijaya , Daisy Natania</i>	A-9
<b>B. Case Histories in Recent Earthquake</b>	
Strong Ground Motion by September 30, 2009 Pariaman Earthquake and Damage to Large Scale Buildings <i>Mulyo H. Pradono, Yozo Goto, Rusnardi P. Rahmat, Akio Hayashi, and Kazuhiro Miyatake</i>	B-1

Lessons Learned from the 2010 Canterbury Earthquake and Aftershocks, New Zealand B-11  
*Sugeng Wijanto, Clark W.K. Hyland and Takim Andriono*

Seismic Performance Evaluation of an R/C Beam-Column Joint Damaged by the 2009 B-19  
West Sumatra Earthquake  
*Yasushi Sanada, Yoshiaki Nitta, Takuya Tomonaga, Yuta Sashima and Maidiawati*

### **C. Community-based Disaster Risk Management**

Group Decision in Reducing Impact of Natural Disaster C-1  
*Christiono Utomo and Arazi Idrus*

Lessons for Building Safety Evaluation Systems from the 2010 Canterbury Earthquake C-9  
and Aftershocks  
*Clark W.K. Hyland and Sugeng Wijanto*

Strategy for Managing Disaster of Sidoarjo Mudflow C-19  
*I Putu Artama Wiguna and Amien Widodo*

### **D. Geotechnical Earthquake Engineering**

Use Of Microtremors For Site Effects Evaluation In Singapore D-1  
*Cheng Zhu, Kusnowidjaja Megawati, and Meya Yanger Walling*

Local Site Effect of a Landslide in Jember Based On Microtremor Measurement D-11  
*Dwa Desa Warnana, Ria Asih Aryani Soemitro Widya Utama and Alain Tabbagh*

Depth Estimation of Seismic Bedrock of the Kanto Sedimentary Basin of Japan by the D-17  
Nonstationary Ray Decomposition Method  
*Haitao Zheng and Kusnowidjaja Megawati*

Characterization of Sediment Cover Based on Fundamental Frequency - Case Study of D-25  
Surabaya, Padang and Pariaman  
*Meya Yanger Walling and Kusnowidjaja Megawati*

Random Vibration Theory (Rvt) Based Seismic Site Response Analysis	D-31
<i>Sindhu Rudianto</i>	

## **E. Non-engineered Buildings**

Simple House Earthquake-Resistant With Precast System	E-1
<i>Harun Alrasyid, Munarus Suluch</i>	
Comparing Damage to Building Structures Due to the 2009 West Java Earthquake in Indonesia	E-9
<i>H. Choi, Y. Sanada, M. Kuroki, M. Sakashita, M. Tani, Y. Hosono, S. Musalamah and F. Farida</i>	
Study The Traditional Joint Of Bamboo Houses In The Earthquake by Tilting Table	E-19
<i>Purwito</i>	

## **F. Performance-based Design**

Behavior of R/C Columns Confined With Code Non-Compliance Confining Reinforcement Plus Supplemental Pen-Binder Under Axial Concentric Loading	F-1
<i>A. Kristianto, I. Imran and M. Suarjana</i>	
Effect of Suppressing Number of DOF on the Response of NLTHA and MPA of a Rigid Connection RC Multi Span Bridge under Strong Earthquake Motion	F-11
<i>B. Budiono, E. Yuniarsyah</i>	
Seismic Performance of Structures With Vertical Geometric Irregularity Designed Using Partial Capacity Design	F-21
<i>I. Muljati, B. Lumantarna</i>	
Seismic Risk of Important Buildings (Case: Hospitals in Indonesia Recent Earthquakes)	F-29
<i>I. Satyarno</i>	

Tire Base Foundation For Earthquake Resistant Houses <i>Ingemar Saevfors</i>	F-37
The Behaviour of Cross Nail-Laminated Timber (CNLT) Shearwall Under Cyclic Loading <i>J.A. Tjondro and A. Onky</i>	F-45
Pushover Analysis of Jacket Structure in Offshore Platform Subjected to Earthquake with 800 Years Return Period <i>M. Irmawan, B. Piscesa and I. A. Fada</i>	F-55
In-elastic Performance of 2D-Two Bay Ordinary Concentrically Braced Steel Frame <i>P. Pudjisuryadi, and Tavio</i>	F-65
Optimization of Sensor Locations for Bridge Seismic Monitoring System Using Genetic Algorithms <i>Reni Suryanita, Azlan Adnan</i>	F-71
Evaluation of Performance of Six-Story Structures Using Pushover Analysis in Soft Soil and Medium Soil <i>S. A. Nurjannah, Y. Megantara, C. Yudha</i>	F-79
A Numerical Study of Three Dimensional Structural Models Controlled by Passive Tuned Mass Dampers Against Seismic Excitations <i>S.Shahrokhi , and F.R.Rofooi</i>	F-89
Investigation on Performance of Active Tuned Mass Dampers (ATMD) on Vibration Control of Three-Dimensional Structural Control <i>S.Shahrokhi , and F.R.Rofooi</i>	F-97
Comparing Different Bottom Shear Stress Calculation Method for Irregular Waves <i>Taufiqur Rachman and Suntoyo</i>	F-107



Prediction of Peak Stress for Concrete Confined with Welded Wire Fabric	F-117
<i>B. Kusuma, Tavio, and P. Suprobo</i>	

## **G. Probabilistic and Deterministic Seismic Hazard assessment**

Community-Based Open Standards and Data for Hazard Modeling in the Global Earthquake Model	G-1
<i>M. Pagani, H. Crowley, R. Pinho</i>	

## **H. Retrofit, Rehabilitation, and Reconstruction**

Shear Strengthening Effect of RC Beams Retrofitted by CFRP Grid and PCM Shotcrete	H-1
<i>A. Arwin Amiruddin</i>	
Comparison Study of Concentrically Braced Frames (CBF) and Buckling Restrained Braced Frames (BRBF) on Steel Structure Building Subjected to Earthquake Load	H-9
<i>B. Suswanto and D. Iranata</i>	
Finite Element Modeling for Reinforcing Steel Subjected to Reversed Cyclic Loading with Severe Tensile and Compressive Strain Demands	H-19
<i>D. Iranata and B. Suswanto</i>	
Seismic Response on Jointless Composite Retrofitted Bridges Using Link Slab	H-27
<i>H. Sugihardjo</i>	
Fracture Mechanics Approach in Determining Pressure and Injection Time To Repair Concrete Cracks	H-37
<i>Jonbi, Ivindra Z Pane</i>	
A Study on The Effect of Earthquake Resistant Reinforcement Using Ground Solidification Body for Underground Structure	H-45
<i>K.Urano, Y. Adachi, T. Nishimura, M. Kawamura, and J. Tanjung</i>	



