Doctoral Thesis

Automation in shallow seismic data acquisition

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AUTOMATION IN SHALLOW SEISMIC DATA ACQUISITION

A dissertation submitted to the
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presented by

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CONTENTS

ZUSAMMENFASSUNG ........................................................................................................ 1

ABSTRACT ....................................................................................................................... 3

1 GENERAL INTRODUCTION ....................................................................................... 5

1.1 Motivation and General Objectives ....................................................................... 5

1.2 Review of Near-Surface Reflection Seismic Techniques ...................................... 5
   Historical aspects and applications ........................................................................ 5
   Acquisition ............................................................................................................... 6
   Processing shallow seismic reflection data ............................................................ 8
   Pitfalls ...................................................................................................................... 9

1.3 Instrumentation ..................................................................................................... 9
   Sources ................................................................................................................... 9
   Receivers ............................................................................................................. 11

1.4 Goals of the Thesis: Problems and Solutions ....................................................... 12

2 LAND-STREAMER FOR SHALLOW SEISMIC DATA ACQUISITION:
   EVALUATION OF GIMBAL-MOUNTED GEOPHONES ........................................... 21

2.1 Introduction .......................................................................................................... 21

2.2 Towed Land-Streamer ......................................................................................... 22

2.3 Geophone-to-Ground Coupling Tests .................................................................. 22

2.4 Multichannel Test Reflection Survey .................................................................... 23
   Acquisition ........................................................................................................... 23
   Processing ............................................................................................................ 24
   Geological interpretation ..................................................................................... 24

2.5 Conclusions .......................................................................................................... 24
3 EVALUATION OF HIGH-FREQUENCY SEISMIC SOURCES FOR IMAGING SHALLOW (10-250 m) STRUCTURES

3.1 Introduction

3.2 Survey Area and Local Geology

3.3 Seismic Sources
   Impulsive sources
   Vibratory sources

3.4 Acquisition

3.5 Processing

3.6 Resultant Data
   Profile A: Sledgehammer, pipegun and weightdrop system
   Profile B: Sledgehammer and OYO and GGA vibrators

3.7 Discussion
   Profile A: Sledgehammer, pipegun and weightdrop system
   Profile B: Sledgehammer, and OYO and GGA vibrators
   Further details of the OYO vibrator data
   Comparison of profiles A and B
   Comparison with the results of Doll et al.'s study

3.8 Conclusions

4 DESIGN AND APPLICATION OF A LAND-STREAMER SYSTEM FOR COST-EFFECTIVE 2D AND PSEUDO-3D SHALLOW SEISMIC DATA ACQUISITION

4.1 Introduction

4.2 Towed Land-Streamer System
   Land-streamer
   Field effort for acquiring 2D profile data: Land-streamer versus conventional technique
   Choosing the acquisition geometry for acquiring 2D profile data: Uniform versus non-uniform receiver spacings

4.3 Data Quality: Land-Streamer Versus a Conventional Technique
   Meadow
   Asphalt
   Compacted gravel track

4.4 Using the Towed Land-Streamer to Acquire Pseudo-3D Data:
   A Feasibility Study
Acquisition geometry .................................................................70
Processing ..................................................................................71
Stacked data ..................................................................................72
Comparison of field efforts ...........................................................73
Need to check for azimuthal effects .................................................73

4.5 Conclusions and Outlook ........................................................94

5 OUTLOOK ................................................................................101

5.1 Additional Steps to Increase Efficiency of Towed
Land-Streamer System .................................................................101
System positioning ........................................................................101
In-field processing ..........................................................................103

5.2 Three-Component Seismic Data .................................................104
Land-streamer with three-component geophones ...........................105

5.3 Statistical Experimental Design to Optimize Shallow Seismic Surveys 105
Problem definition .........................................................................106
Problem constraints .......................................................................106
Mathematical formulation of the statistical experimental design problem .107

6 REFERENCES .............................................................................115

ACKNOWLEDGMENTS .................................................................125

CURRICULUM VITAE ...................................................................127

APPENDICES
A Overview of High-Frequency Sources for Shallow Seismic Experiments ..129
B Field Effort for 2D Profiling: Land-Streamer System Versus
  Traditional Approach......................................................................135
C Non-Uniform Receiver Geometries .............................................137
D Technical Details Seismic Land Streamer....................................143
E Improvements in High-Resolution Seismic and Georadar Acquisition
  Techniques..................................................................................159
F High-Frequency Sources in Shallow Seismic Experiments ............163
G Determining Elastic Soil Parameters at Small Strains ....................171
Hochauflösende seismische Reflexionstechniken werden zur Lösung vielfältiger Fragestellungen im Ingenieur- und Umweltbereich benutzt. Obwohl instrumentelle Entwicklungen in den letzten Jahrzehnten grosse Fortschritte gemacht haben, bleibt die Akquisition ausreichend redundanter Daten weiterhin ein zeit- und kosten aufwendiger Aspekt.

Um die Schnelligkeit und Effizienz oberflächennaher seismischer Untersuchungen zu erhöhen und dadurch die Akquisitionskosten zu verringern, habe ich ein “Land-Streamer-System” entwickelt. Die wesentlichen Komponenten dieses Systems sind: (i) rotationsfähige und selbstorientierende “Gimbal”-Geophone in einem relativ schweren, zylindrischen Gehäuse, (ii) eine verstärkte Gummimatte, welche die Geophone bedeckt und so die Geophonausrichtung beibehält und durch zusätzliches Gewicht den Anpressdruck erhöht, und (iii) seismische Kabel mit verstärktem Kevlarmantel. Jedes Kabel ist mit 12 Geophon-Ausgängen in 1 m oder 2 m Intervallen ausgestattet. Die Hauptvorteile dieses innovativen Ansatzes zur Akquisiüon oberflächennaher seismischen Daten sind:

- kein manuelles Stecken der Geophone;
- kein manuelles Auslegen der Kabel;
- Zunahme der Akquisition-Geschwindigkeit um 50-100 %;
- Reduktion des Personalbedarfs im Feld um 30-40 %;


Ein kritischer Aspekt in der Effizienz des Land-Streamer-Systems ist die seismische Quelle. Der relativ langsame Wiederholdrate moderner Quellen (z.B. etwa 1 oder 2 Quellpositionen pro minute für eine Schussquelle oder eine Hammerquelle) hat die Akquisitions geschwindigkeit mit dem Land-Streamer-System bestimmt. Durch die Auswertung verschiedener seismischer Quellen, darunter Impaktquellen und kleine bis mittelgrosse Vibratoren, habe ich diese Problematik untersucht. Aufgrund ihrer relativ kurzen Wiederholraten, der Bedienung durch nur eine Person und der Möglichkeit zur Kontrolle des Ausgangssignals können Vibratoren sehr vorteilhaft bei der Benutzung mit dem Land-Streamer-System sein. Ein einfacher Vorschlaghammer lieferte jedoch die Ergebnisse mit der höchsten Auflösung im interessierenden Tiefenbereich meines Untersuchungsgebietes. Dagegen konnte ein kleiner (60 kg) Vibrator nicht ausreichend Energie erzeugen und die Datenqualität des mittelgrossen (2,300 kg) Vibrators war durch


Durch dieses kostengünstige Vorgehen bei der seismischen Datenakquisition werden reflexionsseismische Untersuchungen für eine Vielzahl von Anwendungen im Ingenieur- und Umweltbereich attraktiver.
ABSTRACT

High-resolution seismic reflection techniques are used for resolving a wide variety of engineering and environmental problems. Although instrumental developments and data processing have advanced very rapidly over the past few decades, a time consuming and costly aspect of 2D and 3D seismic surveys continues to be the acquisition of sufficiently high-fold data.

To increase the speed and efficiency of shallow seismic surveying and thereby decrease acquisition costs, I have developed a towed land-streamer system. Principal components of this system are: (i) self-orienting gimbal-mounted geophones housed in relatively heavy cylindrical casings, (ii) a reinforced rubber sheet overlying the geophones, which helped prevent cable snagging, maintained geophone alignment and provided additional hold-down weight, and (iii) seismic cables with reinforced kevlar outer casings. Each cable was equipped with takeouts for 12 geophones at 1 m or 2 m intervals. Major advantages of this innovative approach to shallow seismic data acquisition were:

• no need to plant geophones;
• no need to lay out seismic cables manually;
• increase in acquisition speed by 50-100 %;
• reduction of field-personnel by 30-40 %;

By using non-uniform streamer configurations (e.g., short receiver intervals at near offsets and long intervals at far offsets) the costs of the land-streamer system and the total weight to be pulled could be minimized. Short receiver intervals at near offsets were necessary for identifying and mapping shallow reflections, whereas larger receiver intervals at far offsets were sufficient for imaging deeper reflections and for estimating velocity-depth functions.

A critical issue in the efficiency of the land-streamer system is the seismic source. The relatively long cycle time of modern sources (e.g., approximately 1 or 2 source locations per minute for a piggun and sledgehammer, respectively) controlled the acquisition speed of the land-streamer system. I have addressed this issue by evaluating a suite of potential seismic sources that included impact devices and small- and intermediate-size vibrators. Due to their relatively short cycle time, their one-person operation, and the ability to control their output signal, vibrators could be practical for use in the land-streamer system. However, a simple sledgehammer provided the highest resolution images throughout the depth range of interest at my study site. In contrast, the small-size (60 kg) vibrator did not generate sufficient energy and the intermediate-size (2,300 kg) vibrator data were plagued by relatively strong airwaves and imprecise vibroseis correlation such that the identification of reflections from depths shallower than ~40-50 m was not possible. For the land-streamer system, I have adopted the
sledgehammer and pipegun sources for surveying relatively shallow- and intermediate-depth targets, respectively.

The land-streamer system has been tested successfully on a variety of recording surfaces (e.g., meadow, asphalt road, and compacted gravel track). The relatively heavy weight of the cylindrical geophone casings combined with the hold-down weight of the rubber sheet provided good geophone-to-ground coupling. Detailed coupling comparisons demonstrated that the closest match between standard gimbal-mounted and spike-mounted geophones was achieved on the meadow. On the asphalt road, the gimbal-mounted geophones recorded higher frequency (above 300-350 Hz) signals than the baseplate-mounted ones. This indicated that the land-streamer system could be a practical and efficient means for surveying urbanized areas.

Acquisition and processing of a pseudo-3D shallow seismic data set with the land-streamer system was simulated by appropriately decimating and reprocessing an existing high-fold 3D shallow seismic data set. The effort required to collect the simulated pseudo-3D data set would have been approximately 7% of that needed for the original field campaign. The application of important data-dependent processing procedures (e.g., refraction static corrections and velocity analyses) to the simulated land-streamer data did not influence significantly the quality of the 3D images. Different intervals between in-line and cross-line profiles (6 m versus 3 m) of the pseudo-3D data set and relatively low subsurface fold (5) resulted in a pattern of high and low amplitudes on the cross-sections and time-slices at early traveltimes (<50 ms). At greater traveltimes, all major reflections could be identified and mapped on the pseudo-3D land-streamer data set.

With this cost-effective approach to seismic data acquisition, it is expected that shallow seismic reflection surveying will become financially attractive for an even wider range of engineering and environmental applications.
1 General Introduction

1.1 Motivation and General Objectives

Detailed information about the structure of the shallow subsurface is required for resolving a wide variety of engineering and environmental problems (Steeples et al., 1997). To obtain such information, sparse networks of boreholes and outcrops are often employed. An alternative approach involves determining accurate and reliable images of the shallow subsurface through integrated applications of complementary wavefield-based geophysical methods, such as the seismic or georadar techniques (Figure 1.1). Although there are various seismic methods (e.g., tomography, vertical seismic profiling, surface wave analysis, refraction, reflection), attention is focussed in this study on high-resolution seismic reflection surveying.

High-resolution seismic reflection surveying is an appropriate tool for the detailed imaging of shallow geological structures at depths ranging from ~10-1000 m. The resolution provided by seismic reflection techniques for exploration deeper than ~20 m cannot be matched by any other technique. Since more than 95 % of all geophysical exploration funds are used for seismic reflection surveying, developments have advanced very rapidly over the past few decades. A time-consuming and costly aspect of seismic surveys continues to be the acquisition of high-fold data. A general objective of this study is to develop a more efficient seismic acquisition strategy that results in the recording of data with sufficient fold to image the target structures. With more cost-effective acquisition techniques, it is expected that seismic reflection tools will become more attractive for an even wider variety of engineering and environmental applications.

1.2 Review of Near-Surface Reflection Seismic Techniques

Historical aspects and applications

The earliest referenced attempts to apply hydrocarbon exploration-type seismic reflection techniques to near-surface investigations were made in the 1950's (Allen et al.,
Chapter 1

Since then, shallow seismic reflection profiling has been the focus of several research activities, with a significant increase in effort during the 1980's. As examples, Ziolkowski and Lerwill (1979), Mair and Green (1981), and Greaves (1984) presented results of high-resolution seismic reflection studies associated with coal exploration and nuclear waste disposal in crystalline rocks at depths of 100 to 1000 m. During this same period, seismic reflection methods were used to resolve small-scale structures in the very shallow subsurface (<100 m depth) by Herber et al. (1981), Ruskey (1981), Steeples and Knapp (1982), Doornenbal and Helbig (1983), Hunter et al. (1984), Steeples (1984), and Pullan and Hunter (1985).

It was not until the late 1980's that the first attempt was made to record low-fold three-dimensional (3D) high resolution seismic reflection data (Corsmit et al., 1988). Reports of larger surveys based on “standard” 3D acquisition techniques started to appear in the literature in the mid-1990's (Green et al., 1995; Lanz et al., 1996; Barnes and Mereu, 1996; House et al., 1996; Büker et al., 1998b, 1999; Siahkoohi and West, 1998). In contrast to hydrocarbon exploration, 3D high-resolution seismic surveys have not been widely used for commercial applications. In areas characterized by highly complex near-surface geology, it is, however, the only technique capable of yielding reliable 3D images of such small-scale structures as sand and gravel lenses. Figure 1.2 shows an example state-of-the-art 3D shallow seismic reflection data set recorded across an alpine valley in northern Switzerland (Büker et al., 1998b, 1999).

Significant progress has been made over the past 20 years in the application of high-resolution seismic reflection techniques in engineering and environmental investigations. Yet, Steeples et al. (1997) have recognized that, although seismic techniques have been used successfully in many studies, they have been “oversold” in others. Table 1.1 provides an overview of the applicability of shallow seismic reflection techniques for resolving different engineering and environmental problems.

Acquisition

An effective method for recording shallow reflections at many locations is the optimum-window technique (Figure 1.3) proposed by Hunter et al. (1984). Source-receiver configurations that allow shallow reflections to be recorded in a minimum-noise window between the first breaks (either the direct and/or refracted waves) and the first arrivals of the surface waves (ground roll) are chosen. A comprehensive summary of diverse applications of the optimum-window technique is presented by Pullan and Hunter (1990). This technique is simple and inexpensive. Disadvantages are the:

- effort required to determine optimum recording windows along long lines;
- single-fold subsurface coverage and associated low signal-to-noise ratios of some data sets;
- ability to focus only on arrivals within a limited depth range;
- lack of consistent and reliable velocity information.
Common mid-point (CMP) techniques (Figure 1.4) were developed for very shallow seismic surveying in the Netherlands (Herber et al., 1981) and at the Kansas Geological Survey (e.g., Steeples and Knapp, 1982). Since multi-fold data generally provide better and more reliable results than single-fold data (Green et al., 1995), CMP surveying is now applied in the vast majority of shallow seismic reflection investigations.

Acquisition of CMP data involves sampling of the seismic-wave field in time and space. Parameters for shallow seismic recording are best established once estimates of the wavefield and noise properties of the study site are available. This can be achieved by conducting walk-away noise tests (Knapp and Steeples, 1986b), which involve acquiring extended shot records using closer than normal trace spacings, larger offset ranges and higher sampling rates. Eventually, the acquisition parameters are determined by the results of these walk-away noise tests and by the limitations of available hardware (e.g., maximum number of channels).

A critical acquisition parameter is the distance between adjacent CMP’s. According to Yilmaz (1987), the maximum CMP spacing $\Delta CMP$ required to avoid spatial aliasing and to migrate data correctly should satisfy the following:

$$\Delta CMP \leq \frac{v_{\min}}{4 \cdot f_{\max} \cdot \sin \alpha_{\max}},$$

where $v_{\min}$ is the minimum stacking velocity, $f_{\max}$ the maximum significant frequency contained in the data and $\alpha_{\max}$ the maximum structural dip. Extracting these parameters from the seismic data set shown in Figure 1.2 (i.e., $f_{\max} \sim 250-360$ Hz, $v_{\min} \sim 1400$ m/s and $\alpha_{\max} \sim 30^\circ$) demonstrates that, for this example, CMP spacing should be $\sim 2.0$ m or less. Depending on the target depth and desired resolution, high-resolution seismic surveys in Switzerland typically require a CMP spacing between 0.25 and 3.0 m.

The CMP spacing is related to the source-receiver configuration:

$$\Delta CMP = \min\left(\frac{1}{2} \Delta S, \frac{1}{2} \Delta R\right),$$

where $\Delta S$ and $\Delta R$ are source and receiver spacings, respectively. Reducing the CMP interval may be achieved by reducing either the source or the receiver spacing, whichever is the smallest. The number of receivers $N$ and the ratio of receiver to source spacing determine the subsurface coverage:

$$Fold = \frac{1}{2} \cdot \frac{\Delta R}{\Delta S} \cdot N,$$
as long as $\Delta S \geq \Delta R$. An increased number of source positions over a given distance (i.e., smaller source spacings) results in either higher fold and associated higher signal-to-noise ratios (for $\Delta S \geq \Delta R$) or decreased CMP spacing (for $\Delta S < \Delta R$).

After determining the maximum allowed CMP spacing (Equations 1.1 and 1.2) and taking into account the desired fold (Equation 1.3), the recording spread (i.e., source-receiver offset distribution) can be designed. Efficient field handling requires that the number of sources and receivers should be minimized. However, there are some important additional points to consider:

- a relatively 'wide' distribution of source-receiver offsets is essential for accurate velocity analyses over the entire range of recorded traveltimes;
- a dense receiver distribution at short offsets (e.g., <24 m) is generally required to distinguish true shallow reflections from other events (e.g., direct, refracted, guided, and surface waves);
- large numbers of receivers result in high CMP fold and associated improved signal-to-noise ratios (S/N);
- efficient conventional seismic reflection profiling requires 'roll-along' of seismic cables and geophones, which for practical reasons dictates that uniform receiver spacing is desirable.

Firm rules for designing source-receiver spreads do not exist. A common rule-of-thumb is that the maximum source-receiver offset should be at least 0.7 to 1.5 times the distance to the deepest structures of interest (e.g., a feature at 150 m depth would require a spread length of ~105-225 m (Knapp and Steeples, 1986b)).

**Processing shallow seismic reflection data**

Most processing operations employed routinely in deep seismic surveying can be applied to shallow seismic data sets. A common processing flow is illustrated in Figure 1.5. It consists of four main sequences ranging from data preparation to data presentation. For each sequence, a suite of processing routines may be chosen, depending on the data quality, local geology and the targets of interest. In addition to standard filtering, shallow reflections may be enhanced by application of spectral balancing or deconvolution. Careful surgical muting or attenuation of any remaining coherent noise may be needed in cases where these processing operations are less than 100% efficient.

Seismic data that have been subjected to a standard processing flow (i.e., to the stage of stack in Figure 1.5) represent a somewhat distorted image of the subsurface. Migration is the process that corrects these distortions and transforms the stacked section into a geologically interpretable image (e.g., Yilmaz, 1987). Black et al. (1994) have demonstrated that migration may be unnecessary when dealing with low near-surface velocities (<1000 m/s) and gently dipping reflections at very shallow depths (< 50 m). Under such conditions, the migration operator will only affect marginally the position of the seismic signals. By comparison, Büker et al. (1998b) found that migration was
necessary to determine the position of the east-dipping events IV in Figure 1.2, which are characterized by stacking velocities of 1000-3000 m/s, have dips of $25^0$, and range in depth from 90-250 m.

**Pitfalls**

Problems in acquisition, processing and interpretation of high-resolution seismic reflection data can impede the practical implementation of seismic reflection techniques. Steeples et al., (1997) and Steeples and Miller (1998) have reviewed many types of pitfalls. The most important ones are:

- spatial and temporal aliasing;
- interpreting refracted or guided waves (multiply refracted-reflected waves) as primary reflections;
- inappropriate application of static corrections;
- using overly narrow data windows when applying automatic static routines;
- inaccurate definition of top and stretch mute functions;
- interpreting events dipping at angles greater than $45^0$ on unmigrated stacked sections as reflections.

To illustrate some of the difficulties associated with investigating depths shallower than ~200-300 m, a typical shot gather recorded in the Suhre valley (Switzerland) is presented in Figure 1.6. It is affected strongly by the presence of guided waves that travel with velocities very similar to those of the direct and refracted waves. They are characterized by multiple oscillations that mask any shallow reflections. Detailed analyses of guided waves and their effects on near-surface seismic experiments have been presented by Robertson et al. (1996a, 1996b) and Roth et al. (1998). They have shown that guided waves must be properly accounted for when processing shallow seismic reflection data.

**1.3 Instrumentation**

**Sources**

There are many types of energy sources that can be used for high-resolution seismic experiments. Several studies have been concerned with comparisons of these sources: Miller et al. (1986, 1992, 1994), Pullan and MacAulay (1987), Bühnemann and Holliger (1998), Herbst et al. (1998), and Doll et al., (1998). An overview of most sources used in shallow seismic exploration is given in Appendix A.
**Impulsive seismic sources**

A simple explosion is amongst the oldest type of energy sources employed for shallow seismic experiments. A wide variety of other impulsive sources exist. The most prominent among them, which are tailored for high-resolution seismic applications, are blasting caps, sledgehammers, pipeguns, and weightdrop systems. An ideal impulsive source should:

- generate sufficient energy to detect the deepest structures of interest;
- generate a wavelet of short duration (i.e., with high frequency content and broad bandwidth) to optimize resolution;
- be repeatable and fast;
- generate a minimum of source-related noise.

The principal variable associated with impulsive sources is the amount of radiated energy. Ziolkowski et al. (1980) have evaluated the effect of charge size on the dominant frequency and resolution of a seismic wavelet. They have shown that, theoretically, energy increase is related to wavelet amplitude according to a scaling law:

$$w_B(t) = \alpha w_A(t/\alpha), \quad (1.4)$$

where $\alpha$ is a scaling factor, and $w_A(t)$ and $w_B(t)$ are the amplitudes of wavelets generated by impulse sources A and B, respectively. The maximum amplitude of source $B$ is $\alpha$ times that of the source $A$. The scaling law implies that if the amplitude of the emitted signal increases (e.g., by using a larger charge or a different source), the wavelet is stretched according to $t/\alpha$ and, consequently, the resolution decreases. This suggests that if both depth penetration and resolution are important, it may be better to vertically stack numerous small signals than to increase the charge of an explosive source.

