

Elastic wave 2D modeling of seismic surveys

Joe Wong, Peter M. Manning, and David Henley

ABSTRACT

We have developed a 2D finite-difference time-stepping code in MATLAB for simulating seismic surveys in heterogeneous isotropic elastic media. The code, named mFD2D, is designed for easy input of moderately complex velocity structures. Acquisition parameters can be set for a variety of survey types, most notably for reflection and VSP surveys. Output data are common shot gathers that are saved on SEGY files. On a desktop PC with a 3.20 GHz CPU and 4 GB of RAM running 32-bit MATLAB, a synthetic 2D seismic reflection survey with about 100,000 traces can be produced overnight. We present synthetic common source gathers of vertical and radial component seismograms for moderately complex velocity structures. These examples indicate that the code should be useful for educational and research purposes and for pre-survey planning of real-world seismic surveys.

INTRODUCTION

Manning (2007) has written a collection of modules in MATLAB that models elastic wave propagation through 2D heterogeneous isotropic media. The code is an implementation of the finite difference and time-stepping scheme proposed by Virieux (1986). We have modified Manning's original code to facilitate production modeling of seismic surveys over moderately complex geological structures. Modeled gathers of seismograms are stored on SEGY files that can be used directly in processing packages. The production code is named mFD2D, and it executes on desktop or laptop computers with MATLAB installed. On a desktop computer with a CPU running at 3.20 GH and 4 GB of Ram, the mFD2d code can produce a complete 2D seismic reflection line with about 100,000 traces in about 15 hours.

Before mFD2D can run a particular velocity model, an input/output folder must be created, and two input ASCII files with names associated with the model must be set up in that folder. The first ASCII file is named with an extension .acq, signifying that it defines survey acquisition parameters. The second is named with an extension .geo, signifying that it defines geometrical structure and property values of the velocity model.

When mFD2D begins execution, a query on the Command Window asks for a folder name to be entered. Once this name is entered, an initial menu allows the selection of an *.acq file in that particular folder. A particular model is chosen by clicking on the associated *.acq file. Then, the *.geo file named within the chosen *.acq file is read, and a second menu CHANGE pops up to give the user an opportunity to modify certain important acquisition parameters. Parameters are changed by clicking on the choice, which brings up an input request on the command window. After typing the required changed value and pressing <ENTER>, the user is returned to the CHANGE menu for another desired change. When no more change is desired, clicking on All OK starts the time-stepping process. When the program runs to completion, messages indicating the elapsed time and the names of the SEGY files written are displayed in the command

window. The output consists of plots of the model's geometrical structure specified by the relevant *.geo file, and four separate SEGY files, one for each of the vertical and radial components of the horizontal seismic profile (HSP) and the vertical seismic profile (VSP). The base name for the output SEGY files is in the *.acq file, and extra characters are appended to this base name to differentiate between the four types of output files.

FEATURES OF THE mFD2D CODE

Main features

1. 2D finite-difference time-stepping algorithm implemented in MATLAB.
2. Buried explosive source, or surface vertical/horizontal force source.
3. Heterogeneous, isotropic, lossless velocity fields.
4. Model consists of zones characterized by different V_p , V_s , and density values.
5. Model geometry easily parameterized by an input ASCII file with .geo extension.
6. Acquisition parameters easily set up by ASCII file with .acq extension.
7. Output is in SEGY format with proper trace headers, designed to be used in processing packages such as Landmark's ProMax and GEDCO's Vista.

The mFD2D software has many options for the parameters specifying the details of how a real-world survey is simulated. These options give a great deal of flexibility to the modeling, and in what follows, we describe some of the more important parameters.

Model size, grid size, and time step

A generic model size might be 2000m in the horizontal (x) dimension and 1000m in the vertical (z) direction. Typical grid dimensions are on the order of 2m by 2m, so arrays of size 500 by 1000 must be stored in memory for the P-wave velocity (V_p), shear wave velocity (V_s), and density (ρ) values.

There are conditions and limitations on the grid size Δxz and on the time-step Δt (Kosloff and Baysal, 1982):

$$\Delta xz < \lambda_{min}/10 , \tag{1}$$

$$\Delta xz/\Delta t > \sqrt{2} \cdot V_{max} , \tag{2}$$

$$\lambda_{min} = V_{min}/f_d . \tag{3}$$

V_{min} and V_{max} are the largest and smallest velocity values defined in the *.geo file; f_d is the dominant frequency of the source wavelet defined in the *.acq file. These theoretical limits ensure stability of the finite difference time-stepping technique. If these parameters are grossly out of agreement with Equations 1 and 2, grid dispersion artifacts, characterized by late-arriving high-frequency coda immediately following each "valid"

event, will appear in the final seismograms. In heterogeneous media where zones of very low velocity co-exist with zones of very high velocities, it may be impractical to meet these limits precisely, since the low-velocity zones require small Δxz , and the high-velocity zones require small Δt . For a given model size, small values of Δxz will lead to excessive memory requirements, and small values of Δt would result in a large number of time steps in order to yield seismograms with the required maximum trace length. If the low-velocity zones are limited in size and number (for example, a relatively thin overburden, or a thin coal bed imbedded in high-velocity sandstone layer), useful results still may be still be obtained with values of Δxz and Δt not in strict conformance with conditions (1) and (2) for all zones, as long as they are met for the bulk of the model.

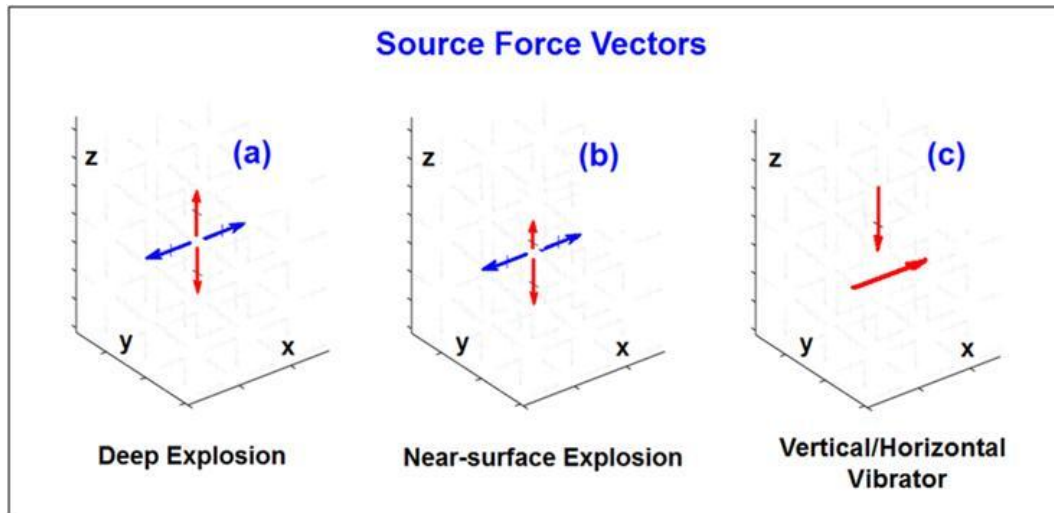


Fig. 1: Force distributions in mFD2D for representing common source types.

Source characteristics

The seismic source in mFD2D is characterized by a distribution of force vectors. Figure 1 shows the most common force distributions suitable for surface and subsurface surveys. For the deep explosive source, it is assumed that the solid media resists the explosive force isotropically, so the four force vectors are identical in magnitude. For the shallow explosive source, the upwardly directed force vector is less than the downwardly directed force vector because it is assumed that much of the upward force on the solid medium is dissipated due to shot-hole blowout. Other force distributions such as the double dipole and the squeeze-bulge (associated with microseismic sources) are also available. Particular force vector distributions result in particular radiation patterns.

The source is also characterized by its wavelet time dependence, i.e., the wavelet shape and dominant frequency. Figure 2 shows examples of realizable minimum-phase wavelets and their amplitude spectra. Zero-phase Ricker wavelets can also be specified, but since our goal is to simulate real field data as closely as possible, we prefer to use minimum-phase wavelets for our modeling.