Behavior of Precast Beam Connections For Seismic-Resistant Houses Under Cyclic Loading	H-51
<i>L. S. B. Wibowo, Tavio, H. Soegihardjo, E. Wahyuni, and D. Iranata</i>	
Method for Improving Adhesion Between Concrete Structures Surface and External Fiber System Reinforcing	H-61
<i>Mauricio Iván Panamá, Amando Padilla, Antonio Flores, Luis Rocha</i>	
Alternative Strategies to Enhance The Seismic Performance of a Non-Ductile RC Structure	H-71
<i>Marco Valente</i>	
Dissipative Friction Devices for Seismic Upgrading of Precast Buildings	H-83
<i>Marco Valente</i>	
Seismic Protection of Steel Structures by Fluid Viscous Devices	H-93
<i>Marco Valente</i>	
Rehabilitation of Earthquake-Damaged and Seismic-Deficient Structures Using Fibre-Reinforced Polymer (FRP) Technology	H-105
<i>Ong Wee Keong</i>	
Bamboo Use for Earthquake Resistance Housing	H-111
<i>Sri Murni Dewi</i>	
Behavior of Precast Column Connections For Seismic-Resistant Houses Under Cyclic Loading	H-119
<i>Tavio, H. Soegihardjo, E. Wahyuni, D. Iranata, and L. S. B. Wibowo</i>	
Incremental Rapid Visual Screening Method for Seismic Vulnerability Assessment of Existing Buildings	H-127
<i>Yadollahi. M, Adnan. A, and Rosli. M. Z.</i>	

Transverse Stress Distribution in Concrete Columns Externally Confined by Steel Angle Collars H-139

*P. Pudjisuryadi, Tavio, and P. Suprobo*

## **I. Seismic and Tsunami Disaster Mitigation and Management**

Damage Mitigation Using Structural Health Monitoring Based on Wireless Sensor Networks Technology I-1

*Amin Suharjono, Wirawan, Gamantyo Hendrantoro*

Minimizing Earthquake Threat To School Building By Using Sustainable Visual Assessment And Detail Analysis I-11

*Choo Kok Wah, Dr. Rozana Zakaria and Mohd. Zamri Bin Ramli*

Evaluation of Building Structure Using Shearwall on Soft Soil By Performance-Based Design Method I-19

*Christanto Yudha, Yoga Megantara, S.A Nurjannah*

Tsunami Evacuation Simulation for Disaster Awareness Education and Mitigation Planning of Banda Aceh City I-29

*Muzailin Affan, Yozo Goto and Agussabti*

Test of Coupling Beam Systems with an Energy Dissipation Device I-45

*Taesang Ahn, Youngju Kim and Sangdae Kim*

Evacuation Response of the People in Meulaboh after the May 9, 2010 Earthquake I-51

*Yudha Nurdin, Diyah K. Yuliana, Ardiansyah, Muzailin Affan and Yozo Goto*

## **J. Seismic Zonation and Microzonation**

Shear-Wave Velocity Structure Underneath Surabaya Inferred From Microtremor Survey J-1

*Kusnowidjaja Megawati, Xiaofang Deng, Meya Yanger Walling and Hiroaki Yamanaka*

Site Response Evaluation for Earthquake Hazard Analysis of Surabaya Metropolitan J-9  
*M. Farid Ma'ruf, Amien Widodo, and Suwarno*

Soil-Structure Resonance Base on Observations of Horizontal-To-Vertical Spectral J-15  
Ratios of Microtremor (Case Study: Pare, Kediri District-East Java)  
*Triwulan, W. Utama, D.D. Warnana and Sungkono*

### **K. Soil-structure Interaction**

Effect of Soil Condition on Response Control of Adjacent Structures Connected by K-1  
Viscous Damper  
*Chirag Patel*

### **L. Tsunami Modeling**

Numerical Modeling of Tsunami L-1  
*M. Cahyono, Gneis Setia Graha and Andi Abdurachim*

### **M. Tsunami Early Warning System**

### **N. Disaster Management**

Visualisation in The Implementation of Seismic Codes on Residential Houses as an N-1  
Educational Tool For Construction Actors  
*Setya Winarno*

### **O. Any Related Topics**

Identification of Dynamic Characteristics of a Building Using Recorded Seismic O-1  
Response Data  
*Agung Budipriyanto*

Development of Artificial Neural Networks With Different Value of Learning Rate and O-11  
Momentum For Predicting The Compressive Strength of Self Compacting Concrete at  
28 Days  
*Akhmad Suryadi, Triwulan, and Pujo Aji*



Response of Adjacent Structures Connected by Friction Damper <i>Chirag Patel</i>	O-23
Progressive Collapse of RC Frames Under Blast Loading <i>Elvira</i>	O-33
Structural Behaviour of Submerged Floating Tunnels With Different Cable Configurations Under Seismic Loading <i>Endah Wahyuni, IGP Raka, Budi Suswanto and Ery Budiman</i>	O-43
Study of Eccentricity Effects on Reduction Factors of Square Reinforced Concrete Columns Using Visual Basic 6.0 Program <i>Iman Wimbadi, Tavio, and Raditya Adi Prakosa</i>	O-53
Numerical Simulation of Seismic Wave Propagation Near a Fluid-Solid Interface <i>Pranowo, Y. A. Laksono, W. Suryanto, Kirbani SB</i>	O-63
Behavior of Hybrid Reinforced Concrete T-beams with Web Opening under Monotonic Loading <i>Tanijaya, J.</i>	O-77

# NUMERICAL SIMULATION OF SEISMIC WAVE PROPAGATION NEAR A FLUID-SOLID INTERFACE

Pranowo<sup>1</sup>, Yoyok Adi Laksono<sup>2</sup>, Wiwit Suryanto<sup>3</sup>, Kirbani Brotopuspito<sup>3</sup>

<sup>1</sup> Department of Informatics Engineering, Atma Jaya Yogyakarta University (pran@staff.uajy.ac.id)

<sup>2</sup> PhD student of Department of Physics, Gadjah Mada University & Lecturer of Department of Physics, Malang State University

<sup>3</sup> Department of Physics, Gadjah Mada University

## ABSTRACT

We introduce a high-order discontinuous galerkin method for modeling wave propagation in complex media with both fluid (acoustic) and solid (elastic) medium, as for instance in offshore seismic experiments. The problem is formulated in terms of velocity-stress in both media. A nodal high order discontinuous galerkin finite element is used for the spatial discretization while an explicit low storage fourth order Runge Kutta scheme is used to march in the time domain. The numerical scheme provides stable and accurate methods for simulating seismic wave across a fluid – solid interface, the comparisons with finite element method and analytical solutions show a good agreement.