Consequences of the scaling law are illustrated by the following example. The solid line A in Figure 1.7a shows typical ground displacement generated by an impulsive source. Using Equation 1.4, the displacement of a signal with twice the amplitude of A is presented as the dashed line B in the same figure. Associated signals recorded by velocity sensors (geophones) are displayed in Figure 1.7b. Corresponding amplitude spectra of the two recorded velocity signals (Figure 1.7c) demonstrate that the dominant frequency of the large charge (~90 Hz) is much lower than that of the small charge (~175 Hz). From Figure 1.7 it is clear that an unfiltered source gather obtained with a small charge should provide higher resolution than that of a larger charge, assuming that the background noise is small enough. The spectra also show that spectral amplitudes of the large charge are higher than those of the small charge at most frequencies. Thus, if the higher amplitudes of the large charge can be recorded without clipping, an appropriately filtered version of the signal may provide higher resolution information than that of the small-charge signal.
**Vibratory sources**

Vibratory sources are widely and successfully used in hydrocarbon exploration, whereas today they are rarely used in shallow seismic experiments. They may offer the following significant advantages over impulsive sources:

- the emitted signal can be tailored for particular targets of interest (e.g., optimized resolution or optimized depth penetration);
- they can be employed in urban areas.

Nijhof (1989) first reported on the design of a special vibrator for high-resolution seismic applications. He developed an electromagnetic vibrator capable of generating frequencies up to 1000 Hz. Since then, only a few uses of vibratory sources in shallow seismic experiments have been reported (e.g., Ghose et al., 1995, 1998; Schneider and Vanderkooy, 1996; Buness et al., 1997; Doll et al., 1998)

Although vibratory systems are generally very complex, their operational principles are relatively straightforward. An oscillatory signal, i.e., the sweep, with a limited bandwidth (e.g., 70-400 Hz) is generated over a certain time, the sweep time. Factors that influence the data quality (signal-to-noise ratios) are the sweep length, vertical stacking fold and the ground force. Because of the long (typically 4-10 s) sweep lengths, vibroseis wavelets need to be compressed by cross-correlation with a reference signal to simulate an effective impulsive wavelet. This process is called vibroseis correlation. Usually, an estimate of the ground force is used as a reference signal (Sallas, 1984). Van der Veen et al. (1999a) have shown that inaccurate estimates of this reference signal can result in significant correlation noise, especially at high frequencies (>150-200 Hz). For shallow seismic applications, good knowledge of the vibrator behaviour at higher frequencies is essential.

**Receivers**

Electrodynamic-based geophones are the most commonly used sensors for recording high-resolution seismic reflection data. The principle of a geophone is illustrated in Figure 1.8. Its main components are a magnet connected rigidly to an outer casing and a coil that encircles the magnet. This coil is connected by two circular suspension springs to the casing. The casing is generally in rigid contact with the earth’s surface via a metal spike. If the earth moves, the magnet and case must follow, but the coil, because of its inertia and loose coupling with the casing, tends to stay fixed. The relative motion between the coil and magnetic field generates a voltage that may be registered by a recording system.

The usable bandwidth of a geophone is determined primarily by the natural- and spurious frequencies. The natural frequency is the resonant frequency of the geophone in the direction of the working axis. Above this frequency, the amplitude response of a geophone is flat and has few phase distortions. Therefore, the natural frequency sets the lower limit of the geophone. It generally varies between 10 and 100 Hz. In practice, the upper frequency limit of the geophone is determined by the lowest spurious frequencies, which are resonance frequencies perpendicular to the axis. Frequencies at which these
distortions occur depend primarily on the spring stiffness. Typically, spurious frequencies occur at higher values for higher internal spring stiffness, corresponding to higher natural frequencies. Knapp and Steeples (1986a) stated that, as a rough rule-of-thumb, spurious resonances at frequencies greater than ten times the natural frequency of the geophone can be expected. Today, in modern geophones, they occur at frequencies greater than fifteen times the natural frequency. For example, the SM-7 30 Hz geophones used by the ETH’s Institute of Geophysics commonly exhibit spurious resonances at frequencies >500 Hz. (Sensor NL BV, manufacturer specifications).

The choice of geophone is not a trivial task. Until the 1980’s, the limited dynamic range of most recording equipment for shallow seismic surveying necessitated the use of high (100 Hz) natural frequency geophones. They have high spurious resonances and they work as natural low-cut filters, thus limiting the recording of strong surface waves that may saturate the A/D converters (Knapp and Steeples, 1986a). Modern seismographs with 24-bit resolution are capable of recording larger variations in amplitude, so that lower natural frequency geophones (~30 Hz) are now preferred in high-resolution seismic reflection experiments (Steeples et al., 1997). They offer broader bandwidths in the frequency ranges of interest; their maximum distortionless frequencies of ~500 Hz are usually sufficient for typical high-resolution seismic reflection surveys. If higher frequencies are desirable, for example when surveying in crystalline rock terrains, higher frequency geophones (e.g., 100 Hz) may be preferred.

1.4 Goals of the Thesis: Problems and Solutions

When this project was initiated in July 1996, high-resolution seismic reflection techniques were already commonly used in academic projects. Commercial applications were more limited, often due to the relatively high costs involved and the lack of experienced personnel. These costs are controlled primarily by the number of people and the time needed for a field campaign. Particularly time-consuming components of a seismic reflection survey are the planting of geophones and the manual movement of standard seismic cables (roll-along). Subsequent to the van der Veen and Green (1998) paper on the land-streamer, Steeples et al. (1999) introduced a strategy to record efficiently ultra-high resolution seismic data by mounting standard geophones on a wooden board. Bachrach and Rickett (1999) showed the potential of this approach for collecting ultra-shallow 3D seismic data. Because of the generally larger receiver spacings, Steeples et al.’s (1999) approach is, however, not applicable to standard seismic reflection surveying.

The goal of this study has been to increase the efficiency of conventional high-resolution seismic reflection surveying by reducing the acquisition effort (i.e., reducing the number of personnel and the required acquisition time). To achieve this goal, a towed land-streamer system was developed in cooperation with a commercial company (Sensor NL BV). A similar concept was developed for the acquisition of resistivity data by Sorensen (1996). The principal advantages of the towed land-streamer system over traditional techniques are the elimination of geophone planting and roll-along. Chapters 2 and 4 are concerned with the system design, acquisition effort, survey
procedures and detailed analyses of the operational characteristics of the towed land-streamer system. Additional details concerning field effort and non-uniform receiver geometries are discussed in Appendices B and C. The towed land-streamer system is tested on various recording surfaces such as saturated gravels covered by meadow, clay covered by a meadow, an asphalt road and a compacted gravel track. Chapter 4 is also concerned with the possibility of acquiring shallow 3D seismic data with the towed land-streamer system. Using the high-fold shallow 3D data set recorded by Büker et al. (1998b, 1999), recording of a pseudo 3D data set with a series of closely spaced parallel land-streamer profiles is simulated and evaluated. Detailed technical information and a list of manufacturers of components of the land-streamer system are given in Appendix D.

A particular concern in the design of the land-streamer system is the seismic source. Currently, ETH's Institute of Geophysics employs for shallow targets a standard sledgehammer and for deeper targets a pipegun. Down-hole sources, such as the pipegun, are labour intensive and time-consuming. In Chapter 3, a thorough evaluation of the recording characteristics of several impulsive sources and two vibratory sources is presented. A mini-vibrator developed by OYO-CAG was rented and the GGA Institute of Joint Geoscientific Research (Germany) kindly provided their recently developed truck-mounted GGA vibrator for testing purposes. A particular objective was to determine whether vibratory sources are of benefit to shallow seismic data acquisition.

Chapters 2 to 4 represent three independent manuscripts that have either been published (Chapter 2), submitted for publication (Chapter 3), or about-to-be-submitted for publication (chapter 4) in first-class international journals. Some proposals for future developments in high-resolution seismic reflection techniques are described in Chapter 5. Appendices E to G are selected expanded abstracts presented at international conferences.
Table 1.1: Applicability of high-resolution seismic reflection techniques (modified from Steeples et al., 1997)

<table>
<thead>
<tr>
<th>When does it work</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most of the time</td>
<td>Applications where reflection times are &gt;3-5 dominant time cycles after the first breaks:</td>
</tr>
<tr>
<td></td>
<td>- <strong>characterizing gross geological structure</strong>, e.g., depth to bedrock, etc. (Singh, 1983, 1984a, 1986; Hunter et al., 1984; Pullan and Hunter, 1985, 1990; Miller et al., 1988b, 1990; Treadway et al., 1988; Ali et al., 1991; Stephenson et al., 1993; Hawman and Ahmed, 1995);</td>
</tr>
<tr>
<td></td>
<td>- <strong>detecting faults</strong> for studying earthquake hazards, investigating nuclear waste disposal, etc. (Mair and Green, 1981; Green and Soonawala, 1982; Green and Mair, 1983; Sattel et al., 1992; Kim et al., 1994; Gendzwill et al., 1994);</td>
</tr>
<tr>
<td></td>
<td>- <strong>ground water studies</strong> (Haeni et al., 1986; Birkelo et al., 1987; Bachrach and Nur, 1998; Bachrach et al., 1998; Liberty, 1998; Whiteley, 1998);</td>
</tr>
<tr>
<td></td>
<td>- <strong>exploration and exploitation of minerals</strong> (Ziolkowski and Lerwill, 1979; Sing, 1984b; Gochioco, 1990, 1992; Milkereit and Green, 1992; Al-Rawahy and Goulty, 1995; Goleby et al., 1997; Milkereit et al., 1997; Pretorius et al., 1997; Stevenson and Durrheim, 1997).</td>
</tr>
<tr>
<td>Sometimes</td>
<td>Those applications that require both broad bandwidths and high-frequencies:</td>
</tr>
<tr>
<td></td>
<td>- <strong>detecting shallow voids and tunnels</strong> (Steeples et al., 1986; Branham and Steeples, 1988; Miller et al., 1988a; Miller and Steeples, 1991; Miller et al., 1995; Kourkafas and Goulty, 1996);</td>
</tr>
<tr>
<td></td>
<td>- <strong>mapping near-surface seismic facies</strong> (Herber et al., 1981; Ruskey, 1981; Steeples and Knapp, 1982; Doornenbal and Helbig, 1983; Steeples, 1984; Büker et al., 1998a, 1998b, 1999; Carr et al., 1988; Ghose et al., 1998; Wiederhold et al., 1998);</td>
</tr>
<tr>
<td></td>
<td>- <strong>delineating thin beds and shallow faults</strong> (Miller and Steeples, 1986; Myers et al., 1987; Miller et al., 1988a, 1990; Treadway et al., 1988; Ali et al., 1991; Stephenson et al., 1993; Hawman and Ahmed, 1995; Shitivelman et al., 1998).</td>
</tr>
<tr>
<td>Almost never</td>
<td>- <strong>detecting chemically saturated lenses</strong>,</td>
</tr>
<tr>
<td></td>
<td>- <strong>detecting tunnels or voids at depths of 100 m or more.</strong></td>
</tr>
</tbody>
</table>
Figure 1.1: Geophysical techniques offer capabilities for investigating the near surface in two and three dimensions. They are complementary to conventional geological and geotechnical methods. High-resolution seismic reflection profiling is an imaging tool that yields accurate images of shallow targets at depths of ~10-1000 m. Figure adapted from Lehmann (1999).
Figure 1.2: (a) Example state-of-the-art 3D high-resolution seismic reflection data set and (b) associated interpretation. Figure adapted from Büker et al. (1999). Borehole and outcrop information was used to constrain interpretation of shallow geological boundaries and units: I - shallowest detectable reflection from top of shallow glacio-lacustrine clay/silt layer; B - basal till and fluvial sand/gravel; D - lower unit of glacio-lacustrine clay; IV - deepest reflection, which originates from top of Molasse sandstone basement.
Figure 1.3: (a) Simple reflection model of homogeneous overburden above bedrock showing position of optimum-window receiver array. (b) Time-distance graph associated with model in (a). Receiver array is placed beyond zone of surface waves (ground roll) and is limited in extent by the onset of interference between the bedrock refraction and reflection. Figure adapted from Hunter et al. (1984).

Figure 1.4: Common mid-point (CMP) method. Explosion symbols and triangles show source and receiver positions, respectively. For a flat lying interface, reflections recorded on CMP traces with diverse source-receiver offsets originate from a single common point.
Chapter 1

Data Preparation

- Geometry
- Trace Editing
- Elevation and Refraction Static Corrections
- True Amplitude Retrieval

Enhancement of Reflection Events in Shot Gathers

- Application of Gain Functions
- Surface Wave Attenuation
- Air Blast Attenuation
- Spectral Balancing and/or Deconvolution
- Bandpass Filtering
- First Top Mute

Processing of CMP Gathers

- CMP-Sorting
- Velocity Analyses
- NMO Corrections and Stretch Mutes
- Residual Statics
- Second Top Mute

Stack and Post-Stack Processing

- Application of Further Gain Functions
- Stack
- Coherency Filtering
- Migration

Figure 1.5: Typical processing flow for shallow seismic reflection data. Left shows 4 main processing steps. For each step a suite of processing routines may be chosen (right). Note that these routines by no means represent all possibilities. Some iterations of the various steps are inevitably required. Application depends strongly on seismic data, local geology and targets.
Figure 1.6: Trace-normalized shot gather containing ground roll and guided waves.
Figure 1.7: Theoretical effect of impulsive source charge size on wavelet bandwidth. (a) Displacements. Solid line A is typical ground displacement generated by an impulsive source. Dashed line is signal with twice the amplitude of A. (b) Velocities. (c) Amplitude spectra of signals in (b). Vertical axes are normalized to maximum values.

Figure 1.8: Design principle of a modern electrodynamic geophone. The cylindrical core magnet and the cylindrical shell form a toroidal magnetic field (solid lines). In the air gap between core and shell, the field is radial. The moving mass is a thin cylindrical shell carrying a coil (in the lower half wound in the opposite direction). The coil moves axially in the air gap. Figure adapted from Brouwer and Helbig (1998).
Land-Streamer for Shallow Seismic Data Acquisition: Evaluation of Gimbal-Mounted Geophones

Michiel van der Veen and Alan G. Green

Abstract

To increase the speed and efficiency of shallow seismic data recording, and thereby decrease acquisition costs, the concept of a towed land-streamer containing self-orienting gimbal-mounted geophones is being evaluated. Our initial experiments at two locations within Switzerland demonstrate that good coupling with the ground may be achieved when the gimbal-mounted vertical geophones are contained in heavy (~1 kg) casings and pulled along a very shallow (2-3 cm deep) furrow. Such a furrow may be created by mounting a heavy wheel on the towing vehicle. Placing the geophones in even heavier casings may provide the necessary good coupling with the ground, negating the need for the furrow. Shot gathers and stacked sections recorded with the gimbal-mounted geophones are practically indistinguishable from those recorded with conventional spike geophones. The principal advantage of this approach is that significantly fewer field personnel (only two or three) are required than for conventional shallow seismic surveying. When fully operational, the new acquisition system should be faster and less expensive for a wide variety of engineering and environmental applications.

2.1 Introduction

High-resolution seismic reflection techniques are powerful tools for mapping shallow geological structures (Steeples and Miller, 1990; Lanz et al., 1996; Büker et al., 1998a). New technological developments, such as the introduction of inexpensive 24-bit
recording systems with large channel capacity, together with an improved understanding of the various waveforms recorded during typical shallow surveys (e.g., Robertsson et al., 1996a, 1996b), have led to substantial improvements in the quality and reliability of high-resolution seismic reflection data. In addition to increasing our ability to record high-fold and densely spaced data, the new technologies have also markedly increased the logistical complexity of a typical shallow seismic survey. For the same length of survey line, many more geophones must now be planted and many more source points employed (Büker et al., 1998b). Accurate surveying of receiver and source locations and the manual planting of geophones are time consuming and costly aspects of shallow seismic data acquisition.

In light of this, we have initiated a project aimed at increasing the efficiency of high-resolution seismic reflection techniques, with the principle goal of decreasing the number of field personnel, time, and costs involved in conducting shallow surveys. In order to achieve these goals we are adapting the concept of a snow streamer (Eiken et al., 1989) for use in engineering-scale land surveys.

2.2 Towed Land-Streamer

A new type of multi-channel seismic cable has been specially designed and manufactured for efficient shallow data acquisition on land. It consists of 96 takeouts at fixed 1 m intervals. Each takeout is attached to a single self-orienting gimbal-mounted vertical geophone. The seismic cable, or land-streamer (Figure 2.1), is to be towed behind an all-terrain vehicle. A kevlar outer casing significantly increases the strength of the cable and helps prevent it from being damaged as it is pulled across rugged ground. The experiments reported here were conducted with a provisional set of six self-orienting gimbal-mounted test geophones. Long recording spreads were simulated by moving the six-geophone spread and multiple firing of shots at the same locations.

The gimbal-mounted vertical geophones are key elements of this new system (Figure 2.2). Each geophone consists of a self-orienting velocity sensor mounted in a heavy cylindrical outer casing. To damp the motion of the sensor around its rotational axis, the inside of the casing is filled with viscous oil. Technical specifications of the geophones are given in Table 2.1.

2.3 Geophone-to-Ground Coupling Tests

A critical issue of the land-streamer concept is the geophone-to-ground coupling. In seismic reflection surveys, the frequencies of the useful signal depend on the energy spectrum of the source, the attenuation in the ground, and the coupling resonant frequency of the geophones. Krohn (1984) has shown that this resonant frequency depends on the firmness of the soil and the actual coupling. In most practical situations, the maximum recorded frequencies rarely exceed ~500 Hz. We define good coupling as the ability to record the seismic signal in the frequency range of interest (up to ~500 Hz) with a minimum of distortion. To help ensure good coupling, each gimbal-mounted vertical geophone is housed in a heavy casing (~1 kg). Various tests aimed at comparing
the coupling of traditional spike geophones with equivalent gimbal-mounted geophones have been conducted.

At one test site (Zürich, Switzerland), six spike geophones were carefully planted alongside six gimbal-mounted ones, each containing identical 30 Hz vertical sensors. The distance between the two parallel sets of geophones was <10 cm and the common source was a 5 kg sledge hammer. At this site, moist sandy silt and sandy clay covered by grass provided good surface conditions for planting the spike geophones (spike length 10 cm). In Figure 2.3, the response of a standard 30 Hz spike geophone is compared with the "worse-case" response of a 30 Hz gimbal-mounted geophone that is poorly "planted". This experiment was intended to simulate the effect of pulling the land-streamer across rugged terrain without preparation of the surface. Major phase and amplitude differences between the responses of the two types of geophone are shown in the figure.

When the gimbal-mounted geophones are placed in a shallow furrow and the entire experiment repeated (on the same day as the previous experiment), the results are strikingly different (Figure 2.4). This experiment was intended to simulate the towing of the land-streamer along a shallow furrow (2-3 cm deep) generated by a heavy wheel at the back of the towing vehicle. Clearly, the geophone-to-ground coupling of the gimbal-mounted geophone has considerably improved (compare Figure 2.3 to Figure 2.4). Phase and amplitude differences between the two types of geophone have been significantly reduced. Remaining minor differences in geophone response may be due to local variations in near-surface conditions and differences in electro-mechanical characteristics of the individual sensors, but these are likely to be small compared to the effects of varying geophone-to-ground coupling (Faber et al., 1994).

The results of our detailed coupling experiments suggest that gimbal-mounted geophones in good contact with the ground have the potential to record faithfully high-resolution seismic data. Good geophone-to-ground coupling can be achieved by housing the sensors in heavy casings and by pulling the land-streamer along a shallow furrow. We will shortly be testing the practicality of employing even heavier casings in anticipation that eventually the furrow may be avoided.

2.4 Multichannel Test Reflection Survey

Acquisition

Two coincident short seismic reflection profiles were simultaneously recorded within the Reuss Delta, central Switzerland (Figure 2.5). Nominal 18-fold data sets were simulated with six standard spike geophones and six self-orienting gimbal-mounted test units. Moist fine sediments (sandy silts and sandy clays) deposited during recent flooding provided excellent coupling conditions for both sets of geophones. To obtain the nominal 18-fold data, each set of six geophones was repositioned six times, and for each repositioning the shots was repeated. A pipegun source in 0.5-1.0 m deep boreholes provided a repeatable signal. The most significant difference between signals generated by sequential shots at the same location were "time delays" caused by progressive
deepening of the hole. To account for these delay we applied simple static corrections based on air-wave arrival times.

Detailed recording parameters are given in Table 2.2. Typical shot gathers recorded with the spike and gimbal-mounted geophones are displayed on the left and right sides of Figure 2.6, respectively (note the relatively uniform signal character in these shot gathers). Very minor differences between the two shot gathers are mostly due to small differences in the noise characteristics of the two sets of geophones.

**Processing**

The two data sets were passed through the same simple processing sequence (Figure 2.7) using identical processing parameters. Stacking velocities ranged from 1000 to 2000 m/s. As for the shot gathers (Figure 2.6), the resultant stacked sections (Figures 2.8a and 2.8b) are very similar. All important reflection zones are imaged on both sections. Figure 2.8c is a plot of the differences between Figures 2.8a and 2.8b. It demonstrates that the amplitudes of some reflections vary slightly between the two stacked sections (e.g., between 200 and 250 ms on the left side of the section), but that the principal differences are at the noise level.

**Geological interpretation**

The Reuss Delta has experienced a complex history of tectonism and multiple glaciations. Following the last ice age (Würm glaciation) approximately 18000 years ago, the region was covered by a lake in which clays and then fine sands were deposited. Subsequently, a thick sequence of gravels (known as the Reuss gravels) were laid down by a large braided river system. Deposition of the Reuss gravels was periodically interrupted by flooding events, the most recent of which occurred in 1987.

On the basis of information from a 300 m deep borehole approximately 2 km south of the survey area, the strong reflection at 200 to 250 ms is interpreted as the boundary between the Reuss gravels and the underlying fine sands (Figure 2.9). The top of the basement is interpreted as the strong reflection that dips from ~500 ms at the eastern end of the profiles to ~600 ms at the western end.

**2.5 Conclusions**

Results of our acquisition and processing experiments have demonstrated the potential of towed land-streamers with self-orienting gimbal-mounted geophones as a means of efficient shallow seismic data acquisition. Housing the sensors in heavy casings and pulling the land-streamer along a shallow furrow offers a solution to the geophone-to-ground coupling problem. Applying these techniques has shown that high quality data, comparable to carefully planted spike geophone data, may be acquired with gimbal geophones. Major advantages of this innovative approach to shallow data acquisition are:

- no need for geophone planting;
Land-Streamer Concept

- fewer field personnel (only two or three) compared to traditional surveys (typically six to ten);
- significant increase in acquisition speed;
- marked decrease in survey costs.

Clearly, operation of this system will depend on local surface conditions (e.g., the presence of trees, steep slopes, large boulders etc.). Despite these limitations, it is expected that in many areas the acquisition time and costs of shallow seismic data recording can be decreased significantly.
Table 2.1: Technical specifications of the self-orienting gimbal mounted geophone units (SG-1 Sensor)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>45 mm</td>
</tr>
<tr>
<td>Length</td>
<td>185 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>1 kg</td>
</tr>
<tr>
<td>Velocity sensor</td>
<td>30 Hz</td>
</tr>
</tbody>
</table>

Table 2.2: Parameters for the high-resolution seismic reflection profiles collected in the Reuss delta

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey length</td>
<td>210 m</td>
</tr>
<tr>
<td>Receiver spacing</td>
<td>2 m</td>
</tr>
<tr>
<td>Source type</td>
<td>Pipegun in 0.5- to 1.0-m-deep holes</td>
</tr>
<tr>
<td>In-line source offset</td>
<td>2 m</td>
</tr>
<tr>
<td>Source spacing</td>
<td>2 m</td>
</tr>
<tr>
<td>Number of geophones</td>
<td>$2 \times 36$</td>
</tr>
<tr>
<td>Geophone type</td>
<td>30-Hz spike/gimbal</td>
</tr>
<tr>
<td>Surface soil type</td>
<td>Fine-grained sediments</td>
</tr>
<tr>
<td>Sample rate</td>
<td>0.25 ms</td>
</tr>
<tr>
<td>Recording time</td>
<td>1000 ms</td>
</tr>
<tr>
<td>Nominal fold</td>
<td>18</td>
</tr>
</tbody>
</table>
Figure 2.1: Schematic illustration of a land-streamer to be pulled by an all-terrain vehicle. The land-streamer comprises segments, each with 12 gimbal-mounted geophones.