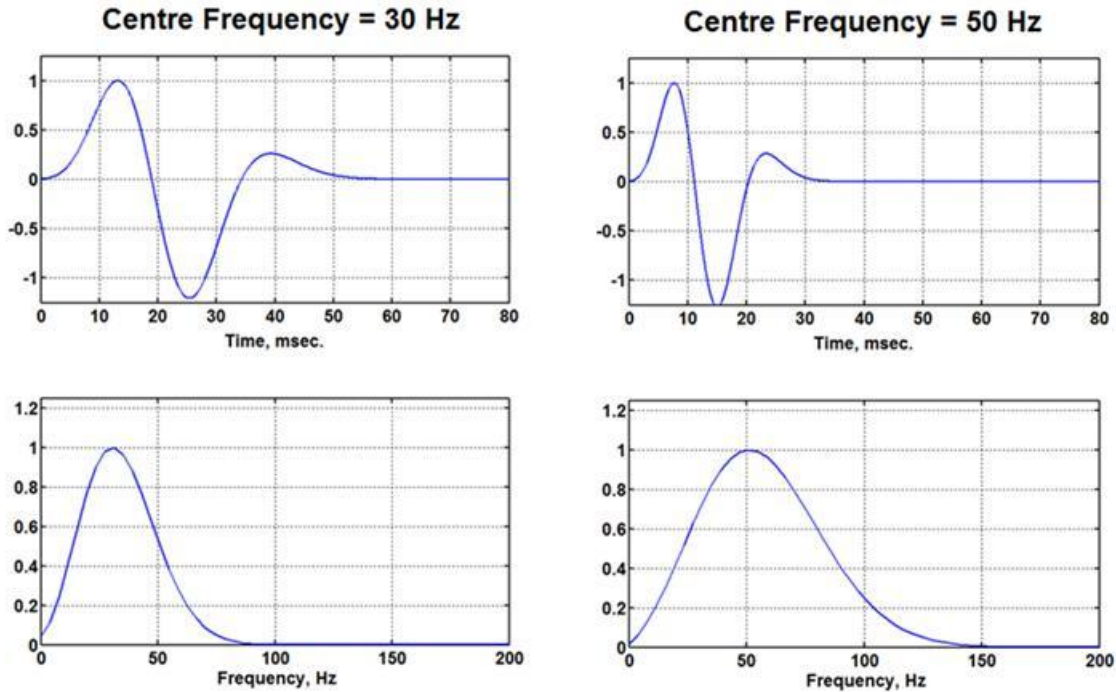


Fig 2: Realizable source wavelets and their amplitude spectra in mFD2D.

Specifying velocity models

A velocity model is first specified by the maximum horizontal and vertical dimensions in meters of area that will be used by the finite difference code. Within the model area, different velocity zones (layers and polygons) are defined by specifying a finite number of points on their boundaries, and by values of V_P (P-wave velocity), V_S (S-wave velocity), and ρ (density). The source is assigned a force vector pattern, and also a zero-phase Ricker or a minimum-phase realizable wavelet with a time-dependence determined by a dominant frequency. Based on the minimum and maximum velocity values in the model, values of Δxz and Δt are chosen in accordance with Equations 1 and 2. The number of time steps must be set to give the desired maximum time of output seismic traces. Shot point and receiver locations are then specified for a horizontal seismic profile (HSP) and a vertical seismic profile (VSP). The output folder name and a base name for the SEG Y files to be written must be given.

The model area is gridded and smoothed values of the Lamé constants λ , μ , and ρ are calculated for each velocity zone and assigned to each grid point. The time-stepping algorithm then begins to generate seismic traces which are written into four files with the extension .sgy, one each for the vertical and horizontal components of the HSP and the VSP.

Simple and moderately complex velocity structures

In principle, the time-stepping FD code is able to handle a velocity-density model that is completely heterogeneous. Useful models representing real geological structures are simpler, consisting of discrete zones in which the velocities and density are homogeneous

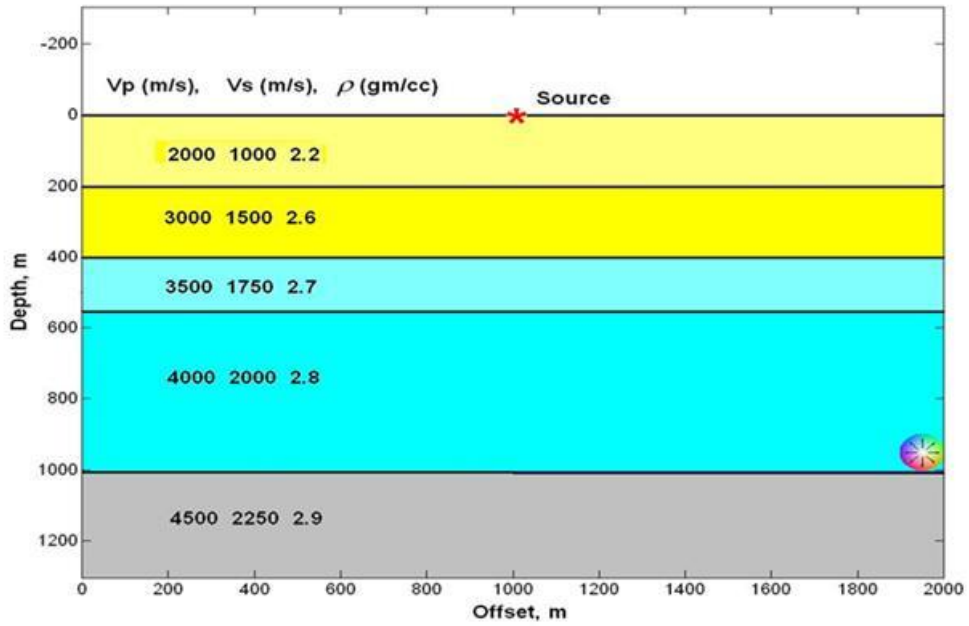


Fig 3: A simple 2D velocity/density model with horizontal layers only.

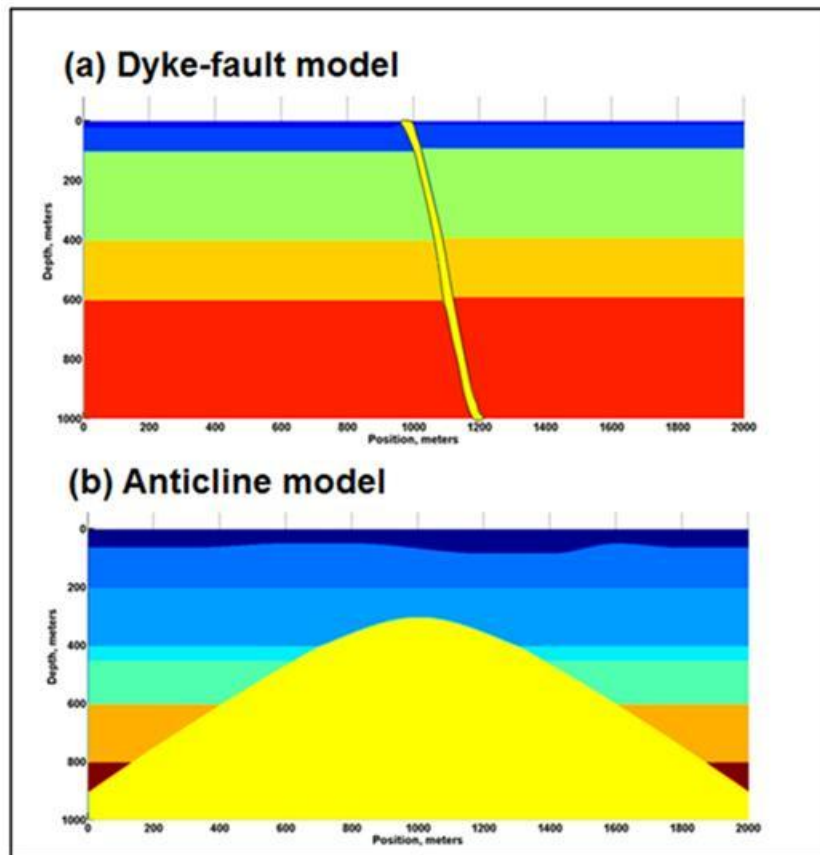


Fig. 4: Dyke-fault and anticline velocity models.

but are different from zone to zone. A simple model with flat layers is shown on Figure 3. Figure 4 displays models with a dyke-fault structure and an anticline geometry. Figure 6 indicates several possible geometries that are fairly complex; however, we warn that constructing intricate models with complex structural details can be tedious and requires both determination and patience.