**Keywords:** seismic wave, fluid – solid interface, discontinuous galerkin.

## 1. INTRODUCTION

Seismic wave propagation near fluid-solid interface problems are found in many scientific and engineering applications such as:

- Seismic exploration in marine environment
- Interaction seismic wave with reservoir dam
- Earthquake induced tsunami

Until now, these problems are still open research area. Many researchers has invesigated these problems experimentally or numerically. Physical modeling has been successfully used in investigation of the seismic wave along liquid-solid interfaces (Person, 1999), from her experimental results she can identify the modes of propagation of interfaces waves, measure velocities, attenuation and re-radiation of these waves. The drawbacks of experimental approach are the measurement and data processing are so complicated, the measurement accuracy depended on the operator skill and the physical models are not easy to be built and expensive. Supporting by tremendous of the increase computational power, numerical modeling has become an important research area. Much attention has been paid by many researchers to solve the seismic wave propagation near fluid-solid interface problems by using numerical approach. Assuming solid as elastic

medium and fluid as acoustic medium is sufficient in that context. Based on that assumption the wave propagation in solid medium can be modeled by elastodynamic equations and the wave propagation in fluid medium can be modeled by acoustic equations. One needs to model wave propagation in fluid as well in the underlying solid.

The oldest and the famous numerical method that have been used widely to model seismic wave propagation in time domain is finite difference method (FDM). Van Vossen et al. (2002) used this method to model seismic wave propagation in fluid-solid configuration. The wave motion is governed by equation of motion and the elastic constitutive equation which are written in a first-order hyperbolic equation system for unknown components of stress and particle velocity. In the fluid medium the Lamé's coefficients  $\mu$  is set to be equal zero. A dipping interface is represented by staircase of vertical and horizontal fluid-solid boundary segments in the numerical scheme and properties of medium near the interface are calculated using arithmetic average. Van Vossen et al. (2002) showed that the accuracy of the FDM is good for small dipping but poor for large dipping angle ( $> 30^\circ$ ). This is the main drawback of FDM which can not be used for modeling of irregular domain.

Diaz and Joly (2005) proposed nonconforming finite element method for solving time dependent fluid-structure interaction problems. They used different formulations for both fluid and solid media. Pressure-velocity formulation is used in fluid medium and velocity-stress formulation is used in solid medium. The coupling between the fluid and solid is done via continuity of normal velocities and of normal stresses. They used staggered mesh for both spatial and temporal domain as FDM did for minimizing the dispersion error. They showed that their numerical results have good agreement with analytical solutions. The use of staggered mesh made the numerical algorithm more complicated and the application of the method is limited for simple spatial domain only.

Komatitsch et al. (2000, 2011) and Madec et al. (2009) developed a high order spectral element method (SEM) for simulating seismic wave propagation near a fluid-solid interface. They showed that SEM is an efficient tool for modeling wave propagation in complex structures, and high order accuracy can be achieved. The spectral element method is developed from conventional finite element method by replacing the basis function with the higher order legendre polynomials. They used second order hyperbolic equation system i.e. velocity potential formulation for fluid medium and displacement formulation for solid medium. The semi discrete equations are integrated in time using explicit predictor-corrector staggered time scheme. This time integration has only second order accuracy.

Wilcox et al. (2010) developed a high order discontinuous galerkin method (DGM) for modeling seismic wave through coupled three dimensional elastic-acoustic media. They used first-order hyperbolic equation system for unknown components of strain and particle velocity. In the fluid medium the Lamé's coefficients  $\mu$  is set to be equal zero. The DG methods allow unstructured mesh configuration and inter-element continuity is not required. The basis function is discontinuous across mesh boundaries. Through a proper choices of flux computation points, the method only requires communication between mesh that have common faces. No global matrix inversion is required and the problem can be solved locally in each mesh. In



their approach, they divided the spatial domain into hexahedral elements. Higher order accuracy can be achieved easily by increasing the order of basis function polynomials.

In this paper we develop a high order discontinuous galerkin (DG) method for simulating two dimensional seismic wave near fluid-solid interface. The wave motion in both fluid and solid media is governed by elastodynamics equations in the form of velocity-stress formulation. The spatial domain is divided into unstructured triangular elements. Perfectly matched layer (PML) is used as as absorbing boundary condition.

## 2. GOVERNING EQUATIONS

Our approach of treating seismic waves numerically is based on the theory elastodynamics. We use the velocity-stress formulation as the governing equations:

$$\begin{aligned} \frac{\partial v_x}{\partial t} - \frac{1}{\rho} \left( \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} \right) &= f_x \quad ; \quad \frac{\partial v_y}{\partial t} - \frac{1}{\rho} \left( \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} \right) = f_y \\ \frac{\partial \tau_{xx}}{\partial t} - (\lambda + 2\mu) \frac{\partial v_x}{\partial x} - \lambda \frac{\partial v_y}{\partial y} &= 0 \quad ; \quad \frac{\partial \tau_{yy}}{\partial t} - \lambda \frac{\partial v_x}{\partial x} - (\lambda + 2\mu) \frac{\partial v_y}{\partial y} = 0 \\ \frac{\partial \tau_{xy}}{\partial t} - \mu \left( \frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right) &= 0 \end{aligned} \quad (1)$$

In which  $v_x$  and  $v_y$  are the components of velocity vectors,  $\tau_{xx}$ ,  $\tau_{yy}$  dan  $\tau_{xy}$  are the elements of the stress tensor and  $(f_x, f_y)$  are body force vector. The elastic medium is described by the density and the Lamé coefficients  $\lambda(x, y)$  &  $\mu(x, y)$ . In the fluid medium the Lamé coefficients  $\mu(x, y)$  is set to be zero

## 3. PERFECTLY MATCHED LAYER

The simulation of seismic waves by discontinuous galerkin method in unbounded domains requires a specific boundary condition of the necessarily truncated computational domain. We propose an absorbing boundary condition called perfectly matched layer (PML). Presented in time domain electromagnetic simulations (Berenger, 1996), PML has since been used extensively in that field. PML has also been incorporated into a variety of wave propagation algorithms. Colino and Tsogka (2001) have formulated and demonstrated PML in the P-SV case via Virieux (1986) finite difference scheme and a mixed finite element algorithms. Excellent results were demonstrated in homogeneous and heterogeneous media, including anisotropy in the finite element scheme.

Starting with the system of equations (1), each equation is split into a parallel and perpendicular component, based on spatial derivative separation. That is, the perpendicular equations contains the spatial derivative term which acts normal to the coordinate plane of interest and a damping term, and the parallel equation

contain the remaining spatial derivative terms. Finally, an additional equation is required to sum the results of the split equations