Figure 2.2: Self-orienting gimbal-mounted vertical geophone (reproduced with permission of Sensor NL BV).
Figure 2.3: Results of ground coupling comparisons between 30-Hz spiked (solid line) and poorly planted 30-Hz, gimbal mounted geophones (dashed line); (a) Traces recorded from a common source (5-kg sledgehammer); this particular comparison represents the worst-case example of the initial field tests (i.e., the similarity of adjacent spike and gimbal-mounted geophones was usually higher than that shown here), (b) Amplitude spectra of the two traces, (c) Phase differences between the responses of the two geophone types.

Figure 2.4: Results of ground coupling comparisons between the same 30-Hz spiked (solid line) and gimbal-mounted (dashed line) geophones as shown in Figure 2.3. The gimbal-mounted geophone was laid in a shallow furrow for this test. (a) Traces recorded for a common source (5-kg sledgehammer), (b) Amplitude spectrum of the two traces, (c) Phase differences between the responses of the two geophone types.
Figure 2.5: Location of the survey site in the Reuss delta, central Switzerland.

Figure 2.6: Two typical shot gathers recorded in the Reuss delta. The left gather was recorded with standard spike geophones, the right ones with gimbal-mounted vertical geophones. The raw data have been scaled with a single individual scaling factor (i.e., trace normalized) for each trace.
Figure 2.7: Data processing flow
Figure 2.8: Seismic reflection data sets recorded simultaneously at the same location. (a) Stacked section recorded with standard spike geophones. (b) Stacked section recorded with self-orienting, gimbal-mounted geophones. (c) Difference between the two stacked sections.
Figure 2.9: Simplified interpretation based on the surface geology and information obtained from numerous nearby shallow boreholes and one deep (300 m) borehole approximately 2 km south of the survey line.
EVALUATION OF HIGH-FREQUENCY SEISMIC SOURCES FOR IMAGING SHALLOW (10-250 M) STRUCTURES

SUBMITTED TO
JOURNAL OF ENVIRONMENTAL AND ENGINEERING GEOPHYSICS

Abstract

Several high-frequency seismic sources (i.e. sledgehammer, pipegun, weightdrop, and small- and intermediate-size vibrators) have been tested at a site characterized by a surface layer of recent sediments overlying unconsolidated glacial and glaciolacustrine units. Reflections from very shallow (~10 m) to moderate (~250 m) depths were recorded. Evaluation of the different sources involved analyzing prominent features (e.g., reflections and signal-generated noise that includes complex patterns of interfering reflections, direct waves, guided waves, refractions, and surface waves) on source gathers, frequency spectra and stacked sections. Our experiments demonstrated that minor changes in local conditions (e.g., changes in ground-water table depth) may influence significantly the characteristics of the resulting data. Of the tested sources, the simple sledgehammer provided the highest resolution images at shallow depths (10-100 m) and comparably good images at greater depths (100-250 m). Local changes in surficial sediments affected the quality of data generated by the small (60 kg reaction mass) vibrator; at many locations, the input energy was insufficient to illuminate the important geological structures. By comparison, the intermediate-size (2,300 kg reaction mass) vibrator provided high quality images to depths as great as 250 m (corresponding to the deepest reflection from near the base of unconsolidated sediments), but relatively strong airwaves and imprecise vibroseis correlation precluded the resolution of reflections from depths shallower than ~40-50 m. Despite recent advances in vibratory systems, the humble, but cost-effective sledgehammer continues to be an attractive source for high-resolution seismic experiments.
3.1 Introduction

High-resolution seismic reflection methods are used for imaging a wide variety of geological structures. To complement innovative rapid data acquisition techniques (van der Veen and Green, 1998; Spitzer et al., 1998, 1999), fast and versatile high-frequency energy sources are required. In a general review of shallow seismic reflection methods, Steeples et al. (1997) identified the need for such sources as a first-order priority. Over the past two decades, many traditional impulsive-type seismic sources have been tested and compared under diverse geological conditions (McCann et al., 1985; Miller et al., 1986, 1992, 1994; Doll et al., 1998; Herbst et al., 1998; Bühnemann and Holliger, 1998). In contrast, only a few tests of high-frequency vibrators have been reported. Vibratory sources, which have a proven track record in hydrocarbon and deep crustal seismic surveys, have the potential to replace conventional sources in shallow seismic experiments. Nijhof (1989) described the first use of a specially designed vibrator system for shallow applications. Feasibility studies of individual vibrator types have since been described by Ghose et al. (1995, 1998), Schneider and van der Kooy (1996) and Buness et al. (1997). Herbst et al. (1998) evaluated the OYO vibrator, but no results from these particular tests were presented in their article. The first comprehensive comparison to include several high-frequency vibrator sources (OYO vibrator, IVI MiniVib and Y-1100A vibrator) was presented by Doll et al. (1998). Their principal goal was to evaluate seismic sources for mapping reflections at travel times >~100 ms.

Here, we report the results of a new suite of comparisons of high-frequency sources. Our study is distinct from most previously reported ones in that:

1. It included two types of high-frequency vibratory sources (OYO and CGA vibrators), one of which has not been evaluated previously.

2. Data were recorded across an environment characterized by glacial, glaciolacustrine and glaciofluvial sediments. Such sediments cover large areas of many countries worldwide. They contain important ground-water reservoirs and valuable gravel and sand deposits, and are the host of numerous landfills (in Switzerland alone, there is approximately one landfill per square kilometer of inhabitable land; Green et al., 1999).

3. Across our survey region, reflections from as shallow as 10 m to as deep as 250 m were observed. Most other studies are based on more limited depth ranges (usually >50 m).

4. We included comparisons of source gathers and stacked sections.

5. The frequency spectra of different packages of arrivals, which include interfering direct waves, guided waves, refractions, reflections, and surface waves, were analyzed.

The comparisons represent the results of seismic surveys conducted for various purposes by ETH-Zurich over the past few years. For this reason, evaluations along two different lines at the same study site are presented.
3.2. Survey Area and Local Geology

Extensive 2-D and 3-D high-resolution seismic reflection surveys were performed in the glaciated Suhre valley in northern Switzerland by Büker et al. (1998a, 1998b, 1999; Figure 3.1). Figure 3.2 shows seismic reflection profile B oriented perpendicular to the dominant north-south flow direction of the former glacier and associated river systems (corresponds to profile 1 in Büker et al., 1998a). It illustrates the typical seismic response of this area. Shotholes along the profiles reveal a thin (0.5-1.5 m) low velocity humus layer close to the surface. At greater depths, the geology is dominated by sequences of glaciolacustrine clay/silt and glacial till (mostly sands and gravels). Molasse basement sedimentary rocks occur at depths ranging from ~32 to ~250 m. Comparison of sources along profile B were made between CMP’s 650 and 940 (Figure 3.2). Here, the ancient glacier has markedly deepened the valley, such that the Molasse basement is recorded at travel times of ~200-250 ms. The depth of the ground-water table during the various recording campaigns was not measured, but likely lay below the surface humus layer.

Profile A was recorded parallel to the flow direction of the ancient glacier. The seismic response along this profile was similar to that along profile B between CMP’s 950-1350 (Figure 3.2). At this location, the Molasse basement was imaged at travel times of 80-100 ms. During the two recording campaigns associated with profile A, the ground-water table was only a few centimeters below the surface.

3.3 Seismic Sources

Three conventional impulsive-type sources and two high-frequency vibratory sources were evaluated: (i) sledgehammer, (ii), pipegun (iii) accelerated weightdrop, (iv) hand-portable mini-vibrator developed by OYO (OYO vibrator), and (v) a truck-mounted mini-vibrator constructed by the Geowissenschaftliche Gemeinschaftsaufgaben (CGA vibrator).

Impulsive sources

A 5 kg sledgehammer is an inexpensive, yet effective seismic source (Figure 3.3a). An accurate piezo-electric sensor triggers the seismograph as the hammer strikes a 225 cm² steel baseplate. Keiswetter and Steeples (1995) have shown that the energy and bandwidth of the resultant seismic signal depend only marginally on hammer mass and baseplate area. It is expected, therefore, that the results shown here are representative of most sledgehammer-baseplate configurations.

A variety of different pipegun types and designs exist (Pullan and MacAuley, 1985, 1987; Miller et al., 1986, 1992, 1994; Herbst et al., 1998; Wiederhold et. al., 1998). Our 12-gauge pipegun source consists of a 1.65 m long hollow metal pipe, down which a metal rod is dropped onto a blank cartridge (Figure 3.3b). It may be used in holes up to ~1.5 m deep. A piezo-electric sensor is mounted at the top of the rod. Advantages of this design are its robustness and mobility under field conditions and its low purchase and operating costs. A disadvantage is the relatively labor-intensive shothole preparation.
Weightdrop systems are often employed in shallow seismic surveys. They may include truck- or trailer-mounted mechanisms that accelerate artificially a large mass towards the ground. A large amount of energy is generated on impact. An example of a weightdrop system (Vakimpak) is illustrated in Figure 3.3c. Advantages of such systems are their robustness and relatively low operating costs. Disadvantages are their high purchase price and maintenance costs and their lack of mobility in rugged terrains.

Vibratory sources

Vibratory sources are not yet commonly used in high-resolution seismic experiments, but may eventually offer significant benefits over traditional impulsive sources, especially for surveying in urban areas. For example, by distributing the generated energy over time (i.e. sweep time), non-linear behavior in the vicinity of the source may be minimized. Moreover, by controlling the sweep parameters it is possible to tailor the source signal for (i) particular targets of interest, (ii) optimized resolution or (iii) optimized depth penetration. Disadvantages are their high purchase price and maintenance costs and the fact that cross-correlation or deconvolution with appropriate reference signals is necessary to generate an impulsive equivalent of the seismic record.

OYO Center of Applied Geoscience (OYO-CAG) in the Netherlands has developed a 65 kg hand-portable vibrator (Table 3.1; Figure 3.3d) that generates a maximum theoretical ground-force of 500 N (Nijhof, 1989). According to the manufacturer’s specifications, it operates in the frequency range 25-1500 Hz (Ghose et al., 1998). Principal advantages of this system are its ability to produce high-frequency signals suitable for imaging ultra-shallow to shallow geological structures and its portability, which allows rugged terrains to be surveyed. A potential disadvantage is the limited maximum ground-force of 500 N and associated limited depth penetration.

CGA-Institute of Joint Geoscientific Research (Germany) has developed a high-frequency vibrator (Table 3.1; Figure 3.3e) that is capable of generating a peak force of ~31,000 N (Buness et al., 1997). The 2,600 kg truck-mounted vibrator can operate in the frequency range 16-500 Hz. A key advantage of this system is the large amount of energy it can generate at high frequencies. One disadvantage may be its limited mobility in areas with difficult access or substantial topographic relief.

3.4 Acquisition

An overview of the tested sources and acquisition parameters is given in Table 3.2. Along profile A, high-frequency data were recorded along a compacted gravel path using the sledgehammer, pipegun and accelerated weightdrop sources. The sledgehammer and accelerated weightdrop sources were deployed on the path, whereas the pipegun was fired in untamped shallow holes drilled beside it. For each suite of recordings, very similar recording parameters were employed. Data were acquired using a fixed spread with single 30 Hz geophones spaced 1.5 m apart. Shot spacing was 3 m. For the sledgehammer survey, a vertical stack of 5 was recorded, whereas for the other
impulsive surveys, single shots or impacts were considered sufficient. Blank 12-gauge cartridges were used in the pipegun.

Beneath the deepest part of the valley, along the central part of profile B, we have evaluated the sledgehammer and both vibratory sources (OYO and CGA vibrators) along a second compacted gravel track. Although the sledgehammer profile extended over the entire width of the valley, we only compare the results from the region between CMP's 640 and 940 (Figure 3.2). All data were recorded with identical 30 Hz geophones. For the OYO and CGA vibrator surveys, we used 70-300 Hz linear upsweeps of 4.5 s and 10 s duration, respectively. During initial tests, 8-fold stacks of OYO vibrator data resulted in approximately equivalent S/N ratios as 2-fold stacks of CGA vibrator data in our area. Using more than 8 stacks may have increased S/N ratios, but it would also have increased the acquisition time. For all three sources employed along profile B, we generated stacked sections with CMP spacings of 1 m.

3.5 Processing

To obtain the stacked sections, relatively standard processing and imaging operations were applied to all data using commercial seismic software. Table 3.3 illustrates the common processing flow. Along each profile, individual processing parameters were varied slightly to optimize S/N ratios. Initial steps involved geometry setup, editing of the entire data set and application of elevation and refraction statics. Spectral balancing and additional bandpass filtering were applied to enhance data quality, especially in the higher frequency range. Finally, stacked sections were displayed after coherency filtering.

In addition to the common processing scheme, pre-processing was necessary to compress seismic signals recorded with the OYO and CGA vibrators. For the OYO vibrator, measured accelerations of baseplate and reaction mass were used to estimate the ground-force (Sallas, 1984), which was then employed as a reference signal for vibroseis deconvolution (van der Veen et al., 1999); vibroseis deconvolution with an appropriate reference signal may reduce harmonic distortions. By comparison, a synthetic pilot sweep was correlated with data recorded with the CGA vibrator; using this relatively standard approach, phase differences between the pilot sweep and true ground-force may introduce correlation noise, especially at higher frequencies.

3.6 Resultant Data

Profile A: Sledgehammer, pipegun and weightdrop system

Diagrams (a) and (b) in Figures 3.4-3.6 show typical unprocessed source gathers and associated amplitude decay curves extracted from data collected along profile A. Ambient noise levels of traces at 114 m source-receiver offset were determined from data recorded before the first-break onsets. Amplitude spectra of selected regions of the source gathers (diagrams (c) to (e) of Figures 3.4-3.6) represent stacks of the spectra of
traces in the respective windows. Regions I are dominated by complex patterns of direct waves, refractions, and reflections. Regions II are focused on reflections that originate from the top of the Molasse basement. Portions of dispersed surface waves are enclosed in regions III. The rather prominent event at ~250 ms in the weightdrop data (marked DB in Figure 3.6) may be associated with a double-bounce of the accelerated mass. In Figure 3.7, identical source gathers are displayed after standard processing up to bandpass filtering in Table 3.3.

Stacked sections from the three sources are displayed in Figure 3.8 and detailed views of the outlined portions of data are presented in Figure 3.9. Reflections R1 and R2 in Figure 3.9 represent small-scale pinch-out structures.

Profile B: Sledgehammer and OYO and GGA vibrators

Three typical unprocessed source gathers and associated amplitude decay curves extracted from data collected along profile B are displayed in diagrams (a) and (b) of Figures 3.10-3.12. Levels of ambient noise at 94 m source-receiver offset were determined from data recorded before first-break onsets. Amplitude spectra of three regions with typical signal characteristics are presented in diagrams (c) to (e) of Figures 3.10-3.12. Along this profile, regions I are dominated by guided waves that are typical of many shallow seismic reflection surveys (Robertson et al, 1996). They may obscure shallow reflections. Regions II are focused on reflections at traveltimes ~200-250 ms, which originate from the top of the Molasse basement and regions III display portions of the surface waves. Stacked sections for all three sources are displayed in Figure 3.14. A thorough geological interpretation of these sections may be found in Büker et al. (1998a). The main units correspond to those displayed in Figure 3.2.

3.7 Discussion

Profile A: Sledgehammer, pipegun and weightdrop system

Source gathers produced with the three source types along profile A are very similar (Figure 3.4-3.6). For example, the dispersed surface waves enclosed in regions III have nearly identical dominant frequencies of ~40 Hz and comparable amplitude-versus-frequency decay curves (at 400 Hz, -65 dB for the hammer and weightdrop gathers and -75 dB for the pipegun gather; Figure 3.4e-3.6e). Differences are observed in the respective amplitude decay curves (Figures 3.4b-3.6b). Maximum signal-to-ambient noise amplitudes of the sledgehammer data (18 dB) are much less than those of the pipegun (36 dB) and weightdrop (33 dB), resulting in significant differences in S/N ratios throughout the source gathers. Nevertheless, penetration of the least energetic source, five impacts of the sledgehammer, is sufficient to image the deepest reflections enclosed in regions II.

Regions I are dominated by a complex superposition of direct waves, refractions and reflections. Simple observation indicates that the sledgehammer data contain more high frequency details than equivalent data from the other two sources (Figures 3.4a-3.6a).
Two distinct peaks marked A1 and A2 are observed in the associated amplitude spectra (Figures 3.4c-3.6c). In the pipegun and weightdrop data, the peak at 40-60 Hz has a significantly higher amplitude than the higher frequency peak at ~125 Hz, thus explaining the relatively low frequency character of these data sets. By comparison, the A2 peak has a slightly higher amplitude than the A1 peak in the spectrum of the sledgehammer data. Due to the complex superposition of signals in regions I, it is difficult to associate the individual peaks in frequency content with specific wave types (e.g., refractions versus reflections). An interpretation of the "quality" of a seismic source based on these data alone is, therefore, equivocal.

Since regions II of the source gathers primarily contain reflections, they provide less ambiguous information. Although the corresponding amplitude spectra for the three source gathers all have high amplitude peaks at ~60 Hz (Figures 3.4d-3.6d), the sledgehammer data appears to contain a relatively higher amount of higher frequency energy. For example, the point at which the signal has decayed to a level of ~40 dB occurs at ~225 Hz in the sledgehammer data, whereas it is at ~140 Hz in the pipegun and weightdrop data. Consequently, reflections in the unprocessed sledgehammer gathers appear to supply higher resolution information (compare Figures 3.4a with Figures 3.5a and 3.6a). To determine whether or not comparable high-frequency details are contained in the pipegun and weightdrop data, we analyze the processed (up to and including bandpass filtering in Table 3.3) source gathers in Figure 3.7. These processed gathers demonstrate that all three source types generated very shallow reflections rich in high frequencies. Nevertheless, the temporal resolution of reflections within the circled area is highest in the sledgehammer data.

Resultant stacked sections (Figure 3.8) show complex reflection patterns to times of ~100-150 ms. Data from all three sources are comparable with respect to maximum penetration depth. Although the shallowest detectable reflections may be identified on all sections at ~25 ms, the relatively higher frequency content of the sledgehammer data result in better resolution of some events. Detailed views of the rectangular areas marked on Figures 3.8a-3.8c show the effect of the differences in resolution (Figure 3.9); small-scale pinch-out features R1 and R2 are clearly identified on the sledgehammer section (Figure 3.9a), whereas they are more smeared on the pipegun section, and hardly recognized on the weightdrop section.

Along profile A, the sledgehammer, pipegun and weightdrop sources generated comparable data sets, possibly because the ground-water table was very close to the surface. Reflections as shallow as ~25 ms (~10 m depth) and as deep as ~150 ms (~150 m) were imaged. The sledgehammer produced less energetic signals that contained relatively higher frequencies than the other sources. Small-scale shallow features were imaged best on the sledgehammer sections.

**Profile B: Sledgehammer, and OYO and GGA vibrators**

At a typical source location along profile B (corresponding to CMP 640 in Figure 3.2), the trace normalized source gathers (Figures 3.10a-3.12a) are dominated at early traveltimes by strong low-frequency oscillatory signals. Simple analysis of
Chapter 3

refracted arrivals recorded along the profile demonstrate that there is a large increase in P-wave velocity from ~350 m/s to ~1900 m/s at depths of ~1.2-1.8 m. This increase is associated with the ground-water table.

We analyse the effect of the relatively thin low-velocity layer via finite difference simulations (Robertson et al., 1994) using a simple 1-layer model \( v_0=350 \text{ m/s}; \ v_1=1900 \text{ m/s}; \ \text{thickness}=1.5 \text{ m} \). The effect of attenuation is minimized by choosing relatively high Q values \( Q_p=100 \) and \( Q_s=50 \). The synthetic section in Figure 3.13 demonstrates that the low-velocity layer is probably responsible for the prominent reverberatory phases in the unprocessed source gathers. These reverberations result from multiple reflections within the low-velocity layer. A consequence of this phenomenon is that the effective source signal is long and complex.

Maximum signal-to-ambient noise levels are comparable for the three sources: 21 dB, 24 dB and 26 dB for the sledgehammer, and the OYO vibrator and CGA vibrators, respectively. For the particular locations represented by the source gathers of Figures 3.10-3.12, all three sources produced sufficient energy to image the deepest reflections at ~200-250 ms.

The amplitude spectra of regions I (Figure 3.10c-3.12c), which are dominated by the low-frequency signals, show two distinct maxima A3 and A4. In contrast to the maxima A1 of Figures 3.4c-3.6c, maxima A3 at a frequency of ~80 Hz are undoubtedly associated with the strong reverberations. Frequency analysis show that the A4 peak may be associated with shallow reflected energy. Based on the relative amplitudes of events A3 and A4, it seems that the sledgehammer produced the highest ratio of guided wave-to-reflection energy.

Reflections in regions II have a “ringy” character similar to that of the first arrivals in regions I. Again, this signature is caused by reverberations in the low velocity layer in the source region. Corresponding amplitude spectra (Figures 3.10d-3.12d) show similar dominant frequencies (~80 Hz) to those of the guided waves in regions I. The strong peak A5 in the high frequency range (~250-280 Hz) of the CGA vibrator spectrum (Figure 3.12d) originates from the airwave, which interferes with the reflections. Although airwaves are either not as prominent or absent on source gathers shown in Figures 3.10 and 3.11, they do not appear on other records acquired along profile B.

One of the major advantages of vibratory sources is illustrated in regions III of the source gathers, which enclose portions of the surface waves. The sledgehammer generated very strong surface waves, similar in amplitude and frequency content to those generated along profile A by all three impulsive sources. The sweep setting of the vibratory sources (70-300 Hz) was tailored to limit the generation of surface waves, while preserving the frequency bandwidth necessary to image the reflections. Dominant frequencies of the surface waves in the OYO and CGA vibrator data are ~70 Hz, corresponding to the start frequency of the sweep.

Significant differences are observed in the shallow parts of stacked sections resulting from data recorded along line B (Figure 3.14). The shallowest reflections R3 at ~25 ms are only observed in the sledgehammer section (Figure 3.14a). In the OYO and CGA
vibrator sections (Figure 3.14b and 3.14c), the earliest reflections occur at ~40-50 ms. A second difference is the variable S/N ratio along the OYO vibrator section relative to the others. This is discussed in the following paragraph. Along the entire profile, both the sledgehammer and CGA vibrator sections show strong reflections from the vicinity of the unconsolidated-consolidated sediment boundary (i.e. top of Molasse basement) at maximum travel times of ~250 ms. Events R4, which are associated with reflections from within the layer of glaciolacustrine clays are most prominent on the CGA vibrator section; they can be traced confidently over a distance of ~200 m. On the sledgehammer and OYO vibrator sections they are continuous over a distance of only ~90 m, either because of lower signal strengths or reduced high-frequency content.