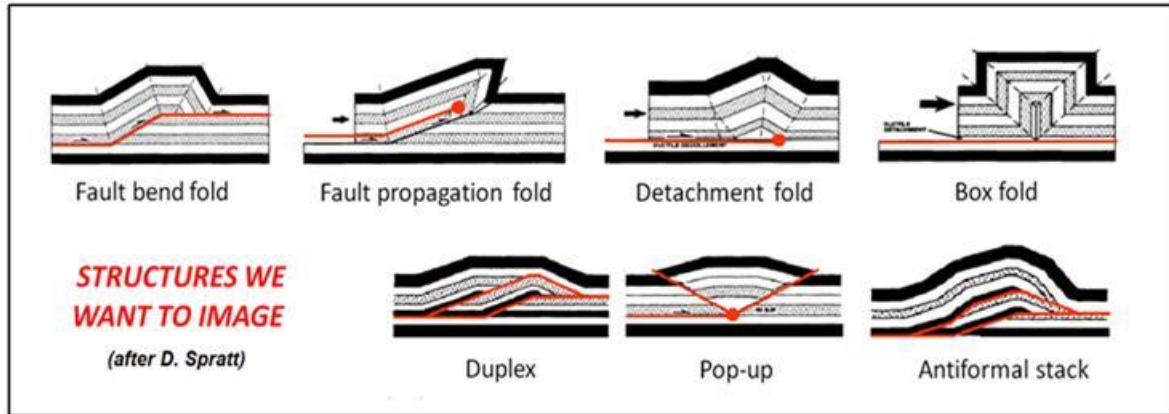


Fig. 5: More complex structural geometries for modeling in mFD2D.

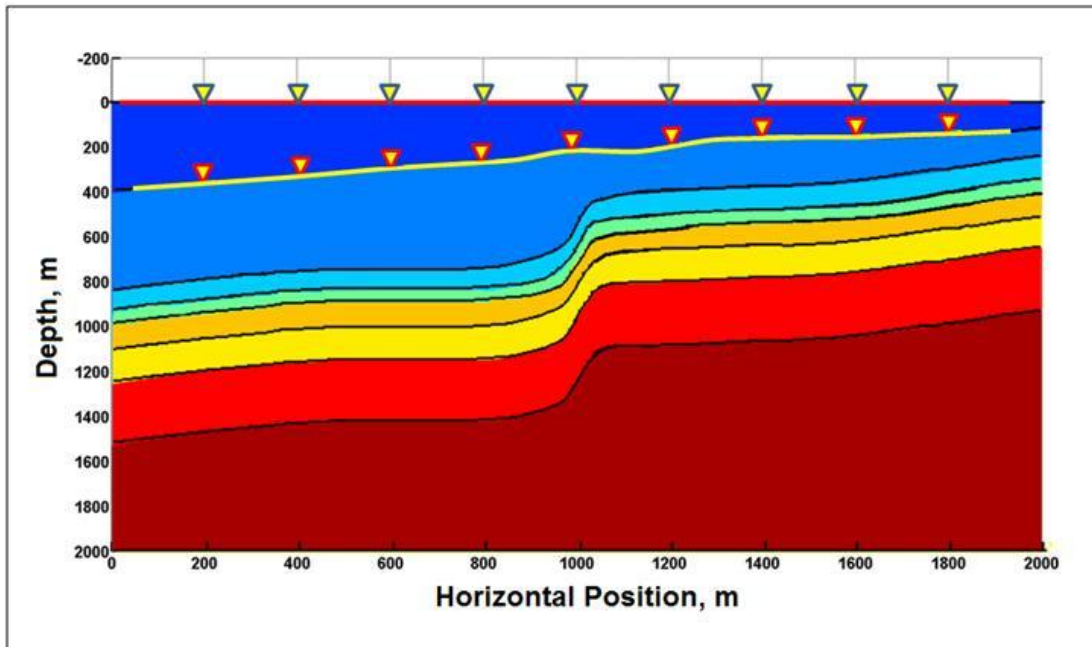


Fig. 6: A fairly complex fault-fold structure for modeling in mFD2D, with separated source and receiver lines for acquisition.

Free and non-reflecting top surfaces

One of the options in the program in Manning's code is the denoting of the top boundary of the model as a free surface or a non-reflecting surface. A free surface will generate high-amplitude Rayleigh-wave arrivals for shot gathers with shots and receivers on or near the free surface. In models with a variable low-velocity overburden, the Rayleigh

waves can produce extremely complex-looking wavefields in the shot gathers. In some cases, it may be desirable to emphasize reflections from subsurface horizons without the interference caused by Rayleigh waves. This can be done simply by specifying the top boundary of the gridded area to be non-reflecting.

Separate source and receiver lines

Normally, in modeling of surface reflection data, the source and receiver lines would be placed on the top boundary of the gridded model. However, it is possible to separate them and/or place them beneath the top surface. In addition, the lines can be defined with (mild) topography. An example of this are the lines over the fault-fold geometry shown on Figure 6, where the source and receiver lines are and is a useful option if one wishes to model 2D seismic surveys in mountainous terrain. Mimicking acquisition on lines with topography by locating them below the top boundary should use the non-reflecting boundary condition for the top surface in order to minimize unwanted reflections from the top boundary.

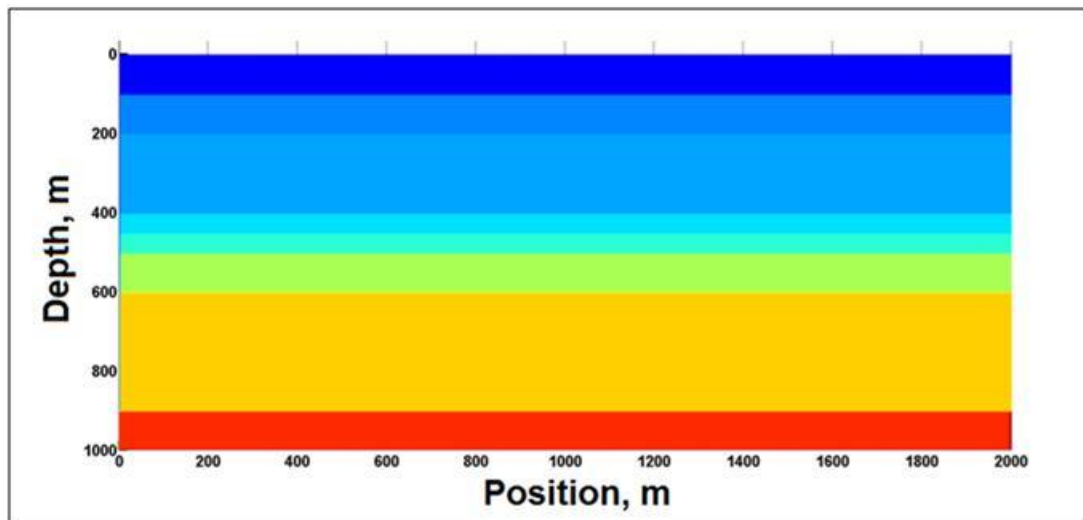


Fig 7: A simple horizontal layer velocity model. Each coloured-coded zone has its own values for P-wave velocity (V_P), shear-wave velocity (V_S), and density (ρ).

EXAMPLES OF COMMON SOURCE GATHERS

Horizontal seismic profiles (HSP)

Figure 7 shows a velocity model with flat layers with V_P values between 2500m/s and 4000m/s and V_S values between 1000m/s and 2500ms. Figure 8 displays the common source gathers of the vertical and radial component seismograms for a single shot. Direct body-wave and surface-wave arrivals with linear moveout, as well as reflections with hyperbolic moveout from the deeper interfaces, are seen clearly and unambiguously.