$$\begin{aligned}
 \frac{\partial v_{xx}}{\partial t} + \sigma(x)v_{xx} &= \frac{1}{\rho} \frac{\partial \tau_{xx}}{\partial x} + f_x & ; & \quad \frac{\partial v_{xy}}{\partial t} + \sigma(y)v_{xy} = \frac{1}{\rho} \frac{\partial \tau_{xy}}{\partial y} \\
 \frac{\partial v_{yx}}{\partial t} + \sigma(x)v_{yx} &= \frac{1}{\rho} \frac{\partial \tau_{xy}}{\partial x} & ; & \quad \frac{\partial v_{yy}}{\partial t} + \sigma(y)v_{yy} = \frac{1}{\rho} \frac{\partial \tau_{yy}}{\partial y} + f_y \\
 \frac{\partial \tau_{xxx}}{\partial t} + \sigma(x)\tau_{xxx} &= (\lambda + 2\mu) \frac{\partial v_x}{\partial x} & ; & \quad \frac{\partial \tau_{xxy}}{\partial t} + \sigma(y)\tau_{xxy} = \lambda \frac{\partial v_y}{\partial y} \\
 \frac{\partial \tau_{yyx}}{\partial t} + \sigma(x)\tau_{yyx} &= \lambda \frac{\partial v_x}{\partial x} & ; & \quad \frac{\partial \tau_{yyy}}{\partial t} + \sigma(y)\tau_{yyy} = (\lambda + 2\mu) \frac{\partial v_y}{\partial y} \\
 \frac{\partial \tau_{xyx}}{\partial t} + \sigma(x)v_{xyx} &= \mu \frac{\partial v_y}{\partial x} & ; & \quad \frac{\partial \tau_{xyy}}{\partial t} + \sigma(y)v_{xyy} = \mu \frac{\partial v_x}{\partial y}
 \end{aligned} \tag{2}$$

$$v_x = v_{xx} + v_{xy}, \quad v_y = v_{yx} + v_{yy}, \quad \tau_{xx} = \tau_{xxx} + \tau_{xxy}, \quad \tau_{yy} = \tau_{yyx} + \tau_{yyy}, \quad \tau_{xy} = \tau_{xyx} + \tau_{xyy}$$

In the absorbing layers we use the following model for the damping parameters:

$$\sigma(x) = d_0 \left( \frac{x}{\delta} \right)^2 \quad ; \quad \sigma(y) = d_0 \left( \frac{y}{\delta} \right)^2 \quad \text{and} \quad d_0 = \log \left( \frac{1}{R} \right) \frac{3c_p}{2\chi}$$

where  $\delta$  is the length of the layer and  $d_0$  is a function of the theoretical reflection coefficient ( $R$ )

For simplicity, the split equations (2) are written in vector form as follows:

$$\frac{\partial \mathbf{q}}{\partial t} + \mathbf{A} \frac{\partial \mathbf{q}}{\partial x} + \mathbf{B} \frac{\partial \mathbf{q}}{\partial y} = \mathbf{f} \tag{3}$$

where  $\mathbf{q} = [v_{xx} \quad v_{xy} \quad v_{yx} \quad v_{yy} \quad \tau_{xxx} \quad \tau_{xxy} \quad \tau_{yyx} \quad \tau_{yyy} \quad \tau_{xyx} \quad \tau_{xyy}]^T$

#### 4. DISCONTINUOUS GALERKIN METHOD

The spatial derivatives are discretized by using a discontinuous galerkin method. The simplified of Eq.(1) according to Galerkin's procedure using the same basis function  $\phi$  within each element is defined below (Hesthaven & Warburton, 2002; 2008)

$$\begin{aligned} \left( \phi, \frac{\partial \mathbf{q}}{\partial t} + \mathbf{A} \frac{\partial \mathbf{q}}{\partial x} + \mathbf{B} \frac{\partial \mathbf{q}}{\partial y} \right)_{\Omega} &= 0 \\ \Leftrightarrow \left( \phi, \frac{\partial \mathbf{q}}{\partial t} \right)_{\Omega} + (\phi, \mathbf{A} n_x \mathbf{q} + \mathbf{B} n_y \mathbf{q})_{\partial \Omega} - \left( \frac{\partial}{\partial x} (\mathbf{A} \phi), \mathbf{q} \right)_{\partial \Omega} - \left( \frac{\partial}{\partial y} (\mathbf{B} \phi), \mathbf{q} \right)_{\Omega} &= 0 \end{aligned} \quad (4)$$

Here  $(\cdot, \cdot)$  represents the normal 2  $L$  inner product, the second term is flux vector and  $(n_x, n_y)$  are normal vector. The mathematical manipulation of the flux vector is calculated as below:

$$\left( \phi, \frac{\partial \mathbf{q}}{\partial t} + \mathbf{A} \frac{\partial \mathbf{q}}{\partial x} + \mathbf{B} \frac{\partial \mathbf{q}}{\partial y} \right)_{\Omega} + (\phi, \mathbf{A} n_x + \mathbf{B} n_y) (\bar{\mathbf{q}} - \mathbf{q}^-)_{\partial \Omega} = 0 \quad (5)$$

where  $\mathbf{q}^-|_{\partial \Omega} = \hat{\mathbf{q}}^-(\mathbf{q}^-, \mathbf{q}^+)$  and the last term of equation (3) is called numerical flux.

The numerical flux along three sides of triangular element is calculated by Lax Friedrich flux.

$$(\phi, \mathbf{A} n_x + \mathbf{B} n_y) (\bar{\mathbf{q}} - \mathbf{q}^-)_{\partial \Omega} = (\phi, \mathbf{A} n_x + \mathbf{B} n_y + C_p) (\mathbf{q}^+ - \mathbf{q}^-) / 2 \quad (6)$$

Here, we took the Kornwinder Dubiner function on straight sided triangle as the basis written in equation 7 (see Figs. 1 and 2):

$$\phi_{ij}(r, s) = \sqrt{\frac{2i+1}{2}} \sqrt{\frac{2i+2j+2}{2}} P_i^{0,0} \left( \frac{2(1+r)}{(1-s)} - 1 \right) P_j^{2=+1,0}(s) \quad (7)$$

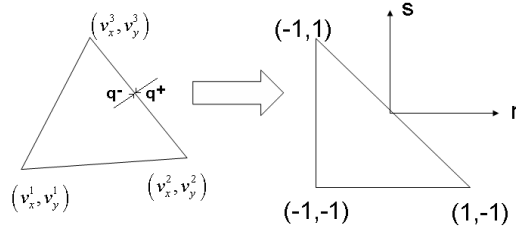
where,  $P^{\alpha,\beta}$  is orthogonal Jacobi polynomial

All straight sided triangles are the image of this triangle under the map:

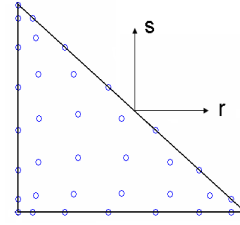
$$\begin{pmatrix} x \\ y \end{pmatrix} = -\left( \frac{r+s}{2} \right) \begin{pmatrix} v_x^1 \\ v_y^1 \end{pmatrix} + \left( \frac{1+r}{2} \right) \begin{pmatrix} v_x^2 \\ v_y^2 \end{pmatrix} + \left( \frac{1+s}{2} \right) \begin{pmatrix} v_x^3 \\ v_y^3 \end{pmatrix} \quad (8)$$

The set of points in the triangle, which we can build the Lagrange interpolating polynomials, can be viewed as Gauss-Legendre –Lobatto (GLL) points.





