A 3D Elastic Modelling Code For Seismic Wave Propagation and 3D SWD surveys

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Abstract

La sismica while-drilling (SWD) è una metodologia geofisica che utilizza il rumore prodotto dallo scalpello durante la perforazione per ottenere informazioni geologiche dei terreni posti davanti ed attorno al pozzo. Le vibrazioni prodotte dallo scalpello sono registrate da sensori pilota montati sull'impianto di perforazione e da linee sismiche stese attorno al pozzo. La cross-correlazione del segnale pilota con quelli registrati dalla linea fornisce dati sismici che sono utilizzati per guidare la perforazione. La simulazione numerica del campo d'onda sismico che si propaga in strutture geologiche complesse è uno strumento estremamente utile, nella fase di progetto di un rilievo sismico 3D "while-drilling". I dati sintetici sono calcolati per ottimizzare i parametri di acquisizione e la geometria delle linee sismiche prima della stesura delle stesse. Essi sono inoltre utilizzati per l'analisi degli algoritmi di elaborazione e separazione del segnale dal rumore e per la comprensione della natura dei diversi segnali sismici (onde convertite, diffrazioni, eventi multipli, etc.) al fine di migliorare l'interpretazione dei dati. La generazione di sismogrammi sintetici richiede calcolatori con grandi prestazioni ed efficienti codici di calcolo al fine garantire i risultati richiesti in tempi ragionevolmente limitati.

The seismic-while-drilling (SWD) is a geophysical methodology that utilises the vibration produced by the working bit to obtain, in real time, geological information ahead and around the well. Numerical modelling of seismic wave propagation in realistic complex geological structures is an important tool for the planning of 3D (SWD) experiments. Synthetic data are calculated to simulate the seismic acquisition prior to the in-situ measurements. These data are used to optimise the seismic line geometry, to assist the signal and noise recognition in the acquired data, to test the processing algorithms for noise and signal separation, and to understand the nature of the different events (wave conversion, diffraction, multiples, etc.) for interpretation and imaging purposes. Synthetic seismograms require a *large amount in computing memory and disk storage, moreover efficient algorithms are needed in order to reduce the computing time of each numerical simulation.*

1. Introduction

Elastic forward modelling in heterogeneous media represent a severe challenge both to computer and numerical technology. Realistic computations require a very huge amount in computing memory and disk storage, moreover efficient algorithms are needed in order to reduce the computing time of each numerical simulation. Various algorithms exist, based on finite-differences, finite-elements, Fourier, and other formulations, that allow for 3D surveys modelling over complicated geology, but numerical solutions of wave equations on a discrete computational grid imply artefacts and local instabilities. Sampling errors, bandwidth limitations, grid dispersion and anisotropy, and approximations to the wave equation are the main source of the numerical artefacts. They often have amplitudes similar to those of real arrivals which means that artefacts may confuse or produce erroneous interpretations. Once a numerically accurate algorithm has been devised its implementation must be done very carefully in order to produce an efficient computational code. In particular, for large scale problems, the huge memory and CPU time requirements can be managed by implementing parallel version of the algorithm to exploit the high speed parallel multiprocessor computers like the Cray T3E.

2. The 3D seismic-modelling code

The algorithm developed and implemented for the 3D forward modelling code used in computing the 3D SWD Seisbit © survey is based on the Fourier pseudo-spectral methods and on the elastic full wave equation for heterogeneous media without compromising material parameter assumptions (Reshef et al., 1988, Carcione et al., 1992). Moreover, for improving the numerical accuracy a staggered scheme (Fornberg, 1990, Carcione, 1999) has been used and efficiency has been obtained by a parallel implementation. Wave equations are expressed in velocity-stress formulation using the equation of conservation of momentum and the stress-strain relations for an isotropic elastic medium undergoing infinitesimal deformation.

In addition to arbitrary compressional velocity and density variation in lateral and vertical directions, elastic modelling allows shear velocity variation as well. The elastic wave equations are solved iteratively by splitting the total time simulation in smaller time steps in which the various field are sequentially computed. Computation of each time step begins by computing six strain components by performing nine spatial partial differentiation operations on the three displacement components from the previous time step. The six strains and the two Lame' con-