Further details of the OYO vibrator data

The quality of data produced with the OYO vibrator is highly variable (Figure 3.14b). In the eastern part of the profile (~0-120 m), S/N ratios are comparable to the sledgehammer and CGA vibrator stacks, but towards the west, signal quality decreases significantly. Coherent shallow to deep reflections cannot be identified in this part of the stack. Diagrams (a) and (b) of Figure 3.15 show OYO source gathers from the western and eastern parts of profile B, respectively. The ground-force was calculated from reference signals recorded on the baseplate and reaction mass (van der Veen et al., 1999). It may interpreted as a measure of the amount of radiated energy. In the eastern part of the profile, the estimated ground-force is well above the average value (Figure 3.15c), resulting in source gathers with relatively high S/N ratios (Figures 3.15b). The source gather shown in Figure 3.11a originates from this region. Source gathers along the western part of the profile have much lower ground-force values (Figure 3.15a) and correspondingly reduced amplitudes (Figure 3.15c).

A possible explanation for the large differences in S/N ratios may be the sensitivity of the relatively lightweight OYO system to local recording conditions, which can be associated with coupling of the base plate to the ground. Figure 3.1 shows that surface recording conditions vary along profile B; the eastern and western parts of the studied sections (between arrows) are covered by recent sediments of diverse origin, whereas the center part is dominated by glacial moraines. The exact boundaries of these glacial deposits are not well determined; they could extend further towards the western and/or eastern parts of the profile. Van der Veen et al. (1999) show that vibrator coupling and the amount of radiated energy depend strongly on local surface conditions. Along profile B, the change from recent sediments to glacial moraines may result in a marked change of coupling and a degradation of the radiated energy.

Comparison of profiles A and B

The only direct links between profiles A and B are the sledgehammer source gathers. Despite the short lateral distance of ~750 m between them, the source gathers of Figures 3.4 and 3.10 are very different. Along profile A, the ground-water table was very close to the surface, so that reverberatory phases were not observed. In contrast, such phases dominate the profile B source gathers at shallow travel times. The large
differences in responses indicate that the performance of any seismic source depends strongly on local recording conditions. For our study, this dependence makes a direct comparison of the various sources employed along the two profiles somewhat ambiguous. It is clear, however, that along both profiles, the sledgehammer produced stacked sections rich in reflections from near the surface to the top of the Molasse basement. Considering its relatively low purchase and maintenance costs and the relatively high repetition rate, the simple sledgehammer continues to be an attractive source for high-resolution seismic profiling.

Comparison with the results of Doll et al.'s study

A comprehensive comparison of several seismic sources has been presented by Doll et al. (1998). Although shallow reflections at ~50-150 ms were observed in some stacked sections at their study site, the dominant reflections occurred at ~150-200 ms (corresponding to depths ~300-400 m). In contrast, our test location yielded prominent reflections over the complete range of ~25-250 ms (~10-250 m).

Very shallow reflections are a priority in many research programs. A number of studies (e.g., Steeples et al., 1997; Büker et al., 1998a, 1999) have concluded that reflections shallower than about 50 ms are more difficult to image than deeper ones, such that the choice of seismic source may be critical for very shallow surveys. At our study site, the shallowest features were imaged best with the sledgehammer. Other impulsive sources provided lower resolution and the quality of shallow images supplied by the vibratory sources was uniformly poor.

For travel times >50 ms, some results of Doll et al.'s (1998) study were similar to ours. For example, at both study sites, the signal strength of the OYO vibrator was poorer than other tested sources, resulting in stacked sections with relatively low S/N ratios. Their conclusions regarding the most effective source differed slightly from ours, probably because of different recording conditions. They found that the weightdrop system and IVI vibrator, which is comparable to the CGA vibrator, provided comparably good images of the subsurface at travel times >50 ms. At our test site, the sledgehammer produced the highest resolution image at early travel times and an image comparable to that provided by the GGA vibrator at later travel times. The combined results of both studies demonstrate that the performance of seismic sources is site dependent.

3.8 Conclusions

Our evaluations were aimed at determining the operational characteristics and applicability of a various seismic sources for imaging shallow (10-250 m) structures at our study site. By analysing critical features on source gathers, frequency spectra and stacked sections, the behaviour of these sources was examined in detail. Important results of our study were:

1. Local conditions, such as the occurrence of glacial moraines at the surface or variations in the depth to the ground-water table, influenced significantly the performance of the sources. A simple modeling
investigation confirmed that large P-wave velocity contrasts across laterally extensive boundaries in the shallow subsurface (e.g., at the shallow ground-water table) may introduce strong reverberatory signals.

2. The common sledgehammer proved to be the best source for imaging all important geological structures at our study site. Of the impulsive sources, it provided the largest ratio of high- to low-frequency energy and the highest resolution information at shallow depths. Although it produced weaker signals than other impulsive sources, at our site it supplied sufficient energy to image the deepest reflections at ~250 m.

3. The pipegun and weightdrop produced comparably good signals. Of the impulsive sources, they generated the largest amount of energy.

4. Previously, the OYO vibrator has provided excellent P-wave reflection data in a variety of soft sediment environments (Ghose et al., 1995; Ghose et al., 1998). At our study site, which is dominated by an upper layer of glacial moraines or recent sediments, this lightweight vibrator proved to be overly sensitive to local recording conditions. With the particular source parameters that we adopted, this resulted in highly variable S/N ratios.

5. The intermediate-size CGA vibrator generated sufficient energy to image the deepest geological structures at ~250 m along the entire profile. Relatively strong airwaves and imprecise vibroseis correlation (especially at higher frequencies) distorted signals at traveltimes <50 ms. Therefore, at our study site, the CGA vibrator was limited to imaging reflections below ~50 ms (~40-50 m).

Vibratory sources offer significant advantages over impulsive sources. However, their relatively high purchase and maintenance costs and potential problems related to the robust reconstruction of high-frequency impulsive signals via deconvolution or cross-correlation may still limit their routine application. When prices drop and our understanding of the relevant physical processes at shallow depths improve, it is anticipated that vibratory sources may become as important in engineering-scale surveys as full-size vibroseis systems are for hydrocarbon exploration.

Considering its relatively low purchase and maintenance costs and the relatively high repetition rate, we conclude that the simple sledgehammer continues to be an attractive source for high-resolution seismic surveying.
**Table 3.1:** Characteristics of tested vibratory sources (from manufacturer’s specifications)

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<tr>
<th></th>
<th>OYO vibrator</th>
<th>GGA vibrator</th>
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</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>0.3x0.3x0.4 m</td>
<td>3.9x1.8x1.9 m</td>
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<tr>
<td>Mass</td>
<td>65 kg</td>
<td>2,600 kg</td>
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<td>Baseplate mass</td>
<td>3.5 kg</td>
<td>181 kg</td>
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<td>Reaction mass</td>
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<td>2,300 kg</td>
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<td>Peak force</td>
<td>500 N</td>
<td>31,000 N</td>
</tr>
<tr>
<td>Frequency range</td>
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<td>16-500 Hz</td>
</tr>
<tr>
<td>Method of signal</td>
<td>Deconvolution with estimated ground-force</td>
<td>Correlation with synthetic pilot sweep</td>
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<tr>
<td>reconstruction</td>
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**Table 3.2:** Acquisition parameters of stacked sections.

<table>
<thead>
<tr>
<th>Profile A</th>
<th>Profile B</th>
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</table>
| **Seismic Sources** | sledgehammer
|             | pipegun
|             | weightdrop
| **Vertical stack** | sledgehammer: 5
|             | pipegun: 1
|             | weightdrop: 1
| **Profile length** | 250 m
| **Number of Channels** | 168
| **Roll along** | fixed spread
| **CMP spacing** | 0.75 m
| **Nominal fold** | 42
| **Sweep time** | -
| **Taper length** | -
| **Sweep frequencies** | -
| **Sweep type** | -

OYO vibrator: 4.5 s (total: 36 s)
GGA vibrator: 10 s (total: 20 s)

OYO vibrator: 0.05 s
GGA vibrator: 70-300 Hz
linear upsweep
Table 3.3: Common processing flow (see Figures 3.8, 3.9, 3.14 and 3.15)

<table>
<thead>
<tr>
<th>Common Processing Flow</th>
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<tbody>
<tr>
<td>Geometry</td>
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<tr>
<td>Editing</td>
</tr>
<tr>
<td>Elevation Statics</td>
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<tr>
<td>Refraction Statics</td>
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<td>Spectral Balancing</td>
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<td>Bandpass Filtering</td>
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<td>Top Mute</td>
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<td>CMP Sorting</td>
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<td>Velocity Analysis</td>
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<tr>
<td>NMO Correction</td>
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<tr>
<td>Residual Statics</td>
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<tr>
<td>Stack</td>
</tr>
<tr>
<td>Coherency Filtering</td>
</tr>
</tbody>
</table>
Figure 3.1: Suhre valley in northern Switzerland. Source comparisons were made along profiles A and B (between arrows). Profiles A and B are parallel and perpendicular to dominant flow direction of ancient glacier, respectively.
Figure 3.2: (a) Previously recorded seismic reflection section along profile B illustrating typical seismic response for survey region (adapted from Büker et al., 1998a). Data were generated with a sledgehammer source. (b) Geological interpretation of seismic section constrained by limited borehole and outcrop information. Along the central part of profile, a sledgehammer, GGA vibrator, and OYO vibrator were evaluated. Geological formations correspond to: A - glaciolacustrine clays/silts; B1 - basal till; B2 - fluvial sands/gravels; C1 - reworked till; D - glaciolacustrine clays; E - reflective Molasse sandstone basement (interpretation tentative); F - Molasse sandstone basement. Figures are plotted with vertical:horizontal scale of approximately 1:1 for average velocity of 2000 m/s.
Figure 3.3: Evaluated seismic sources: (a) 5 kg sledgehammer and 225 cm² baseplate; (b) 12-gauge pipegun; (c) weightdrop (Vakimpak); (d) hand-portable (65-kg) vibrator developed by OYO with cover to reduce amplitude of airwaves; (e) truck-mounted (2600 kg) vibrator constructed by GGA.
Figure 3.4: (a) Trace-normalized source gather produced with sledgehammer and recorded along profile A, and (b) associated amplitude decay curve of trace recorded at 114 m offset (location marked by arrow). Trace spacing was 1.5 m. Amplitude spectra of (c) region I dominated by complex pattern of direct waves, reflections and refractions, (d) region II showing reflections at traveltimes of ~100-150 ms from within the unconsolidated sedimentary section, and (e) region III distinguished by dispersed surface waves. Amplitude spectra are displayed in relative dB scale. A1 and A2 in diagram (c) indicate dominant peaks in amplitude spectra of region I.
Figure 3.5: As for Figure 3.4, but for data recorded with a pipegun.
Figure 3.6: As for Figure 3.4, but for data recorded with weightdrop system. DB shows first-break signal associated with double-bounce on ground.
Figure 3.7: Source gathers of Figures 3.4-3.6 after standard processing (up to bandpass filtering in Table 3.3) and subjected to a 100 ms AGC for display purposes. Highlighted areas illustrate differences in temporal resolution.
Figure 3.8: Stacked reflection sections recorded along profile A using three different sources: (a) sledgehammer, (b) pipegun, and (c) accelerated weightdrop. Processing sequence shown in Table 3.3. Figures are plotted with vertical:horizontal scale of approximately 1:3 for average velocity of 2000 m/s.
Figure 3.9: Enlarged and rescaled data from windowed regions in Figures 3.8a to 3.8c. Figures plotted with vertical:horizontal scale of approximately 1:1 for average velocity of 2000 m/s. Reflections R1 and R2 illustrate differences in images due to varying dominant frequencies.
Figure 3.10: (a) Trace-normalized source gather produced with sledgehammer and recorded along profile B, and (b) associated amplitude decay curve of trace recorded at 94 m offset (location marked by arrow). Trace spacing was 2.0 m. Amplitude spectra of (c) region I dominated by guided waves; (d) region II showing reflections at ~200-250 ms; (e) region III distinguished by dispersed surface waves. Amplitude spectra are displayed in relative dB scale. A3 and A4 in diagram (c) indicate dominant peaks in amplitude spectra of region I.
Figure 3.11: As Figure 3.10, but for data recorded with OYO vibrator. Dashed lines in diagrams (c)-(e) mark corner frequencies of linear sweep.
Figure 3.12: As for Figure 3.11, but for data recorded with GGA vibrator. A5 in diagram (d) marks a dominant peak in the amplitude spectrum of region II associated with airwave signals.
Figure 3.13: (a) 1D Model derived from refraction analyses of source gather in Figure 3.10. (b) Corresponding trace-normalized synthetic source gather. Strong reverberatory signals generated within thin low-velocity layer are similar in characteristic to signals enclosed in region I of source gathers recorded along profile B (Figures 3.10-3.11).
Figure 3.14: Stacked sections recorded at same location along profile B with three different sources (see Figures 3.1 and 3.2b): (a) sledgehammer, (b) OYO vibrator and (c) GGA vibrator. Identical processing sequences were applied to all three data sets (see Table 3.3). Events R3 mark the shallowest detectable reflections that probably originate from top of basal till. Events R4 are associated with reflections within glaciolacustrine clays.
Figure 3.15: (a) and (b) Typical OYO vibrator source gathers with "below-average" and "above-average" ground-force amplitudes, respectively. (c) Average relative ground-forces (70-300 Hz) for each shot point. (d) CDP profile in which variability of estimated ground-force is represented by large fluctuations in S/N.
DESIGN AND APPLICATION OF A LAND-STREAMER SYSTEM FOR COST-EFFECTIVE 2D AND PSEUDO-3D SHALLOW SEISMIC DATA ACQUISITION

Abstract

To reduce the field effort required for 2D and 3D shallow seismic surveying, we have developed a towed land-streamer system. This acquisition system was constructed with off-the-shelf components of which the most important were: (i) self-orienting gimbal-mounted geophones housed in relatively heavy cylindrical casings, (ii) sturdy seismic cables with reinforced kevlar outer casings, (iii) robust waterproof connectors, and (iv) a reinforced rubber sheet that helped prevent cable snagging, maintained geophone alignment, and provided additional hold-down weight for the geophones. Each cable had takeouts for 12 geophones at 1 m or 2 m intervals. By eliminating the need for manual geophone planting and cable laying, acquisition of 2D profiles with this system proved to be 100-50% faster with 40-30% fewer personnel than conventional procedures. Costs of the land-streamer system and total weight to be pulled could be minimized by employing non-uniform receiver configurations. Short receiver intervals (e.g., 1 m) at near offsets were necessary for identifying and mapping shallow (< 50 m) reflections, whereas larger receiver intervals (e.g., 2 m) at far offsets were sufficient for imaging deeper (> 50 m) reflections and for estimating velocity-depth functions. Our land-streamer system has been tested successfully on a variety of recording surfaces (e.g., meadow, asphalt road, and compact gravel track). The heavy weight of the
geophone casings together with the hold-down weight of the rubber sheet ensured good
geophone-to-ground coupling. On the asphalt surface, a greater proportion of high
frequency (above 300-350 Hz) energy was recorded by the land-streamer than by
standard baseplate-mounted geophones. We concluded that the land-streamer system is a
practical and efficient means for surveying in urbanized areas.

Acquisition and processing of 3D shallow seismic data with the land-streamer
system was simulated by appropriately decimating and reprocessing an existing 3D
shallow seismic data set. Average subsurface coverage of the original data set was ~50,
whereas that of the simulated data set was ~5. The effort required to collect the simulated
pseudo-3D data set would have been approximately 7% of that needed for the original
field campaign. Application of important data-dependent processing procedures (e.g.,
refraction static corrections and velocity analyses) to the simulated data set produced
surprisingly good results. Since the spacing between simulated in-line profiles (6 m) was
double that between cross-line profiles (3 m), a pattern of high and low amplitudes was
observed on cross-sections and time-slices at early traveltimes (≤ 50 ms). At greater
traveltimes, all major reflections could be identified and mapped on the land-streamer
data set. With this cost-effective approach to pseudo-3D seismic data acquisition, it is
expected that shallow 3D seismic reflection surveying will become attractive for a
broader range of engineering and environmental applications.

4.1 Introduction

Over the past decade, high-resolution seismic methods have become popular for
resolving a wide variety of geological, engineering and environmental problems. New
equipment, such as 24-bit recording systems with large channel capacity, have led to
substantial improvements in the quality and reliability of shallow seismic data. However,
in addition to increasing our ability to record high-fold and densely spaced data, the new
technologies have expanded markedly the logistical complexity of typical shallow
seismic surveys. Steeples et al. (1997) have stated:

"As the seismograph cycling time decreases, geophones must be posi-
tioned more quickly. Increased acquisition speed is a key to improved
cost-effectiveness. A technique that would allow the rapid, automatic
placement of geophones is needed."

To address this issue, we have developed and extensively tested a new towed land-
streamer system.

Several attempts have been made to increase the efficiency of terrestrial data
acquisition for hydrocarbon exploration purposes. Kruppenbach and Bedender (1975,
1976) introduced and patented the concept of a towed land cable, which was based on the
principle of seismic data acquisition in marine environments. During the 1970’s,
Geophysical Service Incorporated used such a system to collect seismic reflection data
on sea ice in Arctic North America (mentioned briefly in Einarsson et al., 1977). To our
knowledge, no reports on the performance of Kruppenbach and Bedender’s (1975, 1976)
and Einarsson et al.’s (1977) systems were ever published. Somewhat later, Eiken et al.
(1989) constructed a seismic streamer for research and hydrocarbon exploration in Antarctica. Until very recently (e.g., van der Veen and Green, 1998; Inazaki, 1999), surveying with towed land-streamers was restricted to ice or snow, both of which provided smooth sliding surfaces suitable for long (up to 6000 m) streamer use. Deploying long streamers on regular land would have been impractical.

In contrast to hydrocarbon exploration, the imaging of shallow features (< 200 m) in engineering and environmental investigations requires densely spaced sources and receivers distributed over relatively short (mostly <200 m) acquisition spreads. Van der Veen and Green (1998) recognized that relatively short seismic arrays could be towed across most land surfaces. They constructed and successfully tested a very short prototype land-streamer comprising self-orienting gimbal-mounted geophones. Potential advantages of this innovative approach were identified as:

- no need for geophone planting;
- automated roll-along;
- fewer field personnel compared to traditional methods;
- significant increase in acquisition speed;
- marked decrease in total survey costs.

Using the land-streamer described by van der Veen and Green (1998) as a basis, we have developed a complete towed land-streamer system for shallow seismic data acquisition. Here, key technical details of the towed land-streamer are described, and the field effort needed for towed land-streamer surveys is compared with that required for traditional surveys. To reduce the number of relatively expensive gimbal-mounted geophones, acquisition geometries with variable receiver spacings (i.e., increased receiver spacing with increased source-receiver offset) are examined. The performance of the towed land-streamer is then compared with traditional seismic methods in different recording environments (i.e., on a meadow, an asphalt road, and a gravel track). Finally, the potential of using the towed land-streamer system for acquiring pseudo-3D shallow seismic reflection data is evaluated.

### 4.2 Towed land-streamer System

#### Land-streamer

Our multi-channel land-streamer system is built with off-the-shelf items intended for various other purposes (Figure 4.1):

1. Self-orienting gimbal-mounted geophones with 30 Hz velocity sensors record the seismic signals (Figure 4.1). The sensors are mounted in heavy (~1 kg) cylindrical casings to ensure good geophone-to-ground coupling.

2. The gimbal-mounted geophones are attached to sturdy cables with reinforced kevlar outer casings. Each cable has take-outs for 12
geophones, either at 1 m or 2 m intervals. Similar cables are used in surveying swampy regions.

3. Cables are terminated with robust waterproof Titan-II connectors. The towed land-streamer is presently limited by the 96-channel capacity of these connectors. Titan-II connectors are commonly used in land-marine transition zones.

4. The gimbal-mounted geophones and cables are attached to the underside and upperside of a long reinforced rubber sheet, respectively. The purpose of this sheet is to improve field handling, prevent cable snagging, and maintain geophone alignment. It also provides extra weight, thus increasing geophone-to-ground coupling. Our extensive tests have demonstrated that geophone-to-geophone coupling via the rubber sheet is negligible.

To take full advantage of the efficiency of the towed land-streamer, fast sources that provide energetic signals characterized by high frequencies and broad bandwidths are required (van der Veen et al., 1999). For our towed land-streamer system, we use the sledgehammer and pipegun for relatively shallow- and intermediate-depth targets, respectively.

Acquisition with the pipegun requires preparation of drill holes. To speed up field operations, we employ a semi-automated trailer-mounted auger at the front of the towed land-streamer (Figure 4.1e). For 1 m holes in typical clay conditions, an average of 40-50 holes per hour may be attained by a dedicated person operating the auger.

**Field effort for acquiring 2D profile data: Land-streamer system versus a conventional technique**

Acquisition with the towed land-streamer is similar to that of the marine streamer. In Figure 4.2a, the streamer comprises eight modules, each with twelve 1 m take-outs. Initially, the streamer is kept at a fixed location and the shot positions are moved from the back to the front of the array. Once the shot position reaches the front, it is kept at a fixed distance relative to the first receiver. Sources and receivers are then shifted simultaneously after each shot. In contrast to the continuous movement of marine systems, the operational procedure of the towed land-streamer is based on a “stop-start” concept. The streamer is moved up one shot interval, the shot is detonated once the streamer has been stationary for a few seconds, and the process repeated. Since moving the land-streamer generates significant noise, including variable vertical accelerations, it would be unwise to shoot while it is in motion.

Comparable acquisition procedures using spike-mounted geophones and standard CMP cables are more labour intensive (Figure 4.2b). To record with 96 active channels (as for the land-streamer example), a minimum of four 24-take-out engineering cables is required. At least one additional cable is necessary for conventional procedures using a roll-along device to change active channels (not shown in Figure 4.2b). The leap-frog
scheme in Figure 4.2b, which minimizes the number of geophones and cables required and avoids the use of a roll-along device, may be described as follows:

1. 96-channel seismic array is kept at a fixed location and shot positions are moved through it;
2. 24 spike-mounted geophones and cables on the left of the array are repositioned on the right;
3. entire seismic array is kept at a fixed location while shot positions are moved through the newly planted cable;
4. stages 2 and 3 are repeated as necessary.

We have determined the field effort needed to record shallow seismic reflection data using the two strategies displayed in Figure 4.2. Two profiles (I and II in Table 4.1) were examined. The first profile was aimed at obtaining very high-resolution data with 1 m source and 1 m receiver spacing, whereas the second consisted of fewer shot points and 2 m source and 2 m receiver spacing. Evaluations were made for surveys with the sledgehammer and the pipegun.

In general, line preparation and deployment and retrieval of geophones and cables are amongst the most time consuming aspects of seismic surveys. Moreover, relative to the sledgehammer, the pipegun increases significantly the field effort. For an efficient conventional shallow seismic survey on land, a field crew of 5-6 is needed: one person operating the recording equipment, two managing the seismic source, two geophone/cable layers and, if necessary, one person handling the auger. For a comparable land-streamer survey, only 3-4 field personnel are required: as for the traditional survey, but the operator doubles as the driver of the towing vehicle and the geophone/cable layers are not required.