**Figure 1: Coordinate Transformation**



**Figure 2: Seventh Order Gauss Lobatto Quadrature Nodes**

The vector  $\mathbf{q}$  is expanded using equation (3), we take expansion of  $v_x$  as example:

$$v_x(r, s) = \sum_{i=0}^N \sum_{j=0}^{N-i} \phi_{ij}(r, s) \hat{v}_{xij} \quad (9)$$

$$v_x(r_n, s_n) = \sum_{m=1}^{m=M} \mathbf{V}_{nm} \hat{v}_{xm} \quad (10)$$

$$\hat{v}_{xm} = \sum_{m=1}^{m=M} (\mathbf{V}^{-1})_{mj} v_x(r_j, s_j)$$

$$\begin{aligned} \frac{\partial v_x}{\partial r}(r, s) &= \sum_{i=0}^N \sum_{j=0}^{N-i} \frac{\partial \phi_{ij}}{\partial r}(r, s) \hat{v}_{xij} = \hat{\mathbf{D}}^r \mathbf{V}^{-1} v_x(r, s) & \hat{\mathbf{D}}^r &= \frac{\partial \phi}{\partial r} \\ \frac{\partial v_x}{\partial s}(r, s) &= \sum_{i=0}^N \sum_{j=0}^{N-i} \frac{\partial \phi_{ij}}{\partial s}(r, s) \hat{v}_{xij} = \hat{\mathbf{D}}^s \mathbf{V}^{-1} v_x(r, s) & \hat{\mathbf{D}}^s &= \frac{\partial \phi}{\partial s} \end{aligned}$$

where  $\mathbf{V}_{ij}$  and  $N$  are Vandermonde matrix and the order of Jacobi polynomial respectively.

The semi discrete Eq. (4) is integrated in time marching by using five stage of fourth order 2N-storage Runge-Kutta scheme as developed by Carpenter & Kennedy (1994). The final equations are found as written in Eq. (11).

$$\frac{d\mathbf{q}}{dt} = L[t, \mathbf{q}(t)] \quad (11)$$

$$\begin{aligned} d\mathbf{q}_j &= A_j d\mathbf{q}_{j-1} + dt L(\mathbf{q}_j) \\ \mathbf{q}_j &= \mathbf{q}_{j-1} + B_j + d\mathbf{q}_j \end{aligned}$$

where  $dt$  is the time step. The vectors  $A$  and  $B$  are the coefficients that will be used to determine the properties of the scheme. The maximum time step is (Hesthaven and Warburton, 2002):

$$\Delta t \leq \frac{2h}{c_p(N-1)^2} \quad (12)$$

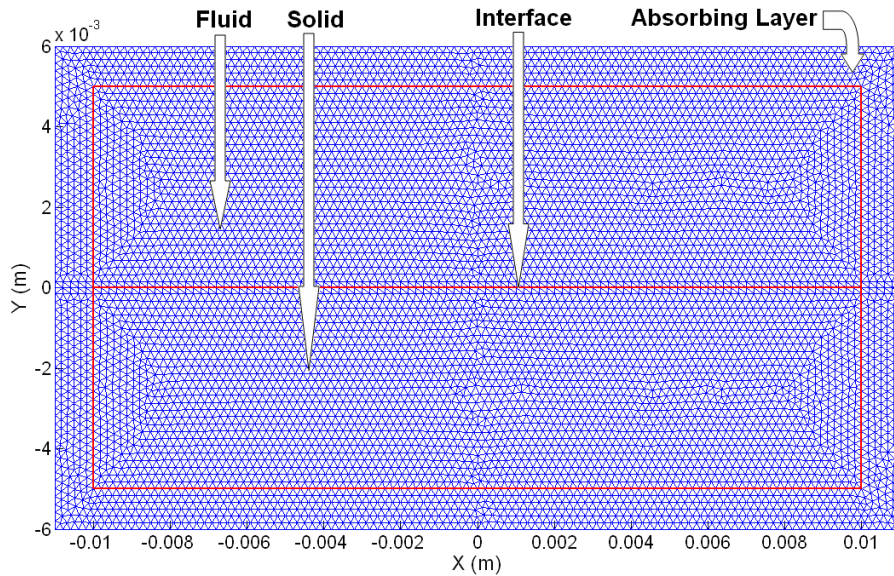
where  $c_p$  is primary wave velocity and  $h$  is the smallest edge length of the element

## 5. RESULTS AND DISCUSSION

In this section we present two numerical examples. The first example aims at showing the accuracy of DGM compared to analytical solution and Fem which proposed by Diaz et al. (2004) and the second example aims at showing that DGM can easily handle problems with complicated interface.

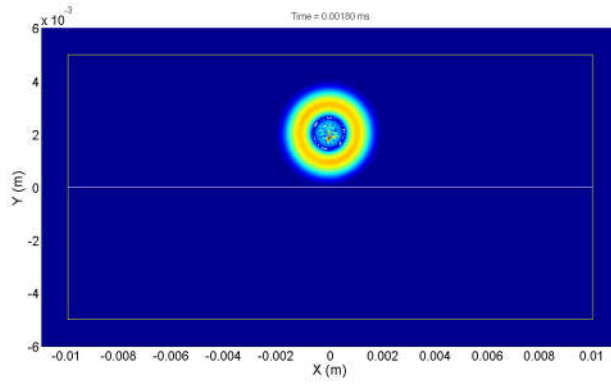
### 5.1. Numerical Example I

The first example has a simple configuration: two half-planes separated by a straight interface, one constitutes the fluid medium and the second one constitutes solid medium. The material properties for the fluid are  $c_p = 1500 \text{ ms}^{-1}$ ,  $c_s = 0 \text{ ms}^{-1}$  and  $\rho = 1000 \text{ kg m}^{-3}$  and the material properties for the solid are  $c_p = 4000 \text{ ms}^{-1}$ ,  $c_s = 1800 \text{ ms}^{-1}$  and  $\rho = 1850 \text{ kg m}^{-3}$ . The size of each medium is  $20 \text{ mm} \times 5 \text{ mm}$ . We added absorbing layer surrounding the domain with the thickness of the layer equals  $1 \text{ mm}$  and total number of triangular elements is 15060. The polynomial degree is  $N = 3$  and the time step  $\Delta t = 10^{-8} \text{ s}$ . The source function is a point source located in the fluid at  $2 \text{ mm}$  above the interface, the time variation of the source is given as Gaussian with dominating frequency is  $1 \text{ MHz}$ .