A more complicated model is shown on Figure 9 that includes a thin low-velocity overburden overlying a thicker weathered layer. Both layers have variable thicknesses. The overburden has a V_P value of 1200m/s and a V_S value of 800m/s. On Figure 10, we

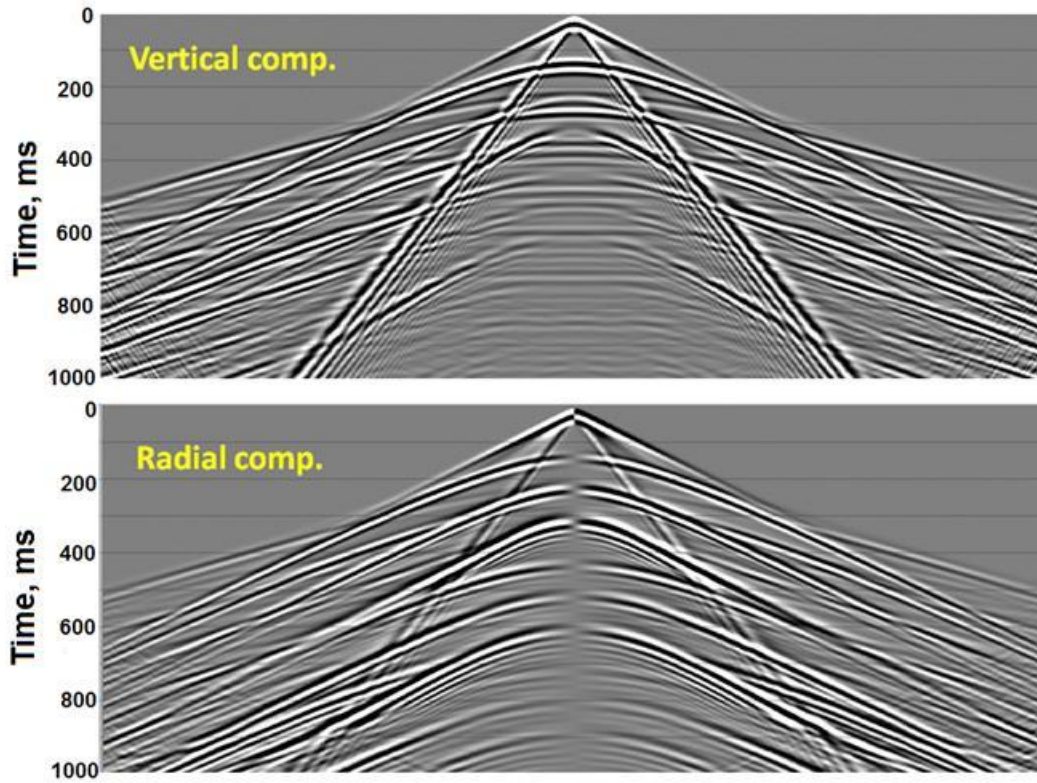


Fig 8: Vertical- and radial-component source gathers for model of Figure 3. The grid size is 0.25m, the time step is 0.25ms, and the number of time steps is 4000.

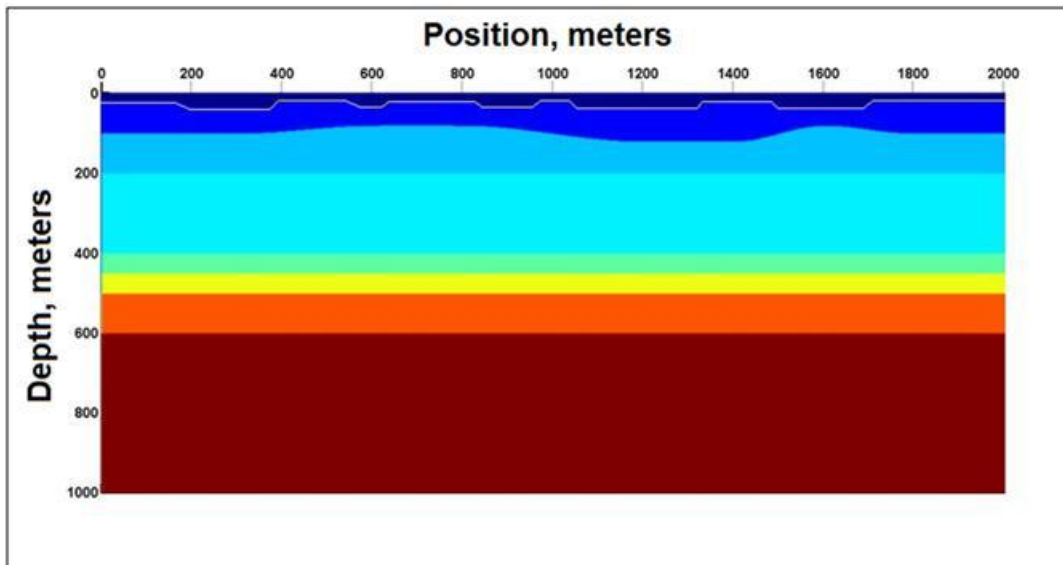


Fig 9: A model with a low-velocity overburden and a medium-velocity weathered layer, both of variable thickness. This model is used to demonstrate the effects of scattering of surface waves within the overburden.

see that appearances of the common-source gathers of the vertical and radial components are more complicated and realistic-looking than those for the simpler model of Figure 7. The increased complexity in appearance is caused by reverberations and scattering of surface waves within the structured overburden.

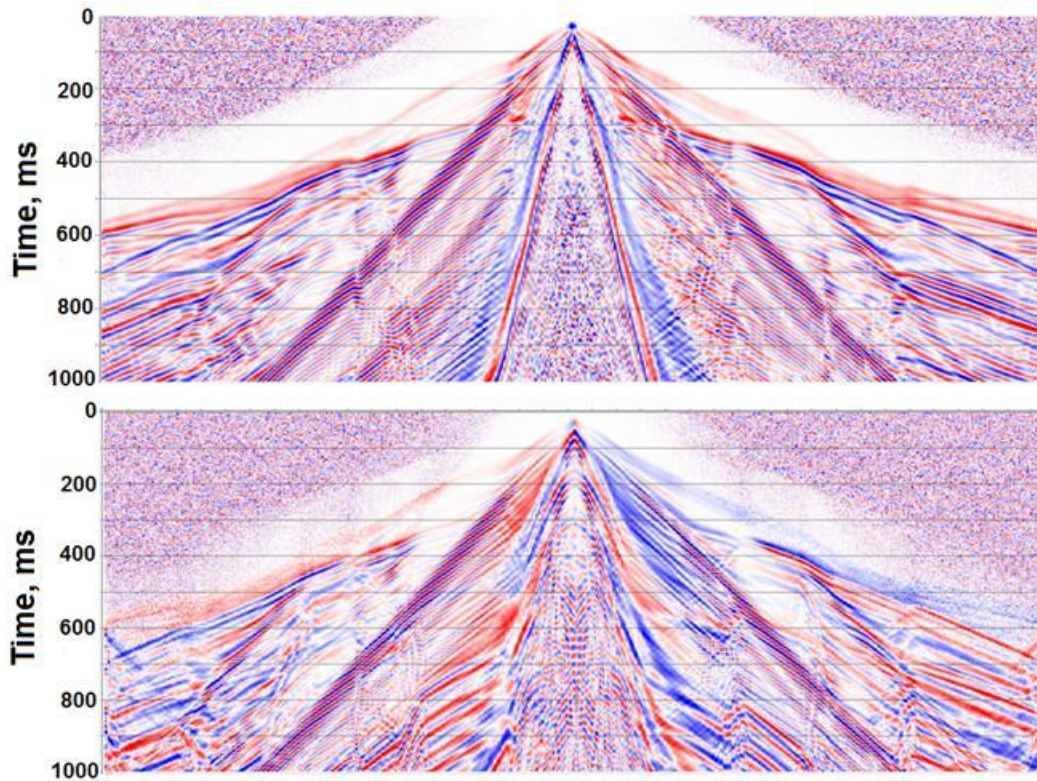


Fig. 10: The vertical- and horizontal-component source gathers for the model of Figure 5. Scattering of Rayleigh waves within the structured low-velocity overburden has caused a much more complex wavefield seen on Figure 4. The grid size is 0.20m, the time step is 0.25ms, and the number of time steps is 4000.