Using traditional recording equipment with the sledgehammer/pipegun, the densely spaced profile I was recorded in ~23/43 hours with a 5/6-person field crew. Acquisition of the equivalent towed land-streamer sections was achieved in ~10.5/30.5 hours with a 3/4-person crew. Thus, the towed land-streamer system was ~100-50 % times faster, and required only ~40-30 % of the personnel. The land-streamer surveys were completed with 25-50 % of the person-hours required for the traditional surveys. For both recording strategies, the more sparsely spaced profile II was recorded in approximately half the time required for profile I.

Figure 4.3 shows estimated total time needed to acquire profiles of various lengths using both recording methods and a sledgehammer source. The solid and dashed lines correspond to acquisition with 1-m source and receiver spacings and the dash-dot and dotted lines to the 2-m acquisition geometry. Vertical time shifts (marked with circles) are associated with repositioning of the standard cables. Using the sledgehammer source, acquisition speed of the towed land-streamer is uniformly faster (~2 times) than the conventional technique.
Choosing the acquisition geometry for acquiring 2D profile data: Uniform versus non-uniform receiver spacings

Several factors should be considered when defining acquisition geometry (Knapp and Steeples, 1986; Büker et al., 1998b):

- choice of source and receiver spacings is governed by the maximum CMP spacing required to avoid spatial aliasing (Yilmaz, 1987):

\[
\Delta CMP = \frac{V_{rms}}{4 \cdot f_{max} \cdot \sin \alpha_{max}},
\]

(4.1)

where \( \alpha_{max} \) is maximum dip of geological features, \( V_{rms} \) is minimum velocity, and \( f_{max} \) is maximum recorded frequency;

- imaging structures at early traveltimes (<50 ms) requires numerous closely spaced sources and receivers - a relatively large number of near-offset traces is needed to distinguish reflections from source-generated noise (e.g., direct, guided, refracted, and surface waves) and to define top-mute functions;

- maximum source-receiver offsets are controlled primarily by the necessity to obtain reliable velocity-depth estimates for the deepest features of interest.

From these criteria, we conclude that source and receiver spacings at near offsets should be short, minimum source-receiver offsets should be small, and the number of near-offset traces and maximum source-receiver offsets should be large. For a given task of mapping both shallow and moderately deep targets, satisfying all of these criteria using traditional seismic acquisition techniques with uniform source and receiver spacings may not be financially possible; because resources for geophysical investigations in engineering and environmental projects are often limited, the number of available sources and receivers are often much fewer than desired.

In contrast to standard roll-along acquisition strategies, receiver spacing may vary along the length of the towed land-streamer. By employing streamer modules with variable receiver spacings (i.e., short intervals at near offsets and long intervals at far offsets), an appropriately designed land-streamer can satisfy all of the above criteria with fewer traces than employed in conventional surveying. Minimizing the number of receivers in a land-streamer also results in a decrease of the overall weight to be pulled (gimbal-mounted geophones are quite heavy) and a reduction in price of the total system; fewer recording channels would be required, and because gimbal-mounted geophones are ~10 times more expensive than traditional spike-mounted ones, minimizing their number is cost effective.
To assess the efficacy of variable receiver spacings, acquisition with two different streamer geometries was simulated from a 240-channel seismic data set recorded in the Suhre valley of northern Switzerland. The data were recorded with 1 m source and 1 m receiver intervals. Beneath the Suhre valley, reflections at very early (<50 ms) to intermediate (200-250 ms) traveltimes were expected (Büker et al., 1998a, 1998b, 1999). Acquisition using the following two streamer geometries with identical minimum and maximum source-receiver offsets was simulated (Table 4.2): (i) uniform streamer - 96 geophones spaced at 1 m intervals, and (ii) non-uniform streamer - 60 geophones of which the first 24 were spaced at 1 m intervals and the remaining at 2 m intervals. The uniform streamer provided a CMP spacing of 0.5 m and regular subsurface coverage of 48 (Figure 4.4). For the non-uniform streamer, the CMP spacing was also 0.5 m, but alternating CMP bins had subsurface coverages of 12 and 48.

Typical source gathers for the two acquisition geometries are displayed in Figure 4.5. The short receiver spacing at near offsets enable the shallowest reflections (200) to be clearly identified and mapped on both source gathers. Deeper reflections (>50 ms) are identified best at larger offsets (>24 m). At these larger offsets, the lower density of traces on the non-uniform streamer gather relative to that on the uniform streamer gather does not result in a major loss of information content. The principal reflections (e.g., reflection IV) are well resolved on both simulated source gathers.

Stacked sections resulting from the two simulated streamer geometries (Figure 4.6) are similar over the entire traveltime range of interest (~25-250 ms). All important reflection zones (I-IV) are well imaged on both sections. However, amplitudes and reflection continuity are rather more variable in the deeper part of Figure 4.6b than in the deeper part of Figure 4.6a (e.g., compare reflections III on the two sections). The marginally lower quality of Figure 4.6b is undoubtedly the result of the non-uniform subsurface coverage represented in Figure 4.4. For the reminder of this paper, streamers with uniform receiver spacings are employed.

4.3 Data Quality: Land-Streamer System Versus a Conventional Technique

To understand the potential and limitations of operating the towed landStreamer under different acquisition conditions, we have recorded data on a variety of surfaces. Initial coupling tests by van der Veen and Green (1998) showed that gimbal-mounted geophones have the potential to record faithfully high-resolution seismic data on saturated gravels covered by grass. In the present study, we have conducted tests aimed at comparing the coupling of gimbal-mounted geophones with that of spike- and/or baseplate-mounted geophones in three additional recording environments that are common in nearly every country: meadow underlain by clay, asphalt-covered road, and compacted gravel track. The recordings were made within the Rhine valley (meadow and asphalt road; Figure 4.7a) and Suhre valley (compacted gravel track; Figure 4.7b). These two areas have been the foci of extensive 2D and 3D seismic investigations by our group (Büker et al., 1998a, 1998b, 1999; van der Veen et al., 1999; R. Spitzer, F. Nitsche and A. Green, in preparation), so the geological settings were well known. Although the
sedimentary sections beneath the Rhine and Suhre valleys differed somewhat, a thin (0.5-1.5 m) near-surface layer of clay underlay all profiles.

Acquisition parameters for these tests are given in Table 4.4. Source and receiver spacings were 2.0 m. Towed land-streamers with 48 (on the meadow and gravel track) or 36 (on the asphalt road) gimbal-mounted geophones were deployed alongside traditional seismic lines with identical numbers of active spike- and/or baseplate-mounted geophones. The distance between parallel profiles was always less than 0.5 m. Profiles in each series of tests were recorded with exactly the same source, so that source-related effects were identical for the coincident or nearly coincident data sets. On the meadow, a piggune was required to generate sufficient energy in the near-surface clay layer. Shotholes were prepared with the semi-automated auger (Figure 4.1). On the asphalt road and gravel track, a 5-kg sledgehammer striking a steel baseplate produced sufficient energy for the entire depth range of interest.

After acquisition, the coincident data sets were passed through the same processing sequence using identical processing parameters (Table 4.3).

Meadow

The furrow suggested by van der Veen and Green (1998) to optimize geophone-to-ground coupling in unconsolidated sedimentary environments was created “automatically” during the towing of the streamer system across the meadow; the cylindrical casings of the gimbal-mounted geophones were pressed 1-2 cm into the soft surface layer by the weight of the geophones and the hold-down weight of the rubber sheet. Selected source gathers recorded on the meadow and detailed views of traces at 14 m and 68 m offsets are displayed in Figures 4.8. At early traveltimes, the unprocessed source gathers are dominated by low frequency (-30-50 Hz) guided phases (Robertson et al., 1996a, 1996b; Roth et al., 1998). At greater traveltimes, reflections and weak airwaves are present. Data from the two geophone types are almost indistinguishable. A detailed comparison of the individual traces (Figure 4.8c) confirm this assertion: phase and amplitude differences between coincident pairs of traces are extremely small. To evaluate geophone-to-ground coupling conditions at different source-receiver distances, the source gathers are divided into offset regions I-IV, each comprising 12 traces. Although minor differences are observed in the corresponding amplitude spectra (Figure 4.9), the general responses of the two geophone types are very similar in the frequency range <500 Hz. Important peaks and troughs in the spectra of the towed land-streamer match those in the spectra of the spike geophone data.

Stacked sections resulting from data recorded by the two suites of sensors are displayed in Figure 4.10. As for the source gathers (Figure 4.8), the resultant stacked sections are nearly identical. All reflection zones are imaged on both sections. A plot of the differences between Figures 4.10b and 4.10a demonstrates that reflection amplitudes vary only slightly between the two stacked sections (Figure 4.10c).
Asphalt

In addition to deploying the land-streamer and a line of baseplate-mounted geophones on the asphalt, a line of spike-mounted geophones was planted in grass-covered soil directly alongside. In Figures 4.11, the responses of the various geophones are compared. Unprocessed source gathers recorded with the gimbal-, baseplate-, and spike-mounted geophones are alike. Signal-to-ambient noise levels are similarly high (compare noise levels before first breaks) and prominent reflections (e.g., at 70-110 ms) are imaged on all records. The superimposed coincident traces in Figures 4.11d and 4.11e provide more detailed information. At a source-receiver offset of 68 m, the phase and amplitude differences between the individual traces are tiny. At 14 m offset, the responses of the gimbal- and spike-mounted geophones match well, whereas the dispersed surface-wave train (traveltimes 50-140 ms) recorded by the baseplate-mounted sensor exhibits small phase variations relative to those recorded by the other sensors. Other differences are observed in the signal characteristics of the airwaves (Figures 4.11a-4.11c). They are strongest in the streamer data and weakest in the baseplate-mounted geophone data, probably because the baseplate-mounted geophones suppress slightly the higher frequency signals.

In regions I, which are dominated by surface waves, the amplitude spectra of the gimbal- and spike-mounted geophones are alike, whereas that of the baseplate-mounted sensor differs somewhat for frequencies >120 Hz (Figure 4.12a). At the larger offsets represented by regions II and III (Figures 4.12b and 4.12c, respectively), important peaks and troughs on all three spectra match reasonably well up to frequencies of ~300-350 Hz. At higher frequencies, the spectra of the baseplate-mounted data fall below the others. It seems that the relatively heavy weight of the gimbal-mounted geophone casing combined with the hold-down weight of the rubber sheet provides better geophone-to-ground coupling conditions than that supplied by the light weight casings of the baseplate-mounted geophones.

Important reflection zones are imaged well on all three stacked sections (Figure 4.13). Although source gathers (Figure 4.11) and associated spectra (Figure 4.12) derived from data collected with the baseplate-mounted geophones differ somewhat from the others, the differences do not seem to affect greatly the stack sections. Because of the filtering applied, variations in the low (<70-80 Hz) and very high (>300-350 Hz) frequencies are mostly absent from the stacks. Differences between stacks resulting from the baseplate- and gimbal-mounted geophones are of the same order as differences between the stacks resulting from the baseplate-mounted geophones deployed on the asphalt road and the spike-mounted geophones set firmly in the adjacent grass-covered soil (Figure 4.14).

Compacted gravel track

Small 10 cm deep drill holes enabled the spike-mounted geophones to be coupled tightly to the compact gravel track. As for the previously described suites of experiments, the data are analyzed via unprocessed source gathers and selected traces (Figure 4.15), amplitude spectra of different offset regions I-IV (Figure 4.16), and
stacked data (Figure 4.17). Source gathers recorded with the land-streamer and spike-mounted geophones are very similar: S/N is comparably high and the same prominent reflections are present on both data sets. In general, the more detailed plots of the selected coincident pairs of traces (Figure 4.15c) confirm these similarities, although small phase differences again occur in the surface-wave trains (e.g., at travel times >200 ms on the traces recorded at 68 m offset). On the corresponding amplitude spectra of the different offset regions (Figure 4.16), major peaks and troughs match well. All important reflection zones are imaged on the two 300 m long stacked sections (Figure 4.17). Only small amplitude variations are revealed on the difference plot of Figure 4.17c.

4.4 Using the Towed Land-Streamer to Acquire Pseudo-3D Data: A Feasibility Study

Figure 4.3 demonstrates that surveying with the towed land-streamer system results in significantly reduced field effort compared to traditional 2D seismic reflection profiling. Although sparse 2D profiles may be sufficient investigating relatively simple and continuous geological features, they may not be adequate for mapping complex structures. Out-of-plane reflections and diffractions may lead to misprocessing and misinterpretation of isolated 2D seismic reflection profiles (Green et al., 1995; Lanz et al., 1996). By comparison 3D high-resolution seismic reflection methods are capable of providing accurate images of shallow heterogeneous structures (Green et al., 1995; Lanz et al., 1996; Barnes and Mereu, 1996; House et al., 1996; Büker et al., 1998b, 1999; Siakoohi and West, 1998). One major drawback of these methods is their high costs.

We study here the possibility of using the towed land-streamer system for shallow 3D seismic surveying. Such an approach could result in a significant reduction of field effort. For early hydrocarbon exploration in marine environments, 3D data sets were commonly recorded with single streamers. Similarly, 3D georadar surveying usually involves the acquisition of data along closely spaced parallel profiles (Lehmann and Green, 1999). The tested strategy for recording shallow 3D seismic data with the towed land-streamer system is identical to that used in early marine and current georadar surveying practices. An existing high-fold 3D seismic data set (Büker et al., 1998b, 1999; location shown in Figure 4.7) is used to simulate pseudo-3D acquisition with the towed land-streamer system. After appropriately decimating and reprocessing this high quality data set, we compare the resultant images with those produced by Büker et al. (1999).

Acquisition geometry

Although somewhat complicated than described here, Büker et al.'s (1998b, 1999) strategy for acquiring the 3D reference data set effectively involved the deployment of receivers on a regular 3 m x 3 m grid and the detonation of shots at intervals of 3 m and 9 m along lines separated by 6 m. Using this approach, they recorded seismic reflection data with uniform source-receiver offset and azimuth distributions. CMP's on a regular
1.5 m x 1.5 m grid, and an average fold of ~50. The total area surveyed was 360 m x 430 m (Figure 4.7b).

For our simulation, we have chosen a subset of data that covers a 150 m x 225 m area east of the Suhre river. By selecting appropriate traces from this data subset, it was possible to generate a suite of parallel 2D profiles, along which receiver and shot intervals were 3 m and 12 m, respectively. Spacing between profiles was 6 m. This combined source-receiver configuration resulted in CMP's being distributed at 1.5 m and 3 m intervals along and perpendicular to the profiles, respectively, and an average fold of ~5.

We emphasize that this simulation data set does not reproduce a pseudo-3D data set that would be acquired with the towed land-streamer system. To bring subsurface coverage to an acceptable level, many more source points along the line would be employed, and to obtain azimuthal information, either off-line shots would be fired into the land-streamer or a cross-profile would be recorded. Nevertheless, many aspects of a pseudo-3D shallow seismic data set recorded with the towed land-streamer can be assessed via the simulation.

Processing

A relatively conventional processing sequence (Table 4.5) was applied to the original and simulated 3D streamer data sets. Among the important steps were the computation and application of refraction static corrections, spectral balancing, bandpass filtering, top-mute definition, velocity analyses and 3D migration. We have tested extensively two data-dependent procedures (i.e., refraction static corrections and velocity analyses) on the two data sets.

To understand the influence of acquisition geometry on the refraction static corrections, receiver and source delay times were. Delay times computed from the original and simulated 3D streamer data sets were very similar (Figures 4.18a-4.18d), ranging from -3 to -10 ms with an average value of ~6 ms. Differences between delay times calculated from the two data sets were uniformly small with absolute differences being mostly < 2 ms (Figures 4.18e and 4.18f). Effects of these small differences were largely eliminated after application of the residual static correction routines, coherency filtering and migration. Consequently, 3D migrated images computed from the simulated 3D streamer data set using the original and the newly calculated refraction static corrections were visually indistinguishable from each other. In the following analyses, the newly calculated static corrections were used in the processing of the simulated 3D streamer data set.

Accurate velocities are important for NMO corrections and for such post-stack processing routines as 3D migration and time-to-depth conversion. Typical CMP supergathers and corresponding semblance plots derived from the original and simulated 3D streamer data sets are displayed in the upper and lower panels of Figure 4.19, respectively. Although reflections and associated semblance maxima are much better defined in Figure 4.19a than in Figure 4.19b, the two resultant velocity-time functions are very similar. To evaluate the reliability of stacking velocities determined from the
simulated 3D streamer data set, velocity-depth functions are determined at a number of
locations across the survey site using NMO-corrected CMP supergathers and semblance
plots (e.g., Figure 4.20). Velocity estimates such as those presented in Figure 4.20
demonstrate that differences between coincident pairs of velocity functions determined
from the original and simulated 3D streamer data sets are generally <6 %.

To examine the effects of varying stacking velocities by ±6 %, the simulated 3D
streamer data were fully processed to 3D migration with stacking velocities (i) equal, (ii)
6 % below, and (iii) 6 % above those derived from the original data set. After application
of coherency filtering and 3D migration, the resultant 3D images were hardly
distinguishable from each other. In the following analyses, velocity-depth functions
determined from Büker et al’s (1998, 1999) original 3D data set were used in the
processing.

**Stacked data**

Three-dimensional seismic images and selected in-line and cross-line sections that
resulted from processing the original and simulated 3D streamer data sets are displayed
in Figures 4.21 and 4.22. Each data set was processed with individually calculated
refraction and residual static corrections. The 3D migrated images reveal a variety of
subhorizontal and dipping reflections. Most prominent in the upper part of the data
volumes is the shallowest reflection I (best seen in Figures 4.22a and 4.22b), which
originates from a boundary between a glaciolastrine clay/silt unit near the surface and
an underlying till unit B. The latter unit is represented by a series of quasi-continuous
reflections between ~25 and ~100 ms. It is distinguished easily from the rather non-
reflective clay/silt unit D below. The junction of unit D with the underlying Molasse
basement is delineated by the east-dipping reflection zone IV between ~100-170 ms. In
the following descriptions of Figures 4.21 and 4.22, it is worth noting that in-line trace
spacing of both the original and simulated 3D streamer data sets is 3 m, whereas cross-
line spacing is 3 and 6 m, respectively.

Although prominent reflections I and reflection zone IV can be identified on the two
suites of in-line sections (e.g., in-line sections 50 and 108 in Figures 4.21 and 4.22),
some notable differences between the pairs of images exist. These variations are
attributed mainly to differences in S/N resulting from the relatively high fold (~50) of the
original data set compared to the much lower fold (~5) of the simulated 3D streamer data
set. For example, the shallowest reflection I can be traced continuously over the entire
length of Figure 4.22a, whereas the same reflection in Figure 4.22c is quite
discontinuous (choppy) with a strong undulating character. Although differences
between these two sections are less significant at greater traveltimes, variations in the S/
N continue to affect the images. Two examples of this effect are worth mentioning.
Chaotically distributed events within geological units B and D appear in Figure 4.22c at
locations where signals are either very weak or absent in Figure 4.22a, and the deepest
reflection zone IV is less continuous in Figure 4.22c than in Figure 4.22a.

Shallow reflection I can be followed continuously along cross-line section 205 in
Figure 4.22b. Because pseudo-3D acquisition with the land-streamer is simulated with
in-line recordings only, and in-line profiles are spaced at 6 m intervals, a pattern of alternating high and low amplitudes is observed on the equivalent cross-line section of Figure 4.22d (see highlighted area). In addition to the lack of direct sampling and the lower sampling rate (6 m versus 3 m) in the cross-line direction, differences in fold and associated S/N affect the cross-line sections in the same manner as the in-line sections. All major reflections and reflection patterns can be mapped in Figure 4.22d, but the reflectivity appears less continuous than in Figure 4.22b.

Features observed on the in-line and cross-line sections are also represented on the horizontal time-slices (Figure 4.21). Time-slices from the original data volume (Figure 4.21a) are characterized by relatively gradual amplitude changes. Although all major trends delineated on Figure 4.21a can be discerned on Figure 4.21b, the latter are distinguished by significantly higher levels of “chatter” or noise that interrupt the trends. Furthermore, the two shallowest time-slices in Figure 4.21b are affected by distinct “acquisition footprints” (Hill et al., 1999), which appear as oscillating sequences of high and low values parallel and perpendicular to the simulated recording lines.

**Comparison of field efforts**

When designing a geophysical survey, it is nearly always necessary to consider tradeoffs between costs and the required resolution and depth penetration of the recorded data. Clearly, the original images of Büker et al. (1998a, 1999) are superior to those that result from the simulated 3D streamer data set. To acquire the comprehensive data set east of the Suhre river, Büker et al.’s (1998b) field campaign required 7 field personnel working a total of 220 hours or 1540 person-hours. To record a land-streamer data set approximately equivalent to that simulated here would require 4 field personnel working a total of 26 hours or 104 person-hours. This would result in a total field effort equivalent to ~7% of that expended by Büker et al. (1998b).

**Need to check for azimuthal effects**

Azimuth dependence of stacking velocities was not considered in the analysis and processing of the simulated 3D streamer data set. Velocity-time functions were only derived for data recorded along the in-line direction. If velocities had been strongly azimuthal dependent, our processing would have resulted in improper alignment of reflections and attenuation of higher frequency components during stacking (Yilmaz, 1987). Fortunately, Büker et al. (1999) have shown that velocity functions determined in different azimuthal ranges at our site deviated only slightly (<5%) from each other. Although azimuth-dependent velocities were not critical for our study, they may be in other areas. In general, to check for azimuthal effects it would be prudent to record a number of cross-profiles.
4.5 Conclusions and Outlook

We have developed a towed land-streamer system that reduces significantly the field effort required for 2D and 3D shallow seismic data acquisition. Important operational characteristics of this new system were evaluated. Key results of these studies were:

1. For 2D profiling, the towed land-streamer system was 100-50 % faster and required only 25-50 % of the field effort used for traditional reflection profiling. This was accomplished by eliminating the need to plant manually the geophones and re-deploy cables.

2. A critical issue in the land-streamer system continued to be the energy source. The relatively long cycle times of our sources (e.g., approximately 1 and 2 source positions/minute for a pipegun and sledgehammer, respectively) controlled the acquisition speed. If the time needed at each source location could have been reduced significantly, streamer positioning and storage of seismic data could have been achieved at a much faster rate of 3-4 source locations/minute.

3. By using a non-uniform streamer configuration (i.e., short receiver intervals at near offsets and long intervals at far offsets), high quality images in the early (~25 ms) to intermediate (~250 ms) traveltime range were obtained by employing ~35 % fewer recording channels and geophones than required for conventional acquisition approaches. Simulations demonstrated that densely spaced near-offsets traces enabled shallow reflections to be identified and mapped faithfully, whereas more sparsely spaced longer offset traces were sufficient for determining reliable velocity functions over the entire traveltime range. Deploying a streamer with non-uniform geometry would have resulted in a reduction of weight to be pulled and a significant decrease (~35 %) in the costs of the total land-streamer system.