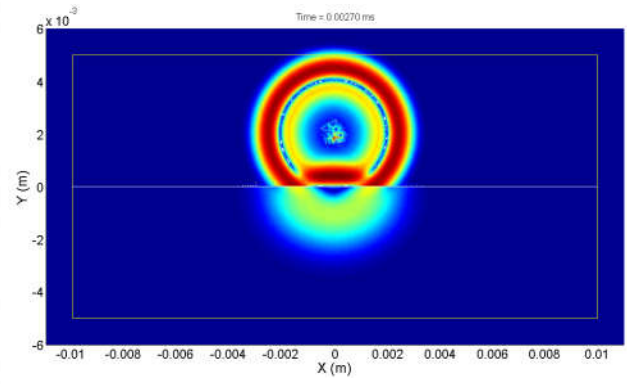


**Figure 3: Mesh of first example**

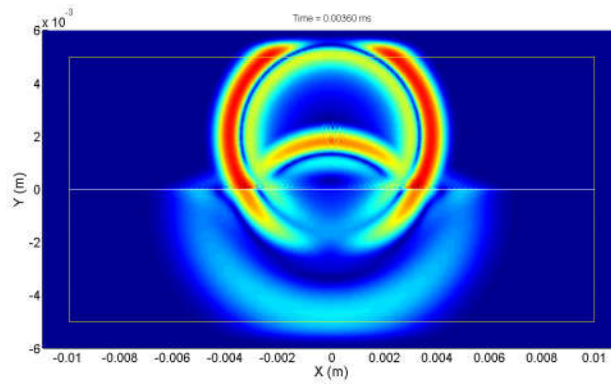
Snapshots of the first example can be seen in figure 4a – 4f.



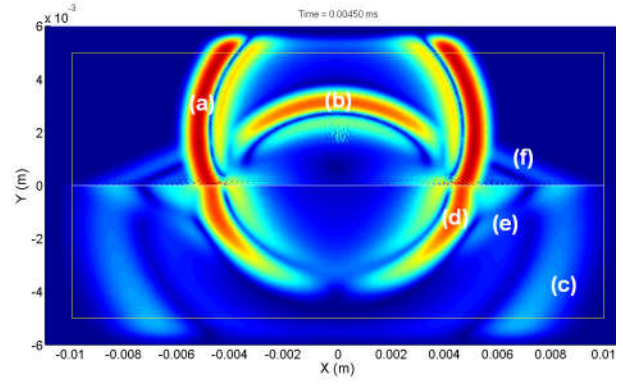
**Figure 4a: Velocity fields of 1<sup>st</sup> example  
at 0.18  $\mu$ s**



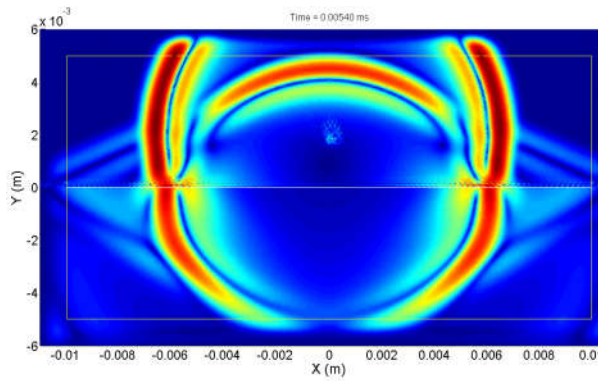
**Figure 4b: Velocity fields of 1<sup>st</sup> example  
at 0.27  $\mu$ s**



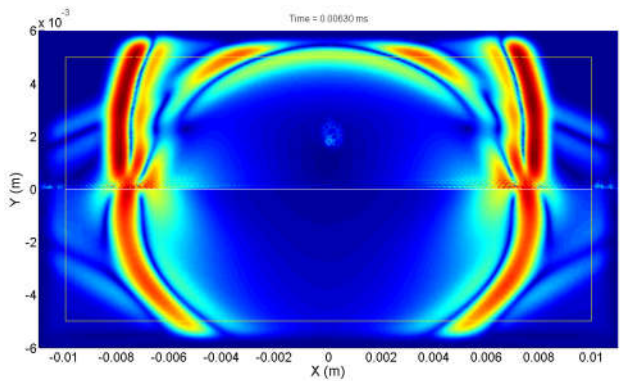
**Figure 4c: Velocity fields of 1<sup>st</sup> example  
at 0.36  $\mu$ s**



**Figure 4d: Velocity fields of 1<sup>st</sup> example  
at 0.45  $\mu$ s**



**Figure 4e: Velocity fields of 1<sup>st</sup> example  
at 0.54  $\mu$ s**



**Figure 4f: Velocity fields of 1<sup>st</sup> example  
at 0.63  $\mu$ s**

Figure (4d) shows that the direct wave (a) and reflected wave can be observed in the fluid, the transmitted P (c) and P-to-S converted (d) waves are clearly visible in the solid. Significant refracted waves are also present (e, f, g).

To validate the DG method, we compare the numerical DGM (the green curve) solution to the FEM solution (the red curve) and analytical solution (the blue curve) which are provided by Diaz et al. (2005). The two components of the numerical and analytical velocity are shown by figure 5a and 5b. The curves are perfectly superimposed, showing the good accuracy of DGM.

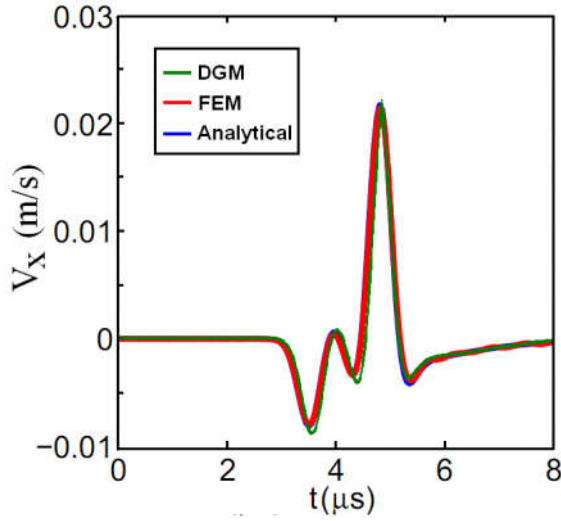


Figure 5a: Horizontal velocity ( $v_x$ )

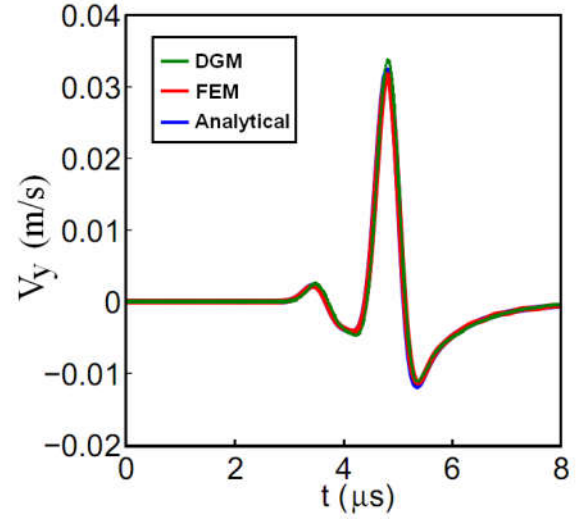


Figure 5b: Vertical velocity ( $v_y$ )

From 4a – 4f we can see no reflection on the left, right and bottom edges. The PML absorbed the outgoing waves well.