Vertical seismic profiles (VSP)

Figure 11 displays VSP vertical and radial component seismograms generated by the mFD2D code for a model with a simple flat-layer velocity structure with a low-velocity overburden. The simulated acquisition was done with the source located 50m horizontally from the top of the receiver well. The chaotic appearance of the seismic traces at shallow receiver depths are caused by reverberations and scattering of Rayleigh waves within the low-velocity overburden layer and also grid dispersion artifacts. However, for the traces associated with receivers below the overburden, there are distinct down-going direct arrivals and up-going reflections. The latest (fairly strong) reflection is from the bottom boundary of gridded area, and it indicates that the Clayton-Engquist method used to simulate a non-reflecting condition on the bottom boundary is not as effective as we might wish.

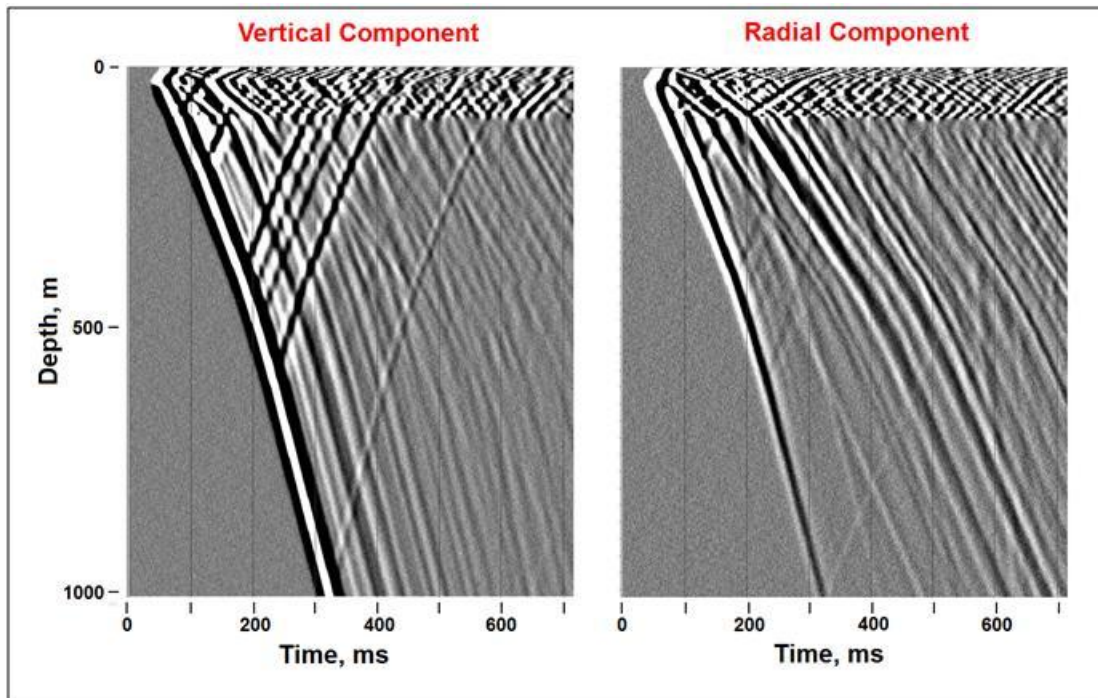


Fig. 11: Example of vertical and radial component VSPs produced by mFD2D. No AGC has been applied for the displays.

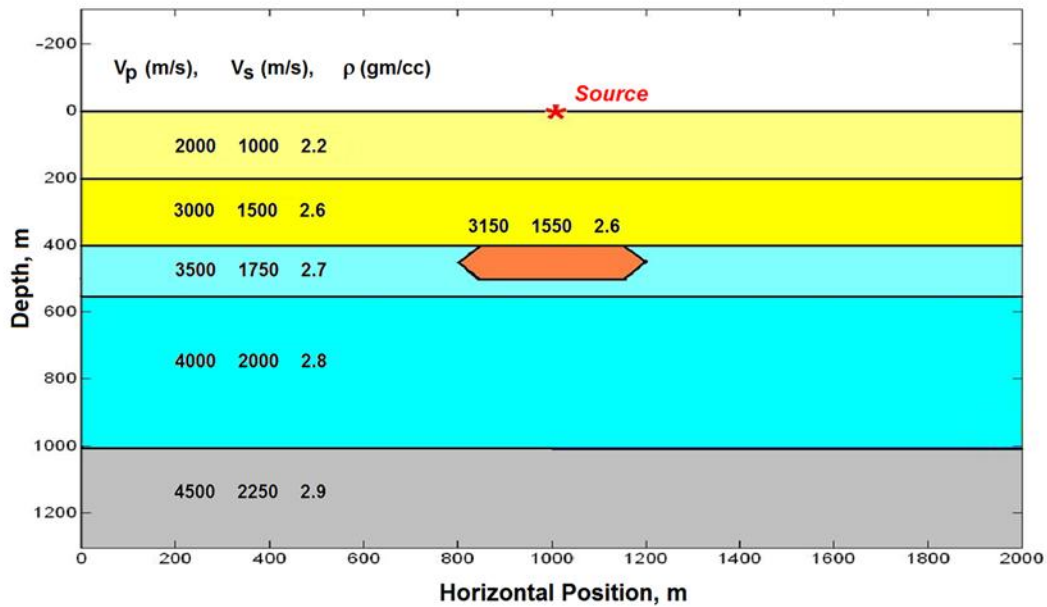


Fig. 12: A time-lapse velocity model. The properties of the target zone in the centre of the model has zero contrast with its host layer in the baseline survey; it has about a 10% decrease in velocities and 4% decrease in density in the monitor survey.

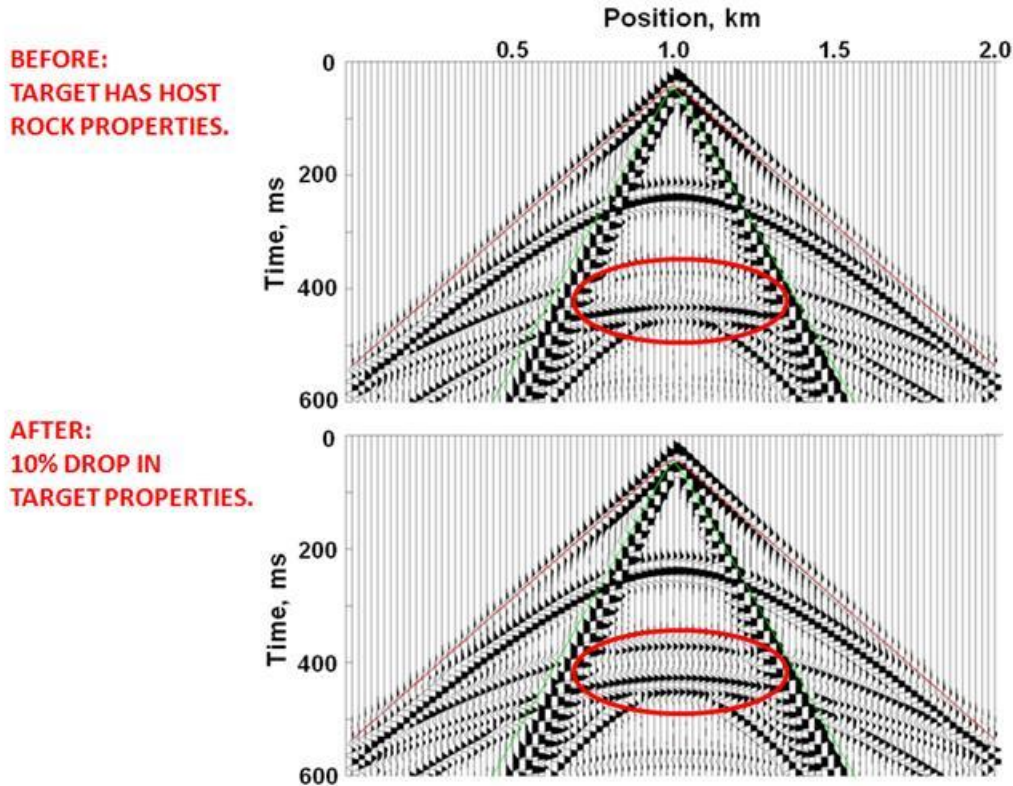


Fig. 13: Time-lapse differences in vertical component amplitudes within the red ovals.