4. Our towed land-streamer system recorded faithfully high-resolution seismic data on a meadow and along an asphalt road and gravel track. The shallow furrow suggested by van der Veen and Green (1998) to improve geophone-to-ground coupling was created on the meadow by the pulling of the heavy gimbal-mounted geophones and the rubber sheet. Relatively good coupling of the gimbal- and spike-mounted geophones resulted in a very close match between the two data sets recorded on this surface. The asphalt road and gravel track were covered with compact material that did not allow a shallow furrow to be created. Nevertheless, our comparisons confirmed that the weight of the gimbel-mounted geophone casings together with the hold-down weight of the rubber sheet resulted in good geophone-to-ground coupling in these recording environments. On the asphalt road, the gimbal-mounted geophones recorded higher frequency (above 300-350 Hz) signals than the baseplate-mounted geophones. We concluded that the land-streamer system may be a practical and efficient means for surveying urbanized regions.
5. By collecting a large number of closely spaced 2D profiles and subsequently applying 3D processing routines, our simulations have demonstrated that the towed land-streamer system may be used for pseudo-3D surveying of the shallow subsurface. Refraction static corrections computed with the simulated land-streamer data set were similar to those computed with the entire original data set. Minor differences between the two suites of refraction static corrections were largely eliminated during subsequent application of residual static corrections, coherency filtering, and migration. Stacking velocities determined from the simulated 3D streamer data set were usually within ±6% of the original stacking velocity estimates. Because spacing between CMP traces in the cross-line direction was double that in the in-line direction (6 m versus 3 m), acquisition “footprints” (i.e., patterns of high and low amplitudes) were observed on time-slices at early travel times. Although all major reflections were identified on the simulated 3D streamer data, continuity of the shallowest reflections at 25-30 ms was significantly less than that produced with the original comprehensive data set of Büker et al. (1998b, 1999).

6. For pseudo-3D surveying with the towed land-streamer system, the field effort would have been only ~7% of that required by Büker et al. (1998b, 1999) to acquire their high quality data set. The resultant subsurface coverage would have been about only 10% of that attained by Büker et al. (1998b, 1999). However, the significant reduction in field effort and associated decrease in subsurface coverage would have resulted in a pseudo-3D data set with ~80% of the information contained in the original high-quality 3D data set.

Building on the accomplishments described in this paper, at least three additional procedures for increasing the efficiency and efficacy of data acquisition with the towed land-streamer system will be explored in the near future:

- Acquisition speed of the towed land-streamer system may be improved by employing vibratory sources. They offer significant advantages over other sources, such as the possibility to generate repeatable signals at high repetition rates. However, in a recent study (van der Veen et al., 1999), two modern vibratory sources provided signals marginally inferior to those generated by the sledgehammer and pipegun. Nevertheless, when prices drop and our understanding of the physical processes that influence vibrator-generated signals at shallow depth improves, they may eventually become the preferred shallow seismic source.

- The speed and accuracy of positioning may be improved by combining a semi-automated positioning unit with the towed land-streamer system. Possibilities include self-tracking laser-ranging theodolites (Lehmann and Green, 1998) and differential global positioning systems (DGPS; Hofmann-Wellenhof et al., 1999).
• As for modern marine seismic surveying, it may be possible to pull multiple short streamers across certain regions, thus increasing data acquisition efficiency and providing limited azimuth-dependent information.

• Finally, in-field processing in near real-time would allow an initial analysis of stacked sections, so that acquisition strategies could be adjusted to meet better the objectives of the survey.

With this cost effective seismic acquisition approach, and possible future developments such as the positioning and/or real-time processing systems, it is expected that seismic reflection tools will become financially attractive for an even wider variety of engineering and environmental applications.

Table 4.1: Typical acquisition parameters for two example seismic reflection profiles using sledgehammer and pipegun sources.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Example Profile I</th>
<th>Example Profile II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile Length</td>
<td>480 m</td>
<td>480 m</td>
</tr>
<tr>
<td>Receiver Spacing</td>
<td>1 m</td>
<td>2 m</td>
</tr>
<tr>
<td>Number of Receivers</td>
<td>96 active</td>
<td>48 active</td>
</tr>
<tr>
<td>Active Spread Length</td>
<td>95 m</td>
<td>94 m</td>
</tr>
<tr>
<td>Seismic Source</td>
<td>Sledgehammer &amp; Pipegun</td>
<td>Sledgehammer &amp; Pipegun</td>
</tr>
<tr>
<td>Source Spacing</td>
<td>1 m</td>
<td>2 m</td>
</tr>
<tr>
<td>Number of Shot Points</td>
<td>480</td>
<td>240</td>
</tr>
<tr>
<td>Fold</td>
<td>48</td>
<td>24</td>
</tr>
</tbody>
</table>
Table 4.2: Acquisition parameters of CMP-profiles using different simulated streamer geometries.

<table>
<thead>
<tr>
<th></th>
<th>Uniform Streamer</th>
<th>Non-Uniform Streamer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Receivers</td>
<td>96</td>
<td>60</td>
</tr>
<tr>
<td>Receiver Spacing</td>
<td>1 m</td>
<td>1 m (chan. 1-24)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 m (chan. 25-60)</td>
</tr>
<tr>
<td>Minimum Source-Receiver Offsets</td>
<td>1 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Maximum Source-Receiver Offsets</td>
<td>96 m</td>
<td>96 m</td>
</tr>
<tr>
<td>Number of Near Offset (&lt;24 m) Traces</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Source Spacing</td>
<td>1 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Subsurface Fold</td>
<td>48</td>
<td>12 and 48 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>alternating bins</td>
</tr>
</tbody>
</table>

Table 4.3: Common processing flow for profile data (see Figures 4.5, 4.10, 4.13 and 4.17).

<table>
<thead>
<tr>
<th>Processing Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
</tr>
<tr>
<td>Editing</td>
</tr>
<tr>
<td>Elevation Statics</td>
</tr>
<tr>
<td>Refraction Statics</td>
</tr>
<tr>
<td>Spectral Balancing (80-350 Hz)</td>
</tr>
<tr>
<td>Bandpass Filtering (80-350 Hz)</td>
</tr>
<tr>
<td>Top Mute</td>
</tr>
<tr>
<td>CMP Sorting</td>
</tr>
<tr>
<td>Velocity Analysis</td>
</tr>
<tr>
<td>NMO Correction</td>
</tr>
<tr>
<td>Stack</td>
</tr>
<tr>
<td>Coherency Filtering</td>
</tr>
</tbody>
</table>
Table 4.4: Parameters used for acquiring shallow multi-fold reflection data on different surface types with towed land-streamer system and traditional seismic equipment.

<table>
<thead>
<tr>
<th></th>
<th>Meadow</th>
<th>Asphalt</th>
<th>Gravel Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile Length</td>
<td>270 m</td>
<td>200 m</td>
<td>300 m</td>
</tr>
<tr>
<td>Receiver Spacing</td>
<td>2 m</td>
<td>2 m</td>
<td>2 m</td>
</tr>
<tr>
<td>Number of Receivers / Line</td>
<td>48</td>
<td>36</td>
<td>48</td>
</tr>
<tr>
<td>Number of Parallel Lines</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Seismic Source</td>
<td>Pipegun</td>
<td>5-kg Sledgehammer</td>
<td>5-kg Sledgehammer</td>
</tr>
<tr>
<td>Vertical Stack</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Source Spacing</td>
<td>2 m</td>
<td>2 m</td>
<td>2 m</td>
</tr>
<tr>
<td>Fold Coverage</td>
<td>24</td>
<td>18</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 4.5: Processing sequence for 3D data (see Figures 4.21 and 4.22).

<table>
<thead>
<tr>
<th>Processing Flow 3D Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
</tr>
<tr>
<td>Editing</td>
</tr>
<tr>
<td>Elevation Statics</td>
</tr>
<tr>
<td>Refraction Statics</td>
</tr>
<tr>
<td>Spectral Balancing (70-350 Hz)</td>
</tr>
<tr>
<td>Bandpass Filtering (70-350 Hz)</td>
</tr>
<tr>
<td>Top Mute</td>
</tr>
<tr>
<td>CMP Sorting</td>
</tr>
<tr>
<td>Velocity Analysis</td>
</tr>
<tr>
<td>NMO Correction</td>
</tr>
<tr>
<td>Residual Statics</td>
</tr>
<tr>
<td>Trace Equalization</td>
</tr>
<tr>
<td>Stack</td>
</tr>
<tr>
<td>Coherency Filtering</td>
</tr>
<tr>
<td>3D Migration</td>
</tr>
</tbody>
</table>
Figure 4.1: (a) Self-orienting gimbal-mounted geophone (left) and conventional geophone with 10 cm spike. (b) Details of gimbal geophone. Velocity sensor is mounted in metal cylinder filled with viscous oil that damps rotational vibrations. (c) Example of streamer module with 1 m receiver spacing. Streamer module is shown upside down to reveal gimbal-mounted geophones attached to underside of reinforced rubber sheet. Seismic cables are mounted on upperside of sheet; (d) Towed land-streamer system in the field. Four 24 m modules form a 96 m long streamer. Towing vehicle is visible at front of line; (e) Semi-automated auger that advances with towing vehicle and streamer whenever downhole source is used.
Figure 4.2: (a) Possible acquisition strategy with towed land-streamer system. Initially, streamer is fixed, and shots moved through profile. When desired minimum source-receiver offset is reached, land-streamer system is towed a distance of one or more receiver intervals after completion of each shot. (b) Comparable acquisition strategy with conventional 24-take-out cables using ‘leapfrog’ roll-along scheme. Again, spread is initially fixed and shots moved through profile. Subsequently, one cable is repositioned to front-end of spread, and shot positions moved through this part of spread. To continue roll-along, procedure is repeated.
Figure 4.3: Comparison of field effort for towed land-streamer system and conventional acquisition technique using a sledgehammer. Solid and dashed lines represent values for CMP profiling with 1-m source and receiver spacings. Dash-dot and dotted lines correspond to field effort for CMP profiling with 2-m source and receiver spacing. Vertical time shifts (marked with circles) are associated with repositioning of cables. Time estimates for 0-m length correspond to sum of times required to deploy and retrieve 96-channel systems.
Figure 4.4: CMP coverage resulting from two streamer acquisition geometries as described in Table 4.2. CMP spacing is 0.5 m for both configurations.
Figure 4.5: Selected source gathers from identical source position acquired with simulated streamer geometries (Table 4.2): (a) uniform streamer; (b) non-uniform streamer. Data are scaled with 75 ms AGC for display purposes. Reflections I and IV are shallowest and deepest reflections interpreted by Büker et al. (1998).
Figure 4.6: Stacked sections derived from data recorded with (a) uniform streamer, (b) non-uniform streamer (Table 4.2). Processing sequence is given in Table 4.3. Data are scaled with 75 ms AGC for display purposes. Reflections and reflection zones I-IV originate from boundaries that delineate distinct unconsolidated sedimentary units.
Figure 4.7: Location of survey areas in northern Switzerland. (a) Rhine valley. Coincident seismic reflection profiles with towed land-streamer system and baseplate- and spike-mounted geophones planted alongside each other were recorded across a meadow and along an asphalt road (solid lines). Highlighted area shows location of previously recorded shallow 3D seismic reflection survey (R. Spitzer, F. Nitsche and A. Green, in preparation). (b) Suhre valley. Coincident seismic reflection profiles with different types of geophones were recorded along a gravel track (solid line). Highlighted area shows location of previously recorded shallow 3D seismic reflection survey (Büker et al., 1998b, 1999).
Figure 4.8: Unprocessed source gathers recorded simultaneously across a meadow with (a) towed land-streamer system and (b) line of spike-mounted geophones planted alongside streamer. Source was a pipegun in a 1 m deep untamped shothole. Frequency analyses of mini-gathers I-IV are displayed in Figure 4.9. (c) Selected traces from offsets 14 m and 68 m. Thick and thin solid lines mark land-streamer and spike-mounted geophone data, respectively. Data are trace normalized.
Figure 4.9: (a) to (d) Amplitude spectra calculated for land-streamer (thick solid lines) and spike-mounted geophone (thin solid lines) mini-gathers I-IV recorded across a meadow. Location of mini-gathers I-IV are shown in Figure 4.8.
Figure 4.10: Stacked sections recorded simultaneously across a meadow with (a) towed land-streamer and (b) spike-mounted geophones. (c) Difference between stacked sections (b) and (a). Amplitude scaling of three sections is identical. Processing sequence shown in Table 4.3.
Figure 4.11: (a) Unprocessed source gather recorded with towed land steamer along asphalt road. (b) Unprocessed source gather from identical location, but recorded with baseplate-mounted geophones. (c) Unprocessed source gather recorded with spike-mounted geophones planted in grass-covered soil directly alongside road. Source was a sledgehammer striking a steel plate. Frequency analyses of mini-gathers I-III are displayed in Figure 4.12. (d) and (e) Selected traces from offsets 14 m and 68 m. Thick solid lines mark land-streamer data. Thin solid lines mark either baseplate-mounted (left panels) or spike-mounted (right panels) geophone data. Data are trace normalized.
Figure 4.12: (a) to (c) Amplitude spectra calculated for land-streamer (thick solid lines), baseplate-mounted geophone (thick gray lines), and spike-mounted geophone (thin solid lines) mini-gathers I-III recorded along asphalt road. Locations of mini-gathers I-III are shown in Figure 4.11.
Figure 4.13: Stacked sections recorded along an asphalt road with following geophones: (a) towed land-streamer positioned on road, (b) baseplate-mounted geophones positioned on road, and (c) spike-mounted geophones planted in grass-covered soil alongside road. Amplitude scaling of three sections is identical. Processing sequence shown in Table 4.13.
Figure 4.14: (a) Difference between stacked sections shown in Figures 4.13b and 4.13a. (b) Difference between stacked sections shown in Figures 4.13b and 4.13c. Amplitude scaling is identical to scaling in Figure 4.13.
Figure 4.15: Unprocessed source gathers recorded along compacted gravel track with (a) towed land-streamer and (b) line of spike-mounted geophones planted alongside streamer. Source was a sledgehammer striking a steel plate. Frequency analyses of mini-gathers I-IV are displayed in Figure 4.16. (c) Selected traces from offsets 14 m and 68 m. Thick and thin solid lines mark land-streamer and spike-mounted geophone data, respectively. Data are trace normalized.
Figure 4.16: (a) to (d) Amplitude spectra calculated for land-streamer (thick solid lines) and spike-mounted geophone (thin solid lines) mini-gathers I-IV recorded along compacted gravel track. Location of mini-gathers I-IV are shown in Figure 4.15.
Figure 4.17: Stacked sections recorded simultaneously along a compacted gravel track in the Suhrer valley with (a) towed land-streamer and (b) spike-mounted geophones. (c) Difference between stacked sections (b) and (a). Amplitude scaling of three sections is identical. Processing sequence shown in Table 4.3.
Figure 4.18: Refraction static corrections shown as source and receiver delay times calculated with following data: (a) and (b) original data set; (c) and (d) simulated land-streamer data set. (e) Differences between (c) and (a). (f) Differences between (d) and (b).
Figure 4.19: CMP supergather (right) and Semblance plots (left) composed of nine adjacent CMP gathers for the following acquisition geometries: (a) original data set, (b) simulated towed land-streamer data set. CMP location corresponds to in-line number 60, cross-line number 160. Data have been scaled with 100 ms AGC for display purposes. Velocity picks are based on a combination of semblance values and NMO-corrected CMP supergather.
Figure 4.20: For original and simulated 3D land-streamer data sets, velocity-depth functions determined at four different locations in the survey area with in-line and cross-line numbers: (a) 60 and 160, (b) 60 and 240, (c) 160 and 160, and (d) 160 and 240. At each location, velocity functions were estimated independently using original (solid line) and streamer (dashed line) data sets. Differences between coincident pairs of velocity functions are generally less than 6%.
Figure 4.21: Sequence of 3D images after 3D migration of data recorded with (a) original acquisition geometry and (b) simulated streamer geometry. Common processing sequence is shown in Table 4.5. Letters correspond to notation of Büker et al. (1998a, 1998b, 1999) and refer to features discussed in text.
Figure 4.22: (a) In-line section 108 recorded with original acquisition geometry. (b) Cross-line section 205 recorded with original acquisition geometry. (c) and (d) as for (a) and (b) but recorded with simulated land-streamer geometry. Common processing sequence is shown in Table 4.5. Letters correspond to notation of Büker et al. (1998a, 1998b, 1999) and refer to features discussed in text.
Outlook

The principal goal of this thesis was to develop a seismic acquisition strategy capable of decreasing markedly the field effort. The resultant towed land-streamer system offered significant time saving benefits by eliminating the manual planting of geophones and avoiding traditional roll-along schemes. This semi-automated recording system was capable of reducing 2D data acquisition costs by approximately 50-70% (i.e., one half to one third of the effort), part of which was a consequence of reducing the number of field personnel by 30-40% (Chapter 4).

Building on these accomplishments, potential procedures for increasing the efficiency of the towed land-streamer system are outlined in section 5.1. The possibility of developing a towed land-streamer system with self-orienting three-component sensors is reviewed briefly in section 5.2. Finally, in section 5.3, I introduce the feasibility of using statistical experimental design for determining optimum recording parameters for a typical 3D seismic reflection survey. This final section is not specific to the further development of the towed land-streamer system. Instead, it represents an alternative method for improving the efficiency of 3D seismic data acquisition.

5.1 Additional Steps to Increase Efficiency of Towed Land-Streamer System

System positioning

Currently, system positioning of the towed land-streamer is achieved via tape measures and/or standard laser theodolite systems. Relative coordinates are surveyed to control points on detailed maps of the study areas. A major concern associated with the former is the accumulation of errors that may result from repeated positioning of the measuring tape when surveying relatively long lines. Standard theodolite systems supply coordinates with an accuracy (mm range) well suited for shallow seismic surveys.
However, their personal-intensive and time-consuming handling prevent them from being used for the towed land-streamer system.

The efficiency and accuracy of the towed land-streamer technique may be improved by employing a semi-automated real-time positioning system, such as the self-tracking laser-ranging theodolite (Figure 5.1a; Lehmann and Green, 1999) or the differential global positioning system (DGPS; Figure 5.1b; Hofmann-Wellenhof et al., 1997). In Table 5.1, characteristics of standard and potential semi-automated positioning systems are listed and briefly assessed. For effective use with the towed land-streamer system, the surveying equipment should satisfy the following criteria:

- coordinate accuracy should be in the decimeter range or better;
- coordinates (x, y and z) must be determined simultaneously for the front and tail of the land-streamer - these two coordinates may be used to reconstruct coordinates of all receivers along the streamer (see Lehmann and Green [1999] for an appropriate interpolation strategy);
- if the positioning system is used for navigating the land-streamer system from one location to the next, it should deliver coordinate fixes at a rate of 6-12/min;
- if the seismic survey is following a predefined route (e.g., a road or path), accurate coordinate fixes should be available at least twice/min - this corresponds to the approximate maximum speed of a land-streamer survey using a sledgehammer source (Chapter 4);

Laser-tracking theodolite

Self-tracking laser theodolites are based on the principle of the standard laser theodolites (LEICA, 1998). They are capable of tracking automatically the movement of a laser signal reflected from a moving optical prism. Positioning requires quasi-continuous visibility between the theodolite and the prism; interruptions in the visibility of 1-2 s can be tolerated. They can track the prism at distances up to ~600 m with an accuracy in the cm range at a rate of 10 measurements per second (LEICA, 1998).

A sketch of the land-streamer system with a laser tracking theodolite is displayed in Figure 5.1a. Real-time coordinates are transferred via a telemetry link and interface to the recording system, where they can be merged rapidly with the seismic data. The ability to supply accurate coordinates in real-time makes this system attractive for navigating the towed land-streamer system. However, to track simultaneously the prism on the towing vehicle and the prism attached to the streamer tail requires two self-tracking theodolites. Although the price of a single system is about half that of a high-quality DGPS system, the need for two systems may restrict their application. In addition, the requirement for continuous visibility between the theodolites and the prisms may limit their practical application to relatively short surveys. Areas characterized by the presence of numerous high-standing obstacles may not be suitable for surveying with these systems.
Global positioning systems (GPS) take advantage of the known location of orbiting satellites. A positive aspect of GPS’s is the ability to determine absolute positions practically anywhere on earth. Signals transmitted from satellites supply information on the distances between the satellites and the GPS receiver. To achieve an accuracy in the sub-meter range, which is needed for high-resolution seismic surveys, the use of an additional fixed GPS receiver as a reference station is essential. For reliable surveying with this so-called differential GPS (DGPS) configuration, at least five “visible” satellites are required. Currently, state-of-the-art DGPS systems are able to provide in a stop-and-go mode, near real-time coordinates (e.g., ~2 positions/min) with typical accuracy of half a meter. Post-processing may result in improved accuracies in the cm range (Hofmann-Wellenhof et al., 1997).

A sketch of the land-streamer with an integrated DGPS is displayed in Figure 5.1b. This system requires a fixed GPS receiver as a reference station and two moving GPS receivers, one mounted on the towing vehicle and one attached to the streamer tail. As for the self-tracking laser system, coordinates of receivers between the end points must be determined using suitable interpolation routines (Lehmann and Green, 1999). Clearly, presently available DGPS’s are too slow and insufficiently accurate to control the navigation of the towed land-streamer system. If a road or path is being surveyed, appropriately accurate coordinates (within the cm range) can be determined via post-processing of the DGPS data. Other limitations on the use of DGPS are imposed by the need for continuous “upward visibility” of the moving satellites. The requirement for at least five “visible” satellites may be difficult to satisfy in urban areas, under tree cover, and in mountainous terrains. Moreover, the relatively high price for those DGPS’s that provide sufficient accuracy may limit their widespread use with the towed-land streamer system.

In-field processing

Shallow seismic reflection surveying (using either the towed land-streamer system or traditional techniques) generally involves data acquisition and subsequent processing on a powerful PC or workstation in the laboratory. Potential disadvantages of this strategy are: (i) inadequate in-field quality control, usually limited to the analysis of unprocessed or primitively processed source gathers, and (ii) stacked data are produced well after the field campaign. A consequence of these disadvantages is that information is not available for determining whether or not acquisition strategies need to be varied, critical areas added to the study, or key regions re-surveyed with denser acquisition parameters. Fast semi-automated in-field data processing may overcome these shortcomings. A possible processing flow could be as follows (Figure 5.2):

1. input initial geometry and, from preliminary processed source gathers recorded for testing purposes, input initial top-mute functions and stacking velocities;
2. acquire simultaneously source gather and coordinates of the source and streamer tail (as described in the previous section);
3. merge and store seismic data and positioning information;
4. apply standard processing (e.g., amplitude scaling, frequency filtering...);
5. apply and, if necessary, update top-mutes;
6. sort according to CMP;
7. adjust stacking velocities using information from standard semblance analyses - typically these would only be adjusted at selected source locations;
8. after application of NMO-corrections, stack and display processed sections;
9. repeat procedure by adding new traces to existing CMP bins and constructing new CMP bins.

This acquisition and processing procedure will result in a progressively stacked section (i.e., after each shot, new data will be added to the stacked section). Assuming the highest land-streamer acquisition speed of ~2 shots/min (Chapter 4), the processing flow would have to be cycled in less than 30 s. Experience with ProMax processing software has shown that 5-10 source gathers (96 channels, 300 ms record length, 0.25 ms sample rate) per minute may be processed according to the flow chart of Figure 5.2 using a Sun Ultra-10 (440 MHz). At these processing speeds, stacked sections using preliminary processing parameters would be obtained in near real-time for provisional analyses of subsurface structures. Of course, processing speed is a function of the chosen parameters and the hardware employed. It is anticipated that a dedicated processing computer and a competent processor would be required to run the system. Nevertheless, I conclude that a fast and robust in-field processing facility connected to the towed land-streamer system would allow for more efficient application of shallow seismic reflection techniques.