## 5.2. Numerical Example II

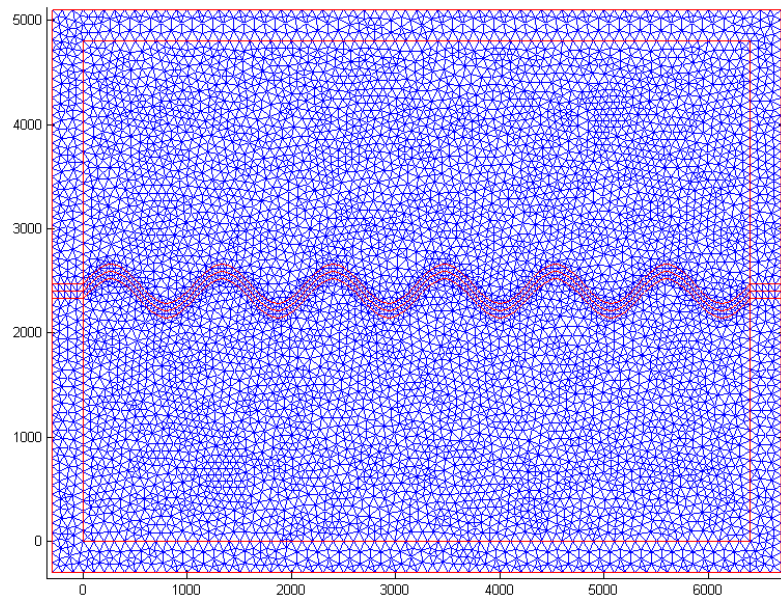
This example is taken from Komatitsch et al. (2000). The domain of the second example consists of two homogeneous half-spaces in contact at a sinusoidal interface, as shown in figure 6. The lower part of the model is elastic, while the upper part is acoustic, a water layer. The material properties for the water are

$c_p = 1500 \text{ ms}^{-1}$ ,  $c_s = 0 \text{ ms}^{-1}$  and  $\rho = 1020 \text{ kg m}^{-3}$  and the material properties for the solid are

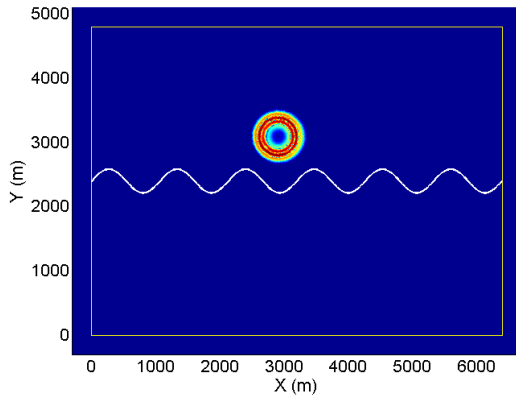
$c_p = 3400 \text{ ms}^{-1}$ ,  $c_s = 1963 \text{ ms}^{-1}$  and  $\rho = 2500 \text{ kg m}^{-3}$ . Total number of triangular elements is 13876.

The polynomial degree is  $N = 5$  and the time step  $\Delta t = 10^{-2} \text{ s}$ . The source function is a point source located in the fluid at  $x = 2900 \text{ m}$  and  $y = 3098 \text{ m}$ , the time variation of the source is given as Ricker (i.e., the first derivative of a Gaussian) with dominating frequency is 7 Hz.

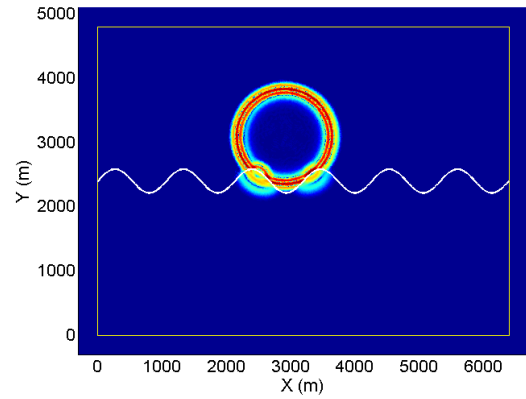




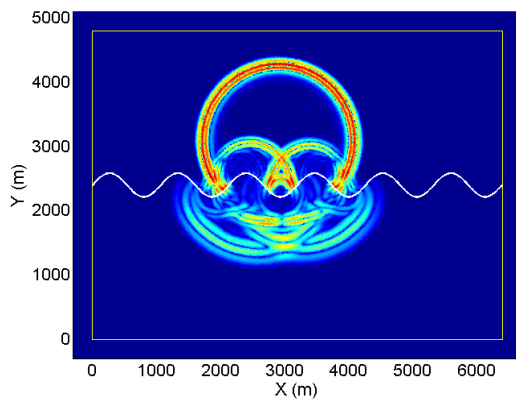
**Figure 6: Mesh of second example**



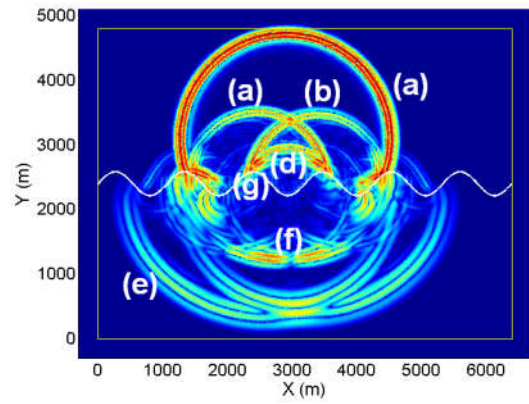
**Figure 7a: Velocity fields of 2<sup>nd</sup> example at 0.3 s**