A TIME LAPSE EXAMPLE

Time lapse surveys can be simulated by running a model repeatedly, but with the geometry and velocity-density properties of a subsurface target zone varied to simulate its changing character under some time-dependent process (e.g., steam injection). Figure 12 shows a simple model with a target zone whose velocities and density change due to a production process. For the baseline survey, the target zone has zero contrast in property values with its host layer. For the monitor survey, the velocities and density have dropped by 10%. Figure 13 shows the common source gathers of the vertical component before and after the change in velocities and density. There is a clear difference in the reflection amplitudes and times within the red ovals.

Figure 14 shows another time lapse example that includes an overburden and a weathered layer with very low P and S velocities and varying thicknesses. The properties of the target zone in the centre of Figure 13b has zero contrast with its host layer in the baseline survey; it has about a 10% decrease in velocities and 4% decrease in density in the monitor survey. The common source gathers of the vertical and radial seismograms displayed on Figures 15 and 16 are very complicated, and coherent reflections have been completely obscured by surface wave reverberations and scattering within the low-velocity overburden. Visually, the baseline data and the monitor data appear to be identical. However, the normalized plot of the differences between the monitor and

baseline seismograms clearly shows an anomaly caused by the altered properties of the target zone.

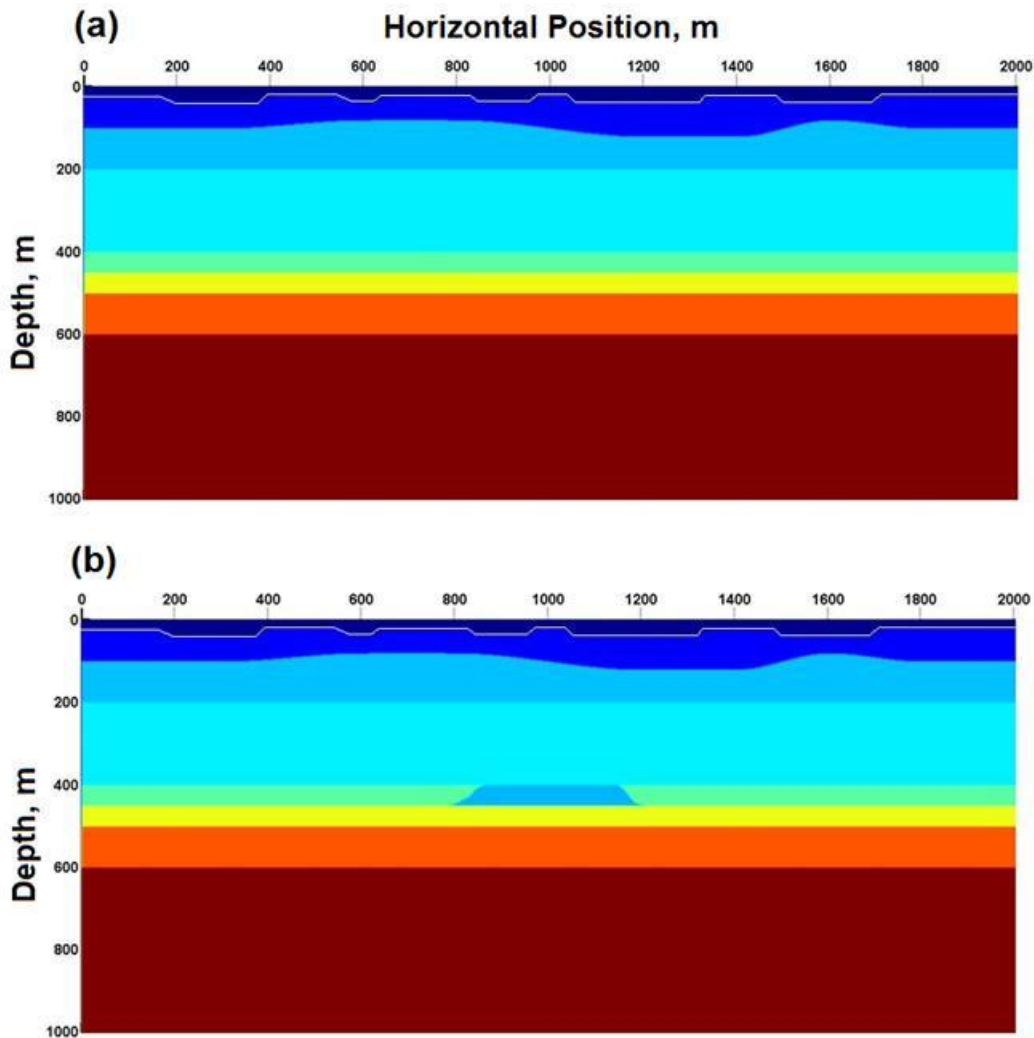


Fig. 14: A more complex time lapse example. The properties of the target zone in the centre of the model has zero contrast with its host layer in the baseline survey; it has about a 10% decrease in velocities and 4% decrease in density in the monitor survey.

A complete 2D time-lapse survey was generated by producing full 2D lines (99 shot points with 20m spacing, 1000 receiver positions with spacing of 2m) over each of the velocity structures shown on Figure 14. Band-limited random noise was added to both sets of data to simulate a situation where the SNR levels of reflections are one or less. In a companion CREWES Research Report, Henley et al. (2012) present a processing flow used to image the time-lapse anomaly for this numerical experiment. After removal of the low-velocity surface-wave related noise, the difference between the brute stacks of the statics-corrected reflections for the monitor and baseline data clearly delineates the time-lapse target (Figure 17). Similar numerical experiments using mFD2D can be

designed to study time-lapse effects in shallow reservoirs such as those found in the Alberta oilsands.