5.2 Three-Component Seismic Data

In general, shallow seismic reflection data are recorded with single-component geophones (usually vertical or transverse-oriented horizontal). To take full advantage of information contained in the diverse wave types, it is desirable to record three-component data. By fully processing three-component data sets, it may be feasible to obtain high-resolution images and determine critical geotechnical properties from a single data set. Polarisation and incident angles of incoming waves can be determined from three-component data recorded at one location. Analyses of such data may lead to better recognition and distinction between the different waves types (e.g., P-, S-, Rayleigh, and Love waves). Inversion of surface waves (Park et al., 1999) or simultaneous inversion of surface and guided waves (Roth and Holliger, 1999) provide near-surface velocity models useful for static corrections and velocity analyses. Reliable locations of reflectors in the shallow subsurface may be obtained via analyses of incident directions of incoming waves. For example, in tomographic experiments,
incident angles provide important constraints on the inversion process, thus increasing the reliability of the resultant models.

**Land-streamer with three-component geophones**

Clearly, three-component surveys require greater operational effort, such that new field techniques are necessary to manage the more complex logistics involved. In principle, it should be possible to adapt for this purpose the concept of the towed land-streamer system. For the development of such a system, two important issues will need to be considered:

- to avoid spatial aliasing, data acquisition geometries (i.e., source-receiver offsets and receiver intervals) will have to be evaluated thoroughly to account for very slow S- and surface waves in the shallow subsurface; acquisition of three-component data will require short source and receiver intervals over a broad range of source-receiver offsets;
- each receiver station occupies three channels of a recording system, so that the availability of seismographs, seismic cables and associated connectors with high channel capacity are even more important than in conventional near-surface seismic investigations.

Although three-component surveys are far from routine, Steeples et al. (1995) anticipate that future civil engineering and environmental studies of the shallow subsurface will involve three-component recording and three-dimensional data analysis. A land-streamer comprising self-orienting three-component gimbal-mounted geophones would improve significantly the procedures for acquiring the necessary data.

To conclude this outlook, I will consider a fundamental alternative to the land-streamer system or other automated receiver deployment concepts.

**5.3 Statistical Experimental Design to Optimize Shallow Seismic Surveys**

Many aspects of the towed land-streamer system are similar to those employed in traditional seismic surveying: a relatively large amount of data is recorded using predetermined geometries. Usually, the data are processed and evaluated after they have been recorded. An alternative approach that might improve the efficiency of shallow seismic data acquisition involves the use of experimental design procedures (Maurer and Boerner, 1998a, 1998b; Liner et al., 1999). Such approaches would involve designing practical experiments that optimally resolve important features of interest, while at the same time reducing the amount of data that only marginally contributes to an improved understanding of the subsurface.
Problem definition

A possible application of an experimental design procedure is illustrated in Figure 5.3. To resolve the detailed geological structure beneath a planned highway, a shallow 3D seismic survey needs to be conducted. The region is characterized by several critical features: (i) a large flat and easily accessible terrain, (ii) an inaccessible area, (iii) a difficult, but accessible mountainous region, (iv) existing roads, and (v) a river and a lake. One objective of experimental design might be to determine the optimum source-receiver configurations that result in a desired CMP distribution while minimizing the field effort and taking into account the various constraints. The experimental design approach to be described is not suitable for application with the towed land-streamer system.

Problem constraints

The optimization process may be subjected to numerous constraints related to, for example: (i) survey design objectives - e.g., focus on an area of interest such as the planned highway in Figure 5.3, (ii) the reflection seismic technique, (iii) equipment specifications, (iv) available financial resources, and (v) site-dependent features. In this section, I list details of potential constraints (ii) to (v) that may be of interest to the survey design problem outlined in Figure 5.3.

Technique-dependent constraints

For the successful application of shallow seismic reflection techniques, the source-receiver configuration should be designed to achieve (Knapp and Steeples, 1986b; Büker et al., 1998b):

- uniformly high level of subsurface coverage to assure sufficiently large S/N;
- uniform azimuthal coverage - neglecting azimuthal velocity variations may result in improper alignment of reflections and unnecessary attenuation of higher frequency components during stacking (Yilmaz, 1987);
- uniform source-receiver offset distributions - minimum source-receiver offsets are determined by the depths of the shallowest reflections, whereas maximum source-receiver offsets are controlled by the need to obtain velocity-depth estimates for the deepest features of interest.

Equipment-dependent constraints

Several equipment-dependent limitations may need to be accounted for, such as:

- maximum length of available cables;
- maximum number of available channels.
**Financial constraints**

Financial constraints are among the most important factors in designing a shallow seismic survey. These money-related constraints may be imposed on the solution as follows:

- number of sources and receivers need to be minimized;
- if the choice is available, the number of sources should be minimized at the expense of increasing the number of receivers - generally, source positions are more expensive than receiver positions;
- because of high costs and logistical problems, the number of sources and receivers in the mountainous region should be minimized (Figure 5.3).

**Site-dependent constraints**

Typical site-dependent constraints relevant to the problem outlined in Figure 5.3 can be imposed on the solution in the following manner:

- because of expected high ambient noise levels, particular effort should be made to avoid or minimize the number of sources and receivers in the near vicinity of roads;
- lack of sources and receivers at some locations (e.g., in the inaccessible area, in the vicinity of roads and in the mountainous regions) will need to be compensated for.

Telemetered acquisition systems would allow flexible receiver layouts to be adopted. However, because most engineering and environmental projects will continue to be based on multi-wire cable-based recording systems, the receiver configurations may be subjected to additional practical constraints, such as deployment along orthogonal lines (also discussed by Liner et al., 1999).

**Mathematical formulation of the statistical experimental design problem**

To help resolve 3D survey design problems using experimental design procedures, Figure 5.4 illustrates a small portion of the survey area under the planned highway of Figure 5.3. It is divided into 10x8 predefined CMP bins. The objective is to resolve adequately subsurface structures with an “optimum” acquisition strategy.

As a first priority, the seismic survey should be focused on the area of interest (i.e., in the direct vicinity of the highway). The CMP bins may be valued with the following weighting factor:

- \( W_B \) - bin importance (e.g., in Figure 5.4, \( W_B=0 \) and \( W_B=5 \) correspond to least and most important bins, respectively)

Each of the technique-dependent criteria (i.e., fold, source-receiver azimuthal distribution, and offset distribution) affect the quality of the recorded seismic data
differently. Their importance may be valued with following user-defined weighting factors:

- $W_F$ - fold distribution;
- $W_A$ - azimuth distribution;
- $W_O$ - offset distribution.

For a particular survey, $W_F$ may be much greater than $W_A$.

A critical issue in statistical experimental design is the quantification of the overall goodness of a source-receiver configuration $G_{conf}$. One possible approach is to introduce the following goodness functions for the different technique-dependent criteria:

- $G_F$ - goodness of the CMP fold relative to a predefined value;
- $G_A$ - goodness of the azimuth distribution relative to an ideal situation - a measure may be variance of the azimuth distribution - small variance corresponds to more uniform distribution of azimuths, whereas large variance corresponds to an irregular distribution (Figure 5.5);
- $G_O$ - goodness of the offset distribution relative to an ideal situation - a measure may be the variance of the offset distribution.

To find the optimum survey layout, all possible source-receiver array configurations should be tested in the computer simulation. Figure 5.4 displays examples of three source positions, each with 4 active receivers. Potential source and receiver locations are indicated by the dense grid of dots. These locations are independent of the CMP bins (sources and receivers may be located at arbitrary positions defined by the user). By “testing” all possible acquisition configurations, a $G_{conf}$ may be defined as:

$$G_{conf} = \sum_{Bins} W_B \cdot W_F G_F \cdot W_A G_A \cdot W_O G_O.$$  \hspace{1cm} (5.1)

This equation shows that the configuration-goodness $G_{conf}$ depends on the products of the weighted “goodnesses” summed over all bins. The contribution of a single bin to the configuration-goodness depends on the product of its relative importance (i.e., $W_B$), with its weighted “goodnesses” of subsurface fold (i.e., $W_F G_F$), azimuth coverage (i.e., $W_A G_A$), and offset distribution (i.e., $W_O G_O$). A bin will not contribute to the configuration-goodness if any of the weights of goodness values is zero.

Obviously, function 5.1 will increase as the number of employed source and receiver positions increases. Therefore, a penalty function $P$ should account for additional financial and site-dependent constraints (Maurer and Boerner, 1998b):

$$G'_{conf} = \frac{G}{P}.$$  \hspace{1cm} (5.2)
where $G'_{\text{conf}}$ is the modified configuration-goodness. The penalty function may be of the form $\alpha^N$, where $\alpha$ is an arbitrary real number $>1$ and $N$ is proportional to the field effort or survey costs. The principle of these penalty functions can be illustrated with two simple examples:

1. Assuming that the effort in planting receivers can be neglected, field effort would be determined solely by the number of source positions. The number of sources can be minimized by setting the penalty function $N$ to the number of sources employed.

2. By neglecting receivers again, but taking into account the extra costs involved in deploying sources in difficult regions (e.g., the mountains in Figure 5.3) relative to the easily accessible areas, a possible penalty function could be defined as: $P = \alpha_M^{N_{SM}} + \alpha_A^{N_{SA}}$, where $\alpha_M > \alpha_A > 1$, $\alpha_M$ and $\alpha_A$ are arbitrary real numbers, and $N_{SM}$ and $N_{SA}$ are the number of source positions in the mountainous and easily accessible areas, respectively. The penalty function $P$ will increase faster (i.e., decrease the modified configuration-goodness $G'$) by increasing the number of sources in the mountainous region than by increasing them in more accessible areas. Therefore, to maximize the modified configuration goodness, the number of easily accessible source positions should be maximized relative to the more difficult ones.

For realistic survey design problems, a very large number of possible source-receiver configurations exist, so efficient statistical approaches (e.g., genetic algorithms) are required to find the optimum configuration.

I conclude that in areas characterized by large obstacles and steep slopes, where the land-streamer system may not be employed, statistical experimental design procedures may represent an alternative method for improving the efficiency of 3D seismic data acquisition.
Table 5.1: Potential advantages and disadvantages of positioning systems for high-resolution seismic reflection surveying

<table>
<thead>
<tr>
<th>Positioning System</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Measuring Tape     | • Cost-effective  
                     • Robust       | • Inaccurate over large distances (cumulative errors)  
                     • Supplies only relative coordinates  
                     • No topographic information  
                     • Impractical for 3D surveys  
                     • Not well suited for automatic procedures |
| Standard Laser Theodolite | • Very high accuracy in x, y and z (cm range) | • Supplies only relative coordinates  
                                          • Not well suited for automatic procedures |
| Laser-Tracking Theodolite | • Very high accuracy in x, y and z (cm range)  
                                • Provides real-time coordinates (~10 measurements/sec) | • Relative coordinates  
                                • Prism and theodolite require visible contact (may be problematic over large distances in rugged terrain)  
                                • Positioning of two locations (front and tail of streamer) simultaneously requires two theodolite systems |
| Differential GPS    | • High accuracy in x, y and z (cm range) after post-processing  
                     • Supplies absolute coordinates | • Relatively high price  
                     • Requires large “upward visibility” for continuous contact with required minimum of 5 moving satellites (may not be practical in regions surrounded by high trees or high buildings)  
                     • In real-time mode, provides only 2 positions / min with an accuracy of half a meter (may be insufficient for navigating efficiently) |
Figure 5.1: Sketch showing principal elements of towed land-streamer with semi-automated positioning systems: (a) self-tracking theodolite; (b) differential global positioning system (DGPS).
Chapter 5

Initial setup

Input:  - Initial geometry
       - Initial mute functions
       - Initial stacking velocities

Storage of raw data and positioning information

Standard single-trace processing

Apply and update mute functions

CMP Sort

Velocity Analysis

NMO Correction

Stack traces to existing data in bins

Positioning of source and streamer tail and update geometry

Acquire source gather

Repeat source position

Display stacked CMP traces

Figure 5.2: Proposed scheme for real-time processing of shallow seismic reflection data recorded with the towed land-streamer system.
Figure 5.3: Potential survey design problem that may be solved using a standard statistical experimental approach.

Figure 5.4: Simplified example of the experimental design approach. Region represents a small portion of survey area shown in Figure 5.3. It is divided in 10x8 CMP bins. Dark gray and white zones represent areas of highest and lowest interest, respectively. They are assigned different weighting factors. Data space contains all possible source and receiver locations and is marked with dense grid. Stars, triangles and circles mark shot and receiver positions and associated CMP locations, respectively.
Figure 5.5: Example where variance is used as measure for goodness $G_A$ of azimuth distribution. Crosses indicate number of traces in specific azimuth range. (a) Uniform distribution of azimuths. (b) Irregular distribution of azimuths. Small and large variances correspond to good and poor azimuth distributions, respectively.
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For the evaluation of seismic sources (Chapter 3), GGA-Institute of Joint Geoscientific Research (Germany) kindly provided their recently developed vibrator system. I thank Hermann Buness for the cooperation and his colleagues Sigfried Grüneberg and Günther Druivenga for field assistance. The land-streamer system was developed in cooperation with a commercial company (Sensor NL. BV, The Netherlands). The expertise of Peter Maxwell and Diederik Schrijvers was of great help. I thank Peter Wild for the technical support and Roman Spitzer for his contributions to the 3D computer simulations using the land-streamer system (Chapter 4).

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En tenslotte nog mijn ouders, Siska en Yvonne, want dat wat to vanzelfsprekend lijkt mag niet onuitgesproken blijven: bedankt voor alle steun en hulp die ik heb mogen ontvangen, op wat voor een manier dan ook. In het bijzonder Yvonne voor haar ondersteuning. Ze was er gewoon, altijd. Ik hoop dat ik binnenkort een proefschrift van jouw in mijn handen heb.

Ik draag dit proefschrift op aan Siska en Yvonne.

“Mensen Bedankt”

Michiel van der Veen
Zürich, November, 1999
**CURRICULUM VITAE**

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1977-1985  Primary education, Den-Helder, the Netherlands.

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*Expanded Abstracts*

van der Veen, M., Wild, P., Spitzer, R., and Green, A.G., 1999, Design characteristics of a seismic land streamer for shallow data acquisition: 61st Annual Meeting of the European Association of Geoscientists and Engineers (EAGE), Helsinki (Finland).


van der Veen, M., Brouwer, J., and Helbig, K., 1996, The Interaction of vibratory sources with the ground: Exp. Abst., 58th Annual Meeting of the European Association of Geoscientists and Engineers (EAGE), Amsterdam (the Netherlands).
A.1 Introduction

This appendix provides brief descriptions of most of the energy sources employed in shallow seismic experiments today. Some are often used, whereas other sources are rarely used. All information is based on literature and/or company brochures. The expected applicability is given for different depth ranges: very shallow (<50 m), shallow (50-150 m), and intermediate (>150 m).

A.2 Impulsive Sources

Air Gun

Source type: shothole/surface
Principle: chamber is filled with high pressure air. Sudden release of air results in a pulse. Source may be used in water filled borehole or water filled vessels at the surface
Depth range: very shallow to deep
Advantages: high repetition rate
Disadvantages: need for air chambers;
Literature: McCann et al. (1985); Doll et al. (1998)
Appendix A

Explosives
Source type: shothole
Principle: detonating explosive charges
Depth range: shallow - intermediate
Advantages: depending on charge size high frequency; energetic
Disadvantages: relatively expensive;
labor intensive;
environmental problems
Literature: Miller et al. (1986, 1992, 1994); Herbst et al. (1998)

Mini Sosie
Source type: surface
Principle: earth tamper hits surface resulting in random impulse series
Depth range: shallow - intermediate
Advantages: high repetition rate;
relatively inexpensive
Disadvantages: operational noise;
correlation required
Literature: Mair and Green (1981); Green and Mair (1983);
Knapp and Steeples (1986b); Doll et al. (1998)

Piezo Electric
Source type: surface
Principle: piezoceramic transducer generates high-voltage discharge impulse
Depth range: very shallow - shallow
Advantages: high frequency
Disadvantages: power supply awkward
very small source (i.e., low energy);
Literature: Miller et al. (1986)
Pipegun / Buffalo gun

Source type: shothole
Principle: detonation of blank cartridges in a shallow shothole
Depth range: shallow - intermediate
Advantages: portable; energetic depending on shells used; robust
Disadvantages: drilling shotholes is labor intensive
Literature: Pullan and MacAulay (1985, 1987); Miller et al. (1986, 1992, 1994, 1996); Doll et al. (1998); Herbst et al. (1998); Wiederhold et al. (1998); van der Veen et al. (1999b).

Sledgehammer

Source type: surface
Principle: sledgehammer hits a metal baseplate
Depth range: very shallow - intermediate
Advantages: high frequency depending on surface condition; efficient field handling; inexpensive
Disadvantages: relatively strong airwave; limited energy output
Literature: Miller et al. (1986, 1992, 1994); Keiswetter and Steeples (1995); Büker et al. (1998a); Doll et al. (1998); Herbst et al. (1998); van der Veen et al. (1999b)

Sparker

Source type: shothole
Principle: discharge of a capacitor bank results in a spark between an electrode and a metal casing
Depth range: very shallow - shallow
Advantages: high frequency; repetitive signals
Disadvantages: power supply awkward; need for saltwater-filled hole/container
Literature: McCann et al. (1985); Miller et al. (1986)
Weightdrop Systems

Source type: surface
Principle: a weight is artificially accelerated toward the ground
Depth range: shallow - intermediate
Advantages: high repetition rate; energetic
Disadvantages: heavy; operational noise; generation of relatively strong airwaves
Literature: Miller et al. (1986, 1992, 1994); Doll et al. (1998); Ghose et al. (1998); Herbst et al. (1998); van der Veen et al. (1999b)

A.3 Vibratory Sources

Acoustic Speaker

Source type: surface
Principle: acoustic signals are generated with a speaker system
Depth range: very shallow
Advantages: very high frequency; bandwidth control; high repetition rate
Disadvantages: correlation required; ground coupling; relatively strong airwaves; low energy
Literature: Herbst et al. (1998)

GGA Vibrator

Source type: surface
Principle: hydraulically driven vibrator system. Synthetic pilot sweep is used as reference signal for correlation
Frequency range: 16-500 Hz
Depth Range: shallow - intermediate
Advantages: high-Frequency; energetic
Disadvantages: correlation/deconvolution required; reference signals for correlation not consistently accurate; problems in rugged terrains
Literature: Buness et al. (1997); van der Veen et al. (1999b)
IVI Vibrator

Source type: surface
Principle: hydraulically driven vibrator system. System may be mounted on a trailer. Commonly water filled tanks are used as hold down weight.

Frequency range: 15-550 Hz
Depth range: shallow - intermediate
Advantages: can be set up to generate either P- or S-waves; high-frequency; energetic

Disadvantages: correlation/deconvolution required; problems in rugged terrains

Literature: Miller et al. (1996); Doll et al. (1998)

OYO Vibrator

Source type: surface
Principle: electro-magnetic driven vibrator. System is controlled by a PC. Accelerometers mounted on base plate and reaction mass can be used to reconstruct reference signals.

Frequency range: 25-1500 Hz
Depth range: very shallow - shallow
Advantages: portable; bandwidth control; high frequency; recording of accurate ground force signal

Disadvantages: correlation/deconvolution required; limited energy; power supply awkward

Literature: Nijhof (1989); Doll et al. (1998); Ghose et al. (1998); Herbst et al. (1998); Van der Veen et al. (1999b)

Y-1100 A Vibrator

Source type: surface
Principle: hydraulically driven vibrator system.
Frequency range: 10-100 Hz
Depth range: intermediate
Advantages: energetic

Disadvantages: correlation/deconvolution required; large weight of 18.000 kg; low frequency

Literature: Doll et al. (1998).
In chapter 4, the field effort of the land-streamer system was compared with that of traditional approaches (Figure 4.3). These evaluations were completed for the two example profiles I and II in Table 4.1. The first profile was aimed at obtaining very high-resolution data with 1 m source and 1 m receiver spacing, whereas the second profile consisted of fewer shot points and 2 m source and 2 m receiver spacing. Since acquisition times depended strongly on the type of source used (e.g., surface versus downhole), evaluations were made for recordings with the commonly used sledgehammer and pipegun.

Detailed estimates of the field effort needed for recording the 480 m long CMP sections are given in Table B.1. In general, line preparation and deployment and retrieval of geophones and cables are the most time consuming aspects of traditional surveys. Using a pipegun increases significantly the required field effort. For an efficient shallow seismic survey on land, a field crew of 5-6 is needed: one person operating the recording equipment, two persons managing the seismic source, two geophone/cable layers and, if necessary, one person handling the auger. For a comparable land-streamer survey, only three to four field personnel are required: as for the traditional survey, but the operator doubles as the driver of the towing vehicle and the geophone/cable layers are not required.
<table>
<thead>
<tr>
<th>Example Profile I</th>
<th>Seismic Source</th>
<th>Line Preparation</th>
<th># Cable Repositionings</th>
<th>Total Repositioning Time</th>
<th>Total Shot Time</th>
<th>Shot Hole Preparation</th>
<th>Line Clean-Up</th>
<th>Field Personnel</th>
<th>Total Time</th>
<th>Total Person-Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>48-fold 0.5 m CMP spacing</td>
<td>'Leap-Frog' Acquisition</td>
<td>Sledgehammer Pipegun</td>
<td>~2 hrs</td>
<td>15</td>
<td>~11.25 hrs (1.33/hr)</td>
<td>~8 hrs (60/hr)</td>
<td>---</td>
<td>~1.5 hrs</td>
<td>5</td>
<td>~23 hrs</td>
</tr>
<tr>
<td></td>
<td>Land Streamer</td>
<td>Sledgehammer Pipegun</td>
<td>~0.75 hrs</td>
<td>384</td>
<td>~1 hr (360/hr)</td>
<td>~8 hrs (60/hr)</td>
<td>---</td>
<td>~0.75 hrs</td>
<td>3</td>
<td>~10.5 hrs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Example Profile II</th>
<th>Seismic Source</th>
<th>Line Preparation</th>
<th># Cable Repositionings</th>
<th>Total Repositioning Time</th>
<th>Total Shot Time</th>
<th>Shot Hole Preparation</th>
<th>Line Clean-Up</th>
<th>Field Personnel</th>
<th>Total Time</th>
<th>Total Person-Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-fold 1 m CMP spacing</td>
<td>'Leap-Frog' Acquisition</td>
<td>Sledgehammer Pipegun</td>
<td>~1.5 hrs</td>
<td>7</td>
<td>~5.25 hrs (1.33/hr)</td>
<td>~4 hrs (60/hr)</td>
<td>~1 hr</td>
<td>5</td>
<td>~12 hrs</td>
<td>~60 hrs</td>
</tr>
<tr>
<td></td>
<td>Land Streamer</td>
<td>Sledgehammer Pipegun</td>
<td>~0.5 hrs</td>
<td>192</td>
<td>~0.5 hrs (360/hr)</td>
<td>~4 hrs (60/hr)</td>
<td>~0.5 hrs</td>
<td>3</td>
<td>~5.5 hrs</td>
<td>~16.5 hrs</td>
</tr>
</tbody>
</table>

Table B.1: Field effort for acquiring 480 m long seismic reflection profiles with (i) land-streamer system and (ii) conventional technique using end-on geometry with leap-frog roll-along scheme (Table 4.1). Estimates are based on field experience.
In chapter 4, land-streamer configurations with non-uniform receiver geometries were introduced. Deploying such streamers would reduce the costs of the land-streamer system and the weight to be pulled. By adapting short receiver intervals at near offsets and longer intervals at far offsets, shallow reflections could be identified and mapped faithfully, and reliable velocity functions could be determined over the entire depth range. Consequences of these non-uniform receiver configurations were variations in subsurface coverage and source-receiver offsets for adjacent bins (Figure 4.5). Here, I explain briefly the origin of these effects and show their implication on the streamer geometries used in Chapter 4.