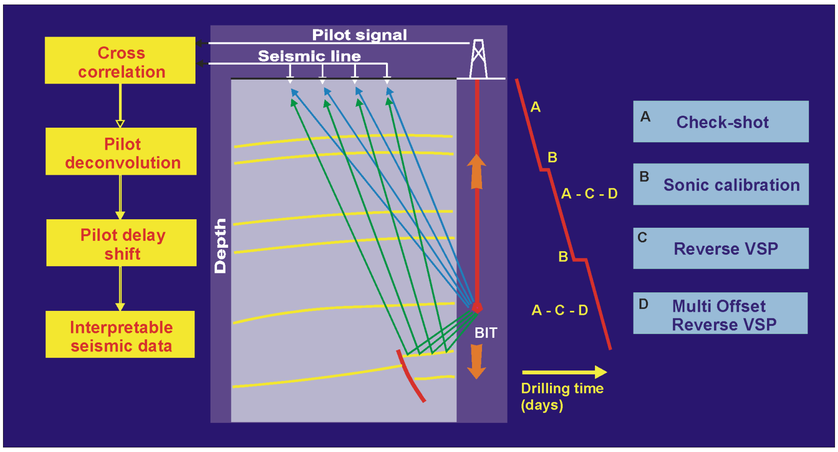


Figure 1 Seisbit © SWD method basic concepts: This methodology utilizes the noise produced by a working drill-bit to obtain interpretable seismic data. The bit vibrations is recorded by pilot sensors on the rig and by seismic lines deployed on the surface. The cross-correlation between the data acquired by seismic line and pilot sensors gives interpretable seismic data, used to drive drilling. The main products of Seisbit © technology are: Check shot, Sonic calibration, Reverse VSP and Multi-offset Reverse VSP.

stants are linearly combined to yield six stress components. Nine spatial partial differentiation operations on the six stresses, three body forces, and density are used to compute second partial time derivatives of the three displacement components.

Time stepping to obtain the three displacement components for the current time step is performed with second-order difference operators. Spatial derivatives are computed globally by using the fast Fourier transform (FFT) which gives very high accuracy that is further increased by using a staggered grid scheme for the various field components.

The effect of free surface, at the soil/air interface, is included, and in order to avoid wave reflections from the model edges an absorbing boundary is applied on the lateral and bottom edges of the spatial grid. Any kind of sources can be used in order to start the wave propagation simulation. Very complex heterogeneous geological models can be defined since the physical properties of the media can be imposed without restriction at each node position of the computational grid. The parallel implementation of the algorithm is obtained by splitting the computations in the physical domain in the equivalent computations in multiple sub-domains.

Efficiency is obtained by using the SHMEM function library that allows for the maximum speed on the Cray T3E multiprocessor. In each sub-domain computations are done concurrently and communications among different CPUs are reduced to the minimum.

3. Simulation and results

The seismic-while-drilling (SWD) is a geophysical technique that utilizes the noise produced by the working bit to obtain, in real time, geological information ahead and around the well (Rector et al., 1991, Miranda et al., 1996). Bit vibration are detected by pilot sensors on the rig and by seismic lines deployed on the surface around the well. The cross-correlation between the data acquired by seismic line and pilot sensors gives interpretable seismic data, used to drive the well drilling (Figure 1).

In the frame of the EC project - SEISBIT 3D RVSP: while drilling seismic imaging and areal velocity investigation by using the drill bit signal - synthetic seismograms was calculated by 3D elastic modelling to optimise the RVSP data acquisition. In the feasibility study we build a 3D geological model utilising seven reflection seismic lines crossing the well area and log information from two wells, drilled near the well site. The main geological formations were interpreted and their location converted from two-way travel time to depth. The 3D interfaces were obtained by the interpolation of 64 1D models sampled along the seismic lines. The P-wave velocities were derived from sonic logs and interval velocities obtained from seismic reflection data. The S-wave velocities were simply computed from the relation Vs= (Vp/3)^« while the densities were obtained by using the empirical formula, D = 0.267 Vp^0.25.