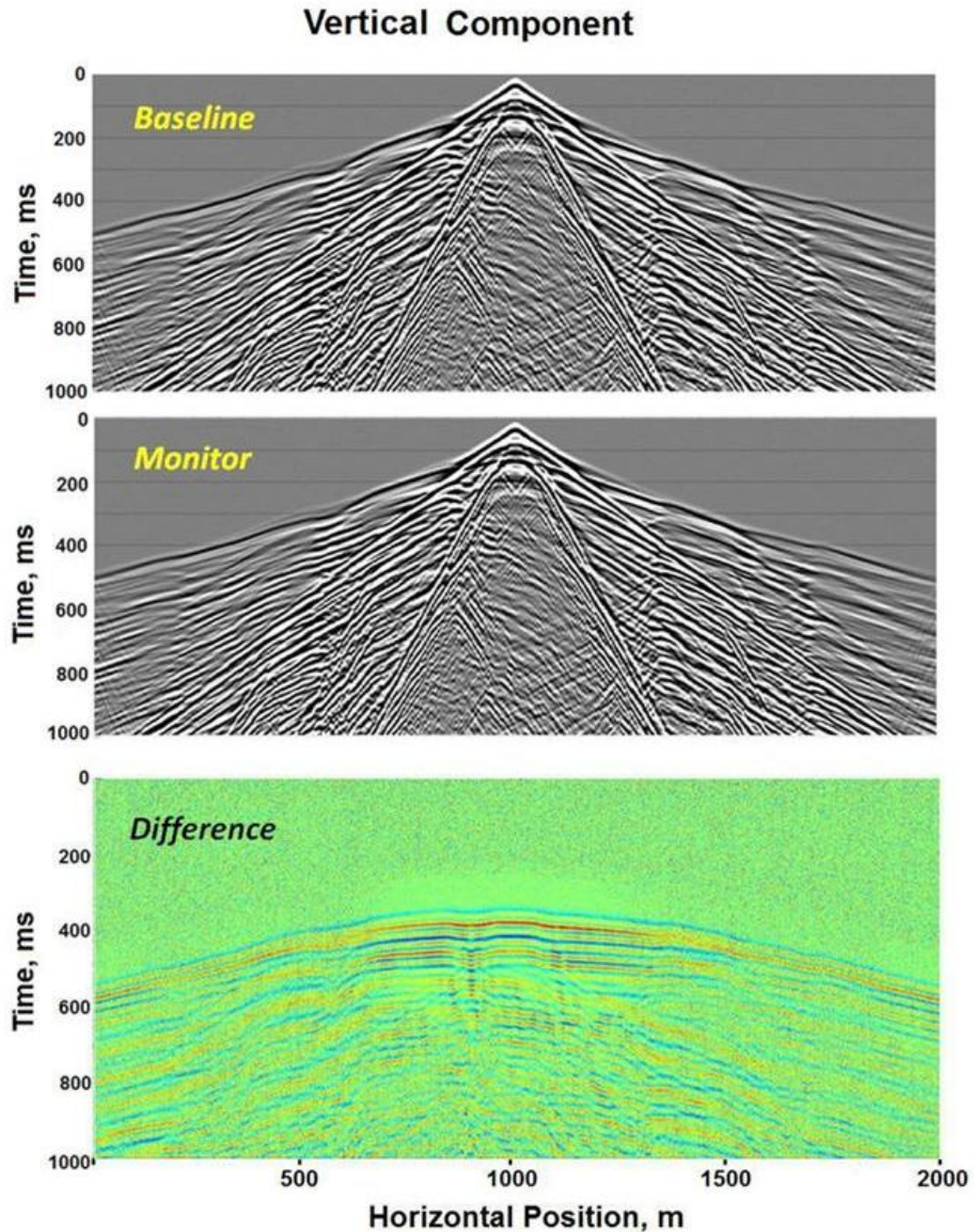


Fig. 15: The vertical component data for fixed source gathers over the models of Figure 13. The grid size is 0.20m, the time step is 0.25ms, and the number of time steps is 4000.

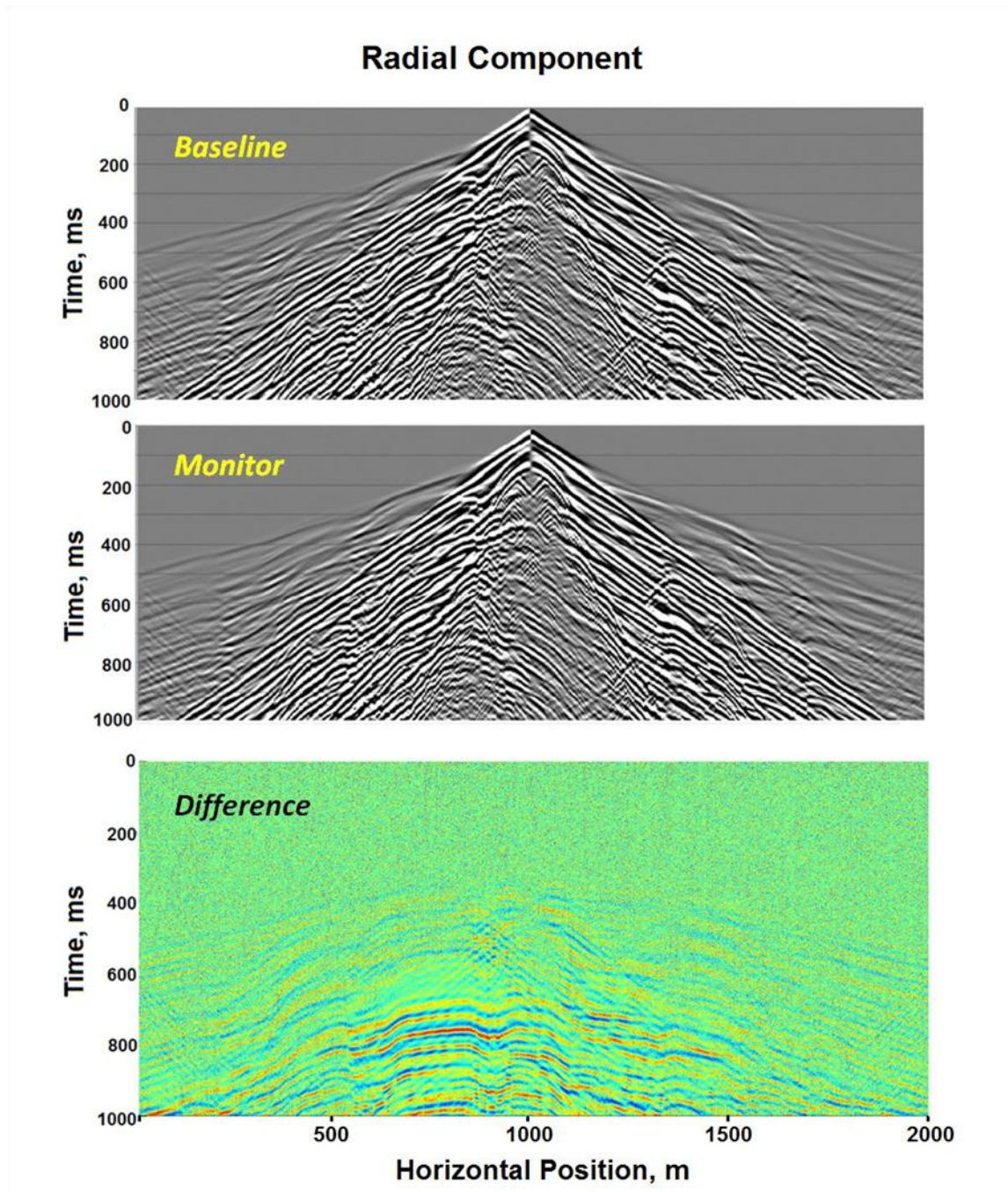


Fig. 16: The radial component data for fixed source gathers over the models of Figure 13. The grid size is 0.20m, the time step is 0.25ms, and the number of time steps is 4000.

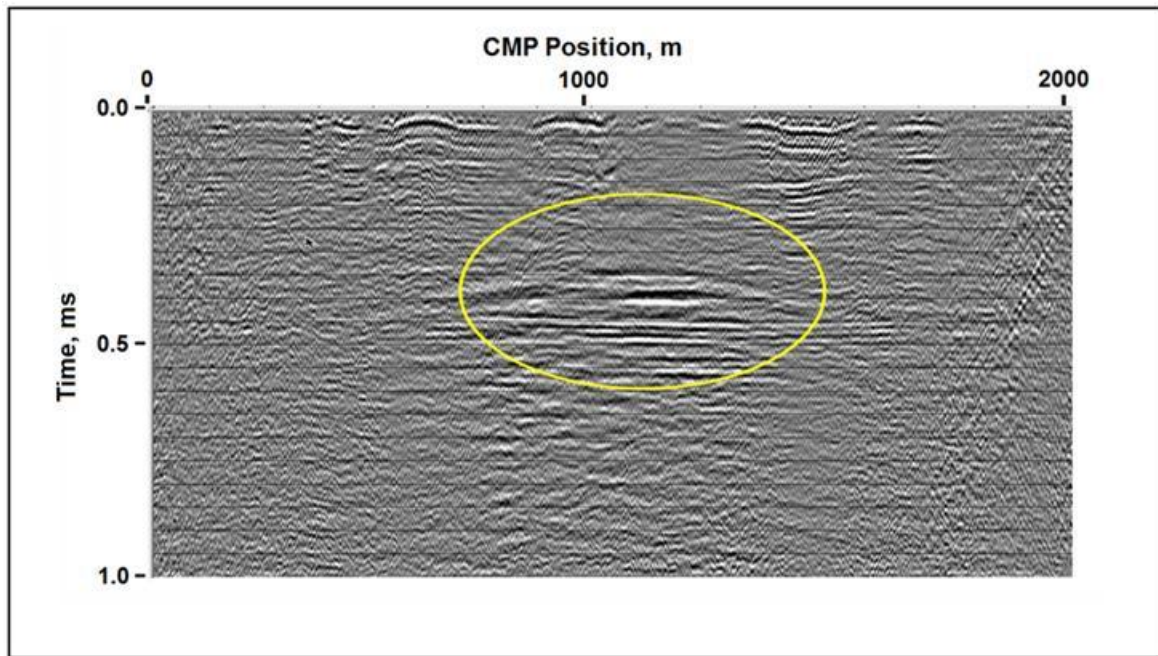


Fig. 17: Difference between brute stacks of complete baseline and monitor 2D surveys over the time lapse velocity structures on Figure 13. The left side of the anomalous target zone appears to have been distorted by the variable thicknesses of the overburden and weathered layers.