**Figure 7b: Velocity fields of 2<sup>nd</sup> example at 0.6 s**



**Figure 7c: Velocity fields of 2<sup>nd</sup> example at 0.9 s**



**Figure 7d: Velocity fields of 2<sup>nd</sup> example at 1.2 s**

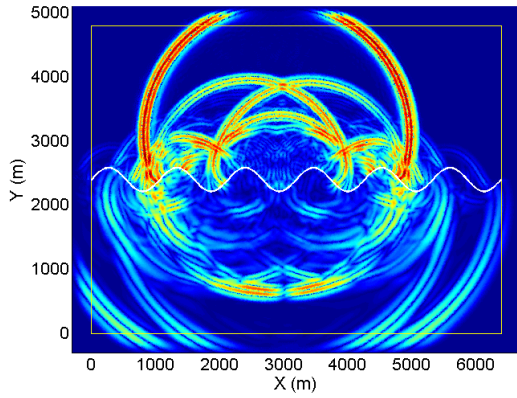


Figure 7e: Velocity fields of 2<sup>nd</sup> example at 1.5 s

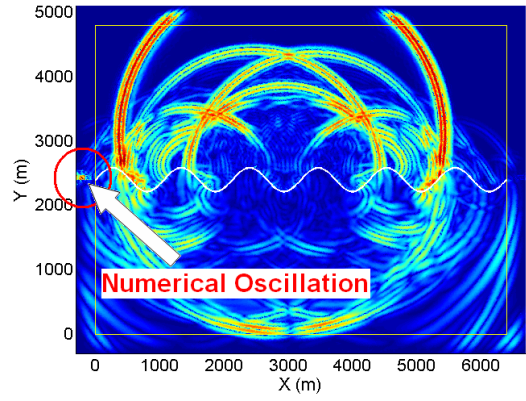


Figure 7f: Velocity fields of 2<sup>nd</sup> example at 1.8s

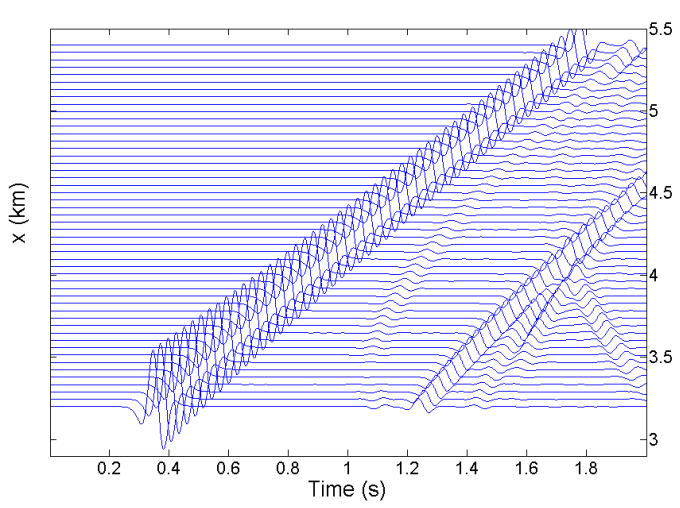


Figure 8a: Seismogram of  $(v_x)$  of DGM

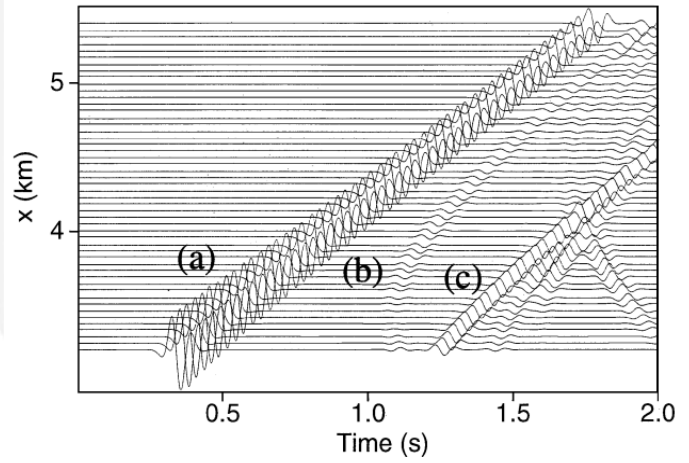


Figure 8b: Seismogram of  $(v_x)$  of SEM

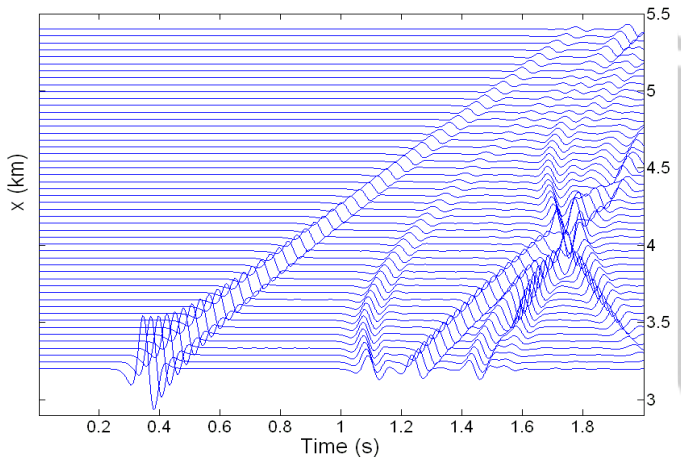


Figure 9a: Seismogram of  $(v_y)$  of DGM

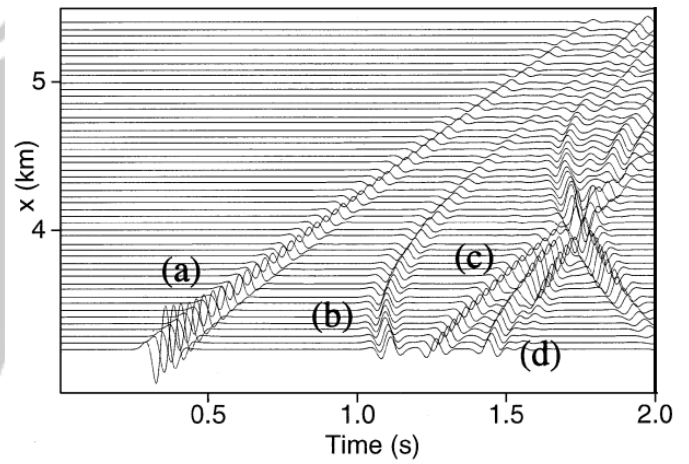


Figure 9a: Seismogram of  $(v_y)$  of SEM



Figure 6a – 6f show the snapshots of seismic wave propagation in two-layered media at  $t = 0.3$ ,  $t = 0.6$ ,  $t = 0.9$ ,  $t = 1.2$ ,  $t = 1.5$ , and  $t = 1.8$  s. Mode conversions of wave reflected at the interface are clearly visible. The entire wavefields are composed of various waves as described by Komatitsch et al. (2000), i.e: (a) the direct P-wave, (b) the strongly curved reflected P-wave on the first anticline on the right, (c) the P-wave reflected off the first anticline on the left [symmetric of phase (b)], (d) the P-wave reflected off the central syncline, which undergoes a time delay and therefore a triplication, (e) various transmitted P-waves, (f) various transmitted P-to-S converted waves, and (h) a slow phase traveling along the interface, which is interpreted to be a Stoneley wave.

Comparisons of seismograms between DGM and SEM results are shown in figure 8a- 8b and 9a -9b. Those figures show a good agreement. Although the numerical calculations show an excellent results, the modeling of fluid medium by using velocity-stress formulation has a drawback. This formulation will generate a small parasitic S-waves near the interface. This parasitic S-waves will be accumulated for long time simulation and can destroy the stability of the numerical scheme.

## 6. CONCLUSIONS AND FUTURE WORKS

We have introduced that the use of high-order discontinuous galerkin methods allows one to model seismic wave propagation across a fluid – solid interface. The numerical scheme provides stable and accurate methods for simulating seismic wave, the comparisons with finite element method and analytical solutions show a good agreement.

Numerical results have shown that the use of velocity-stress formulation will generate very small parasitic S-waves near the interfaces. Therefore in the future we will use velocity strain formulation instead velocity-stress formulation for modeling seismic wave near fluid-solid interface.

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