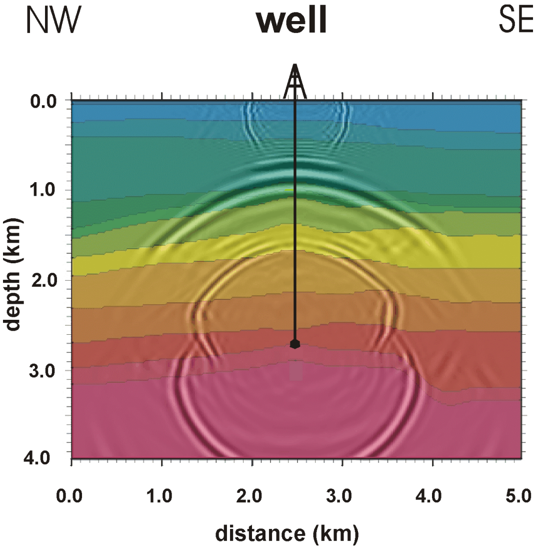
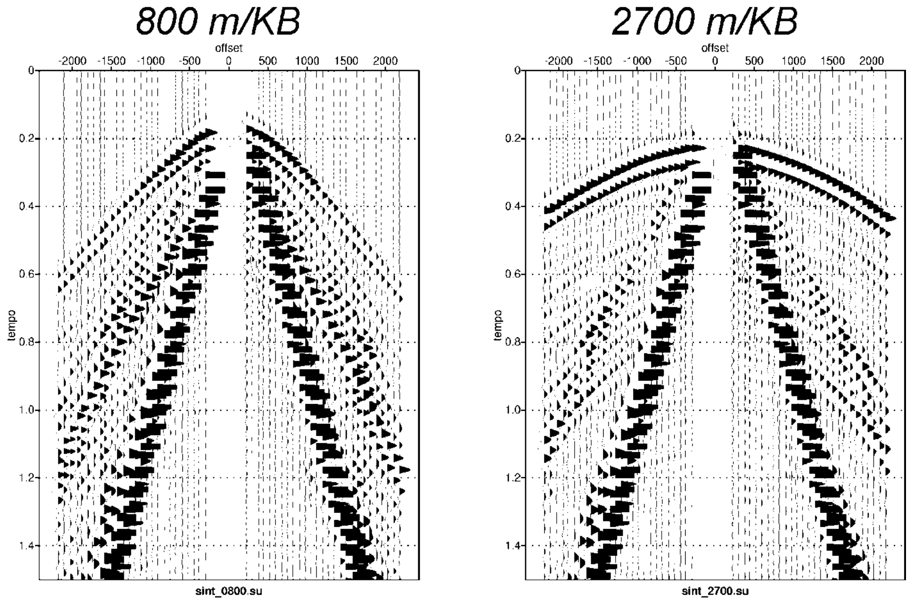


Figure 2 *A vertical section of 3D model with the superposition of the snap-shot representing the wave-field 0.5 seconds after a vertical force simulating the drill-bit source.*

The parameters for modelling are obtained as follows: i) derive the grid spacing from the maximum frequency fmax of the source time wavelet and the minimum shear-wave velocity Vmin with the constraint Max(dx,dy,dz) <= Vmin/(2 fmax) to avoid the spatial aliasing with a sampling of at least two points per minimum wavelength; ii) evaluate the number of grid points of the computational mesh from the size of the model; iii) allocate additional grid points corresponding to a space of at least four wavelengths for each absorbing strip at the sides, top and bottom of the model; and iv) choose the time step according to the stability criterion given by the constrain Vmax dt <= 2 Min(dx,dy,dz)/(pi Sqr(3)), where


800 m/KB

2700 m/KB

Figure 3 Synthetic seismograms simulating correlated signal and noise at 800 and 2700 m/KB bit

Vmax is the maximum compressional-wave velocity. The numerical mesh used to solve the equation has NX = 250, NY = 250, NZ = 240 grid points, and a uniform grid spacing of 20 m. The field is initiated by a vertical force - simulating the drill-bit source - with a Ricker time history and a central frequency of 25Hz. The field is computed by using a time step of 1 ms. The total wall-clock time for a common-shot survey is about 4 h.

We simulated more than 20 common-shot-gathers with source depths intervals of 20 m to generate a 3D RVSP dataset suitable for processing tests. Stationary rig noise was obtained by calculating a shot near the surface in correspondence with the well. Figure 2 shows a vertical section of the model passing through the well location with a superimposition of a snap-shot. Figure 3 shows two examples of signal and stationary noise at a drill-bit depth of 800 and 2700 m/KB, respectively. The velocities and the thicknesses of the shallower layers imply direct and refracted events that do not interfere significantly with the drill-bit direct arrivals. On the contrary, reflections are masked by the direct coherent noise, ground-roll and S arrivals. Multichannel processing techniques were tested on the synthetic data to remove the noise in the azimuth domain.

On the basis of synthetic data and scouting results - to verify the access and topographic condition in the well area - we designed the “saw toothed” configuration of the receivers in the circular lines, located at about 1.1 and 2.2 km offset.

This geometry optimises the acquisition of shallow and deep data, respectively (Bertelli et al., 1998). Furthermore, we used the 3D geological model during the SWD acquisition to help 3D-signal interpretation, assist the first-arrival picking, and discriminate the (not stationary) head-wave noise produced when drilling without drill-pipe rotation.

As a conclusion, the experience accumulated during this experiment demonstrated that, as in other field of science, the use of numerical simulation codes is very important for the optimisation of the available resources, for getting better and more reliable data and for reducing the costs.

Acknowledgments

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