SUMMARY AND DISCUSSION

The MATLAB software package mFD2D was designed to produce synthetic data simulating field results for a variety of acquisition geometries. It is used to model 2D elastic-wave propagation through moderately complex velocity structures defined by flat or undulating layers beds and discrete zones of various shapes. By properly specifying the acquisition and source parameters, the mFD2D code can produce realistically-looking data for practically all types of seismic surveys, namely, refraction, reflection, VSP, crosswell, microseismic, and time-lapse. Such data sets would be useful for planning of real-world surveys, and for testing of processing schemes and imaging techniques.

We caution that mFD2D simulates elastic wave propagation in a 2D geometry, so that the resultant signal amplitudes are not directly comparable to amplitudes associated with real world surveys. The 2D code simulates radiation from a line source into a geometry invariant in the geological strike direction, whereas real world surveys are better represented by a point source. A line source produces amplitudes that decrease with source-receiver distance r as $1/\sqrt{r}$ (cylindrical divergence), while a point source produces amplitudes that decrease as $1/r$ (spherical divergence). Because of this, the seismic amplitudes resulting from the 2D code cannot be compared directly with amplitudes on real-world seismograms.

An important feature of the software is that all shot gathers are written into SEG Y files. This means that the synthetic data can be read directly into processing packages such as

Landmarks's Promax and GEDCO's Vista. We note that the values written into the SEG Y files are displacement amplitudes, so that a time derivative must be applied in processing in order to mimic geophone responses.

The software is easy to use, and it executes fairly efficiently on individual desktop or laptop computers in (a complete 100,000-trace reflection survey surface can be generated in 24 hours or less). For these reasons, the mFD2D software promises to be a very useful tool for pre-survey planning and for educational purposes.

ACKNOWLEDGEMENTS

This research has been supported by NSERC and the industrial sponsors of CREWES.

REFERENCES

- Henley, D.C., Wong, J., and Manning, P.M., 2012. Time-lapse by the numbers: elastic modeling of repeatability issues: CREWES Research Report, **24**, this volume.
- Manning, P.M., 2007. Techniques to enhance the accuracy and efficiency of finite-difference modelling for the propagation of elastic waves, Ph.D. dissertation, University of Calgary.
- Kragh, E., and P. Christie, 2002. Seismic repeatability, normalized rms, and predictability: The Leading Edge, **21**, 640-647.
- Kosloff, D., and Baysal, E., 1982. Forward modeling by a Fourier method: Geophysics, **47**, 1402-1412.
- Virieux, J., 1986. P-SV wave propagation in heterogeneous media: velocity-stress finite-difference method: Geophysics, **51**, 889-901.

APPENDIX A: EXECUTION SPEED

A benchmark for execution speed can be set by running a model with a standard set of parameters. We tested mFD2D using MATLAB 2009a running in Windows 7 on a desktop computer with a 32.0 GHz Intel CORE i5 CPU and 4 GB of RAM. For a model of size 2000m by 1000m, with a grid size of 2.5m and a time step of .00025s, about 15 hours were required to produce vertical and radial component data for 100 shots and 4000 time steps.

We tested a crude but effective way of using the multiprocessor capability of the CPU to decrease the time taken to generate a complete 2D line. By opening three separate MATLAB windows and running mFD2D in a different folder name for each window, the same geological model can be run with different subsets of shot points and a different SEG Y base filename. In this way, we were able to generate the same volume of data for the 100 shots in about 6 hours, a nominal decrease in execution time of about 2.5.

We also found that the execution speed had a drastic dependence on the MATLAB version and its compiler. MATLAB can run with its just-in-time (jit) compiler either on or off, controlled by the commands

> feature jit on

> feature jit off .

Table I summarizes our observations on this point, where the execution times for a fixed (small) number of time steps under two versions of MATLAB with the jit compiler on and off. We do not understand why the quickest execution time occurs with MATLAB 2009a and “jit on”, but we speculate that this behavior is related to the fact that the 2009a version is based on win32, while the 2010b and later versions are based on win64.

TABLE I. Execution speed for different MATLAB versions.

Version	Feature	Execution time	Relative time
2009a (win32)	jit on	49	1
2009a (win32)	jit off	178	3.6
2010b (win64)	jit off	120	2.4
2010b (win64)	jit on	525	10.7

The mFD2D software runs in the MATLAB environment, which is largely an interpreted environment. We expect that if all the functions (or only the computationally intensive functions) within mFD2D were translated to a language such as C, C++, or FORTRAN 95 and compiled fully to machine code, execution speed would increase dramatically.

APPENDIX B: EXAMPLES OF INPUT FILES FOR mFD2D

We present here examples of *.acq files that define the acquisition parameters of the modeling by mFD2D, and of *.geo files that define the geometry and properties of the velocity structure being modeled. Both types of files are ASCII files, easily created or modified by the MATABL Editor or any other text editor. When mFD2D reads these files, all text within a line following the character “%” is treated as comment.

Example *.acq file

```
% mod_02.acq -- Acquisition Input Parameter File for mFD2D
% Lines beginning with % are comments and are ignored by mFD2D.
% Acquisition Input Parameter File for mFD2D
% HSP = Horizontal Seismic Profile, VSP = Vertical Seismic Profile
%
lengthX  2000  % meters, max X value for geological model
lengthZ  1000  % meters, max Z value for geological model
Dxz      2.0   % meters, X-Z cell size for grid
%
Dt        .00025  % seconds, time step increment
resampDt  .001    % seconds, resampled time for saved seismograms
%
zHSP     0      % meters, depth for horizontal receiver line for HSP data
xVSP     950    % meters, X position of receivers in vertical well for VSP data
%
dcmHSP   10     % decimate factor = 1, 2, 3, 4 ... 20 ... for HSP traces in SEG Y file
dcmVSP   10     % decimate factor = 1, 2, 3, 4 ... 20 ... for VSP traces in SEG Y file
%
centreFreq 30   % Frequency in Hertz for source wavelet
```

```

timeSrc  3    % wavelet type: 1 = Ricker, 2 = windowed cosine, 3 = minimum phase
cycleSrc 3.5  % No. of cycles (windowed cosine only)
%
energySrc 21  % Code number of the energy source (10,11,12,13,21,22,23)
%           10-deep explosion, 12-double couple,
%           21- vertical vibrator, 22-horizontal vibrator,
%           31 – shallow explosion
segName = 'mod_02' % a base for SEGY output filename
gfdFile = 'mod_02.geo' % velocity/geometry definition file
%
```

The *.acq file contains the name of the *.geo file to be read, and the base name of the SEGY files that will be written. Four separate *.sgy files will be written, one each for the vertical and radial components of the HSP and VSP. Additional characters will be added to the base name to differentiate between the four.

Example *.geo file

The “box” designation indicate that the (x, z) coordinate pairs that follow will define the vertices of a polygon. Without the “box” designation, the coordinate pairs will define an interface between layers. NB: all layer definitions should be placed before any box definition.

```

% mod_02.geo -- model geometry file for mFD2D
% Vp, Vs, rho, X1, Z1, X2, Z2, X3, Z3, X4, Z4, X5, Z5 –defines layers or boxes
%
2000 1000 2.2  0  0 2000 0
3000 1500 2.6  0 200 2000 200
3500 1750 2.7  0 400 2000 400
4000 2000 2.8  0 500 2000 500
4500 2250 2.9  0 550 2000 550
%
box 1400 700 2.2 1495 500 1705 500 1695 15 1505 15
box 3150 1550 2.6 800 425 850 400 1150 400 1200 425 1150 450 850 450
%
```