Simple land-streamer geometries displayed in a stacking diagram (Figure C.1) may be used to explain the occurrence of variations in subsurface coverage and source-receiver offsets. Eight successive source locations are shown for the following two receiver configurations: (i) uniform streamer - 8 geophones spaced at 1 m intervals, and (ii) non-uniform streamer - 8 geophones with the first 4 spaced at 1 m intervals and the remaining at 2 m intervals. Two typical adjacent CMP locations are marked with solid and dashed vertical lines in Figure C.1. The uniform streamer provides a CMP spacing of 0.5 m with a regular subsurface coverage of 4. For the non-uniform streamer in Figure C.1b, the CMP spacing continues to be 0.5 m, but alternating CMP bins have subsurface coverages of 2 (solid line) and 6 (dashed line). The alternating CMP’s resulting from the non-uniform geometries contain traces from different source-receiver offset ranges. For example, the 2-fold CMP gathers (solid line) provide offsets of 2 m and 4 m, whereas the higher fold CMP locations (dashed line) include traces with offsets ranging from 1 to 11 m.

The subsurface coverage and source-receiver offset distributions provided by the land-streamer geometries discussed in Chapter 4 (Figure C.2) are illustrated in Figures C.3 and C.4. Uniform geometry yields a CMP spacing of 0.5 m with a nominal fold of 48 (Figure C.3a and C.3b). This configurations supplies CMP’s with regular source-receiver offset distributions (Figure C.3c). Minimum and maximum offsets are
1 and 95, and 2 and 96 m in alternating CMP gathers. For the non-uniform streamer, the CMP spacing continues to be 0.5 m, whereas subsurface coverage is highly irregular (Figure C.4a). Detailed views of CMP positions 250-255 m demonstrate that alternating CMP bins have subsurface coverages of 12 and 48 (Figure C.4b). Corresponding maximum source-receiver offsets are 24 and 96 m for the low- and high-fold bins, respectively.

Although non-uniform streamer geometries may be adapted to reduce the costs and weight of the land-streamer system without a significant loss of data quality (Chapter 4), the following important aspects have to be considered:

- only CMP gathers with long source-receiver offsets should be used for velocity analyses (e.g., CMP locations 251.5, 252.5, 253.5 m in Figure C.4b, etc.);
- the presence of numerous traces with short offsets (i.e., <24 m) on all CMP gathers will result in shallow images comparable to data recorded with uniform streamers;
- compared to data sets recorded with uniform streamers, the lack of long offsets on alternating CMP gathers will result in marginally lower image quality in the deeper part of the non-uniform streamer data sets.
Figure C.1: Surface diagram of simple 8-channel land-streamer geometries: (a) uniform streamer with 8 receivers at 1 m intervals; (b) non-uniform streamer with the first 4 receivers spaced at 1 m and the remaining at 2 m intervals. Triangles and stars mark receivers and sources respectively. Solid/dashed lines indicate CMP positions and subsurface fold of adjacent bins.
Figure C.2: Streamer acquisition geometries used in Chapter 4. (a) Uniform streamer comprising 96 receivers at 1 m intervals. (b) Non-uniform streamer with 24 near offset traces at 1 m intervals and the furthest 36 receivers at 2 m intervals. Minimum and maximum source-receiver offsets for both geometries were 1 and 96 m, respectively.
Figure C.3: (a) Subsurface fold for all CMP locations along profile resulting from acquisition with uniform land-streamer configuration in Figure C.2a. Survey consists of 262 source positions. (b) Details of subsurface fold at CMP locations 250-255 m. (c) Source-receiver offset distribution for identical CMP locations in (b).
Figure C.4: As for Figure C.3, but for acquisition with non-uniform streamer in Figure C.2b.
Figure D.1: Schematic and technical details of the gimbal-mounted geophone.

<table>
<thead>
<tr>
<th><strong>Gimbal Geophone Unit</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>45 mm</td>
</tr>
<tr>
<td>Length</td>
<td>185 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>1000 g</td>
</tr>
</tbody>
</table>
| Manufacturer                      | Sensor NL BV  
Rouwkooplaan 8  
2251 AP Voorschoten  
Netherlands  
tel. 31-71-561 39 41 |

<table>
<thead>
<tr>
<th><strong>SM-7 Velocity Sensor</strong></th>
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<tbody>
<tr>
<td>Natural Frequency</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Typical Spurious frequency</td>
<td>&gt; 500 Hz</td>
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<tr>
<td>Open circuit damping for 375 ohm coil</td>
<td>0.65 Ohm</td>
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<tr>
<td>Standard resistance</td>
<td>370 Ohm</td>
</tr>
<tr>
<td>Sensitivity with 375 ohm coil</td>
<td>12.8 V/m/s</td>
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<tr>
<td>Diameter</td>
<td>25 mm</td>
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<td>Weight</td>
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<tr>
<td>Cable Length</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-40 to 100 deg. C</td>
</tr>
<tr>
<td>Guarantee with normal use</td>
<td>2 yrs</td>
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**Figure D.2:** Technical details towed land-streamer system

<table>
<thead>
<tr>
<th><strong>Lead-In Cable</strong> - connects recorder to active part of the line</th>
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<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Number of modules</strong></td>
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<td><strong>Length</strong></td>
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<table>
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<tr>
<th><strong>Seismic CMP Cable - 12 m</strong></th>
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<td><strong>Description</strong></td>
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<td><strong>Takeouts</strong></td>
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<tr>
<td><strong>Number of modules</strong></td>
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<table>
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<th><strong>Seismic CMP Cable - 24 m</strong></th>
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<td><strong>Description</strong></td>
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<td><strong>Takeouts</strong></td>
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<tr>
<td><strong>Number of modules</strong></td>
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<table>
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<tr>
<th><strong>Other Components</strong></th>
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<tbody>
<tr>
<td>12 Spool pieces</td>
</tr>
<tr>
<td>4 Wrenches</td>
</tr>
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**Manufacturer**

Sensor NL BV
Rouwkooplaan 8
2251 AP Voorschoten
Netherlands
tel. 31-71-561 39 41
Contact Person: Mr. Diederik Schrijvers
**Figure D.3:** Technical details additional components towed land-streamer system

<table>
<thead>
<tr>
<th>Rubber mat: 13 m$^{(1)}$ &amp; 25 m$^{(2)}$</th>
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<td></td>
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<td><strong>Description</strong></td>
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<td></td>
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<tr>
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<tr>
<td><strong>Size (2)</strong></td>
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<tr>
<td><strong>Artikel nr.</strong></td>
</tr>
<tr>
<td><strong>Description</strong></td>
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<td><strong>Klemmbereich</strong></td>
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Figure D.4: Cable assembly drawing Lead-in cable (25 m).

<table>
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<th>TOTAL</th>
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<tr>
<td>BC-1371-4</td>
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<tr>
<td>B-2168-2-750-1</td>
<td>CONN., TITAN II 204 MARINE, 750 HANDLE, RED NUT</td>
<td>1</td>
<td>5.00</td>
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<tr>
<td>B-4299-375-4</td>
<td>CONN., 22/55S LINE, 375 HANDLE (BLK)</td>
<td>4</td>
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<td>A-4118-4</td>
<td>OVERMOLD, &quot;Y&quot; MOLD</td>
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<td>.75</td>
<td></td>
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<tr>
<td>RM-1226</td>
<td>TUBING, PU, 3/8&quot;X5/8&quot;</td>
<td>6'-7&quot;</td>
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<td></td>
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<tr>
<td>RM-0881</td>
<td>TUBING, PU, 1/4&quot;X3/8&quot;</td>
<td>13'-2&quot;</td>
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REVISIONS

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<td>A</td>
<td>2/1/99</td>
<td>LC</td>
<td>ECN #902025</td>
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SHT 1 OF 4
NOTES:
1. ACCUMULATIVE TOLERANCE NOT TO EXCEED +6°/-0°
2. SS-171 CABLE PREP
3. SS-187 KEVLAR TERMINATION
4. SS-218 TAPING OF TITAN MARINE BOOT
5. SS-247 "Y" MOLD PROCEDURES
6. SS-355 22/55S CONN TERMINATION
7. SS-187 CABLE MEASUREMENTS
8. SEE S/0 FOR CUST NAME FOR ID LABEL
9. WOLOED ID LABEL 3-0" FROM "A" END
10. SHRINK TUBE ID LABEL 1-0" FROM 22/55S CONN
    WITH CONN# AND CHANNELS
11. ES-177 FOR PRODUCT IDENTIFICATION

CABLE LAYOUT

+/- .003

CABLE LAYOUT

+/- .002
Figure D.5: Cable assembly drawing CMP cable (12 m)
**NOTES:**
1. ACCUMULATIVE TOLERANCE NOT TO EXCEED 6'-0"/-0"
2. SS-171 CABLE PREP
3. SS-187 KEVLAR TERMINATION
4. SS-218 TAPING OF TITAN MARINE BOOT
5. SS-638 TAKEOUT TERMINATION
6. ES-177 CABLE MEASUREMENTS
7. ES-177 PRODUCT IDENTIFICATION

---

**TOLERANCES**
- INPUT/OUTPUT, INC.
- CABLE LAYOUT
- SCALE: 1/4" = 1'0"
- REV: 4 of 4
- DATE: 5/6/91
- APPROVED 05/03/91
- DATE RECORDED: 05/03/91
- K-77564
- REVISION: 4 of 4

**S.CAMPBELL**
- ISSUED BY
- DRAWN BY
Figure D.6: Cable assembly drawing CMP cable (24 m)
APPENDIX E

IMPROVEMENTS IN HIGH-RESOLUTION SEISMIC AND GEORADAR ACQUISITION TECHNIQUES

MICHEL VAN DER VEE, FRANK LEHMANN, PETER WILD AND ALAN G. GREEN
PUBLISHED IN:

E.1 Introduction

High-resolution reflection seismic and georadar techniques are powerful tools for investigating the shallow subsurface. These two techniques frequently complement each other; at locations where the depth penetration of georadar signals is severely limited due to geological conditions (e.g., the presence of electrically conductive clay), good quality reflection seismic data may often be recorded, and vice versa.

During the past few years, the advantages of three-dimensional (3D) over traditional two-dimensional (2D) strategies in high-resolution seismic and georadar surveying have been convincingly demonstrated (Beres et al., 1995; Grasmück and Green, 1996; Grasmück, 1996; Lanz et al., 1996). Although three-dimensional approaches increase significantly the potential of these two techniques, they require a much greater field acquisition and processing effort. A principal goal of the Seismic and Radar Automation Project, which was initiated recently at the ETH-Zürich, is to improve data acquisition efficiency while maintaining data quality. As a result of these improvements, it is anticipated that the costs of 3-D seismic and georadar surveys will decrease markedly. Here, two key aspects of the project will be considered: (i) ground coupling of gimballed
geophones for use in land seismic surveys, and (ii) fast and accurate integration of new topographic surveying techniques with georadar acquisition systems.

E.2 Innovations in High-Resolution Seismic Acquisition Techniques

One significant disadvantage of traditional seismic acquisition techniques is the labour-intensive and time-consuming planting of an ever increasing number of geophones. To address this issue, the concept of a snow streamer, which has successfully been employed in snow covered areas (Eiken, 1989), is being adapted for high-resolution reflection seismic surveying on land. Ground motion will be measured with closely spaced 30 Hz gimballed geophones contained within the land streamer. A major problem associated with geophones not attached firmly to the ground is coupling, which is of particular importance when high-frequency seismic data is to be collected. To ensure adequate resolution, signals with frequencies up to 500 Hz have to be recorded with a minimum of distortion.

A typical result from one of our coupling experiments is illustrated in Figure E.1; the response of a 30 Hz gimbaled geophone is compared to that of a standard 30 Hz spiked geophone. Sensors in the two types of casing were identical. The gimbaled geophone was mounted in a relatively heavy cylinder and placed in a small ditch alongside the planted spiked geophone. Minor differences in the geophone responses may be due to very local variations in near-surface conditions and differences in electro-mechanical characteristics of the individual sensors, but these are likely to be small compared to the effects of ground coupling. The results in Figure E.1 indicate that the gimbaled and the conventionally planted geophones have similar characteristics over the frequency range of interest.
Figure E.1: Results of ground coupling comparisons between 30-Hz spiked and 30-Hz gimballed geophones. Figure (a) shows two typical traces. Figure (b) displays the equivalent amplitude spectrum of the two traces. Figure (c) shows the phase difference between the response of the two geophones.

### E.3 Innovations in Georadar Acquisition Techniques

Typically, surface positioning information for 3D georadar surveys is acquired using either semi-automated measuring wheels, or measuring tapes and field pegs. Elevation data are usually interpolated over many positions. Employing such procedures may result in significant systematic positioning errors of up to 10-20 cm. Furthermore, laying out survey lines and conducting a 3D topographic survey may account for 40 to 60% of the total time required for a georadar field campaign.

To overcome these shortcomings, we have integrated an automated laser tracking theodolite with a georadar acquisition system. Using our new approach, a 3D georadar data set covering a 20 x 20 m² area may be collected within a few hours. A full Cartesian coordinate set for each trace is recorded in real-time with an accuracy of better than ~5 cm (measured at walking speed).

Figure E.2 shows the measured positions for a survey conducted with 100 MHz antennae. The density of in-line coordinates is much greater (2-5 cm between each point) than that of the cross-lines (approximately 25 cm). To take advantage of standard multi-trace processing routines, such as FK-filtering and migration, the entire data set has to be interpolated on to an equally spaced grid. For this purpose, we have developed an interpolation scheme that involves calculating both the convex hull and two-dimensional Fourier transform of the positioning data. (Smith and Wessel, 1990; Edelsbrunner, 1987).
After interpolation and other minor pre-processing steps, the data set is ready for sophisticated processing using a wide variety of software packages.

**Figure E.2:** Coordinates of the collected traces, projected on a horizontal plane. (The insert shows close-up detail.)

### E.4 Conclusions

New developments introduced here include the use of a land streamer comprising gimballed geophones for high-resolution seismic surveying and the integration of an automated laser tracking theodolite with a georadar acquisition system. Our experiments suggest that the ground coupling of gimballed geophones allows seismic signals containing frequencies up to 500 Hz to be faithfully registered. With the theodolite and associated interpolation software it is now possible to record georadar data and the respective spatial coordinates (accuracy better than ~5 cm) simultaneously in real-time, thus reducing the turn-around time required to yield reliable 3D images of the shallow subsurface. With these new developments and future enhancements, 3D high-resolution seismic and georadar surveys will become faster, more accurate and less expensive for a wide variety of engineering and environmental investigations.
Appendix F

High-Frequency Sources in Shallow Seismic Experiments

Michiel van der Veen, Hermann Buness, Frank Nitsche, Frank Büker, Frank Lehmann and Alan G. Green

Published in:

Abstract

We have compared the energy, frequency, and noise characteristics of six high-frequency seismic sources: a 12-gauge pipegun, the Seismic Impulse Source System (SISSY), a 5-kg sledgehammer, an accelerated weight dropper, a vibrator from GGA, and a commercial (OYO) vibrator. Seismic measurements were undertaken in the Reuss Delta (central Switzerland), which is characterized by shallow reflection energy arriving at ~50-200 ms, and the Suhre Valley (Northern Switzerland), which is dominated by reflection arrivals from ~20-200 ms. Both shotgun sources have similar signal and field handling characteristics and are suitable for imaging reflections from ultra-shallow to intermediate depths. A sledgehammer generates less energy, but is relatively rich in higher frequencies. It is therefore best used to image ultra-shallow reflections. The accelerated weight dropper generates a strong airwave that may mask early time reflection information, making it more suitable for shallow to intermediate depth reflection surveying. Both vibratory sources have the advantage of controlled bandwidth, determining to some extent the penetration. The penetration depth and resolution of the GGA vibrator is comparable to that obtained from shotgun. However, the relatively strong airwave suggests it is best used to image shallow to intermediate reflections.
F.1 Introduction

High-resolution seismic reflection methods are widely used to image a variety of geological structures (e.g., Doornenbal and Helbig, 1983; Miller and Steeples, 1991; Green et al., 1995). An important component of these non-invasive imaging techniques is the seismic energy source. To complement innovative rapid data acquisition techniques, such as the land streamer (van der Veen and Green, 1998), a need exists for a fast and versatile energy source. Many impulsive seismic sources have already been tested and compared (e.g., Miller et al., 1994), but comparable investigations have yet to be performed for vibratory sources. We have tested several seismic sources, including two vibratory sources, to determine their suitability for recording ultra-shallow (<50 ms) to intermediate (<700 ms) reflected energy. The following sources were studied: a 12-gauge pipegun, the Seismic Impulse Source System (SISSY) developed by the Geological Survey of Lower Saxony (GGA, Germany), a 5 kg sledgehammer, an accelerated weight dropper, a vibrator constructed by GGA, and the portable OYO vibrator.

F.2 Survey Areas

All experiments were conducted in the Reuss Delta (Central Switzerland) and the Suhre Valley (Northern Switzerland) (Figure F.1). The Reuss Delta has experienced a complex history of tectonism and multiple glaciations. On the basis of previous seismic reflection surveys (van der Veen et al., 1998), it is known that reflected energy up to 700 ms may be recorded. A 300 m deep borehole approximately 2 km south of the survey area shows saturated gravels and sands occur just below the surface humus layer. In this test area, the principle goal is to resolve geological structures at shallow (~50 ms) to intermediate (~700 ms) depths.

The glaciated Suhre Valley (Northern Switzerland) has been the location of extensive 2D and 3D high-resolution seismic reflection surveys (Büker et al. 1998a, 1998b). At this location, the near-surface geology is dominated by glacio-lacustrine clay/silt sequences, reworked till (mostly sands and gravels), and underlying Molasse sedimentary rocks at depths ranging from 32 to 56 m. Clays and silts occur just below the surface humus layer. The main goal in this area is to image the ultra shallow (<50 ms) to shallow (~200 ms) geological structures.

F.3 Source Description

The 12-gauge pipegun consists of a metal pipe in which blank cartridges are detonated. It can be used in holes up to ~2 m deep. A piezo electric sensor triggers the seismograph. The main advantages of this design are flexibility in the field, robustness and relatively low purchase and maintenance costs.

Similar in principle to the pipegun is the Seismic Impact Source System (SISSY) developed by GGA (Germany). "Dynergit" cartridges are detonated electronically, thus...
providing an accurate trigger pulse. The maximum shot depth is ~1.3 m. The main advantages are flexibility in the field and accurate shot time reproducibility.

The weight dropper consists of a truck-mounted mechanism in which a heavy mass is artificially accelerated to hit the ground. This allows a large amount of energy to be generated. The main advantages are its robustness and relative low costs.

OYO Center of Applied Geoscience (OYO-CAG, the Netherlands) in cooperation with Utrecht University (the Netherlands) has developed a portable high frequency vibrator (Nijhof, 1989). The 65-kg hand-portable vibrator generates a maximum peak force of 500 N, and according to the manufacturer specifications, it can operate in the frequency range from 25-1500 Hz. The high frequencies make it suitable for imaging ultra-shallow to shallow geological structures. The main advantages of this source are portability and the possibility to control the seismic signal (bandwidth and to some extent penetration).

GGA (Germany) has also developed a high-frequency vibrator (Buness et al. 1997). In contrast to the OYO vibrator, it is capable of generating a peak force of ~31000 N. The 2600 kg truck-mounted vibrator can operate in the frequency range from 10-500 Hz. A key advantage of this system is the large amount of energy it can generate and the ability to control the seismic signal (bandwidth and to some extent penetration). One disadvantage is limited mobility in areas with difficult access or substantial topographic relief.

F.4 Comparison

We have recorded a high-fold seismic reflection profile in one or both of the survey areas, with each type of source. For comparison purposes we only show a selection of some shot records. Geophone spacing for records in Figures F.2 and F.3 was 1.5 m, and 1.0 m for Figure F.4. Figure F.2 shows unprocessed Reuss Delta shot records (trace normalized) generated by the pipegun (Figure F.2a, F.2b), the SISSY shotgun (Figure F.2c, F.2d), and sledgehammer with vertical stack of 10 (Figure F.2e, F.2f). On all records, clear reflected energy can be identified at depths of ~100 to 300 ms. Corresponding amplitude spectra show a concentration of energy around 30-60 Hz, although the signal is well above the noise level up to ~250 Hz. The pipegun and the SISSY shot records are quite similar. At very early times, relatively strong airwaves mask some of the reflection energy on the sledgehammer record (Figure F.2e). The corresponding amplitude spectrum (Figure F.2f) shows lower amplitudes in the entire frequency range.

Figures F.2 and F.2 show shot records recorded at two different locations in the Suhre Valley, where the principle goal is to resolve ultra-shallow reflections arriving before 50-100 ms. The Figure shows the shot records and corresponding amplitude spectra generated by the pipegun (Figure F.3a, F.3b), the sledgehammer (Figure F.3c, F.3d) and the accelerated weight dropper (Figure F.3e, F.3f). To focus on the shallow reflections and to suppress the dominant guided phases, the shot records are processed using spiking deconvolution and subsequent time variant spectral whitening. All records show clear
reflections at depths ranging from 30-70 ms. The quality of all records is comparable. Different are the relative strong airwaves in the records generated with the pipegun (Figure F.3a) and accelerated weight dropper (Figure F.3d). Corresponding amplitude spectra show that the pipegun (Figure F.3b) and sledgehammer (Figure F.3d) generate stronger high-frequency energy than the accelerated weight dropper (Figure F.3f).

Figure F.4 shows processed Suhre Valley shot records generated by the pipegun (Figure F.4a) and the GGA vibrator (Figure F.4b). We used a 10 s sweep signal ranging from 70 to 300 Hz. The pipegun shot record was subjected to a band pass filter to match the frequencies of the vibrator sweep signal. Both records have been subjected to time variant spectral whitening (70-300 Hz). The two records contain very high-frequency and ultra-shallow to shallow reflection information and are very comparable. The stronger airwaves in the GGA vibrator shot record (Figure F.4b) may mask the ultra-shallow, short offset reflected energy. An overview of the test results is given in table 1.

F.5 Conclusion

Several high-fold seismic reflection profiles have been recorded using a variety of seismic sources. The 12-gauge pipegun produces acceptable results in all profiles, providing an energetic signal containing frequencies up to ~250-350 Hz. Shotgun sources are therefore suitable for imaging ultra-shallow to intermediate reflections. A disadvantage of these sources is its relatively labor intensive field operations. The signal and handling characteristics of the SISSY shot gun are comparable to the pipegun. The sledgehammer generates less energy, but produces frequencies as high as ~300-350 Hz. This makes it an excellent energy source for mapping ultra-shallow to shallow reflections. The weight dropper generates high energy, but the relatively strong airwaves may disturb ultra-shallow reflected energy. It is suitable for resolving shallow reflections. The GGA vibrator is comparable to the pipegun in generating broad bandwidth signals. The relative strong air waves may mask the ultra-shallow reflection events. This system is suitable for mapping shallow to intermediate reflections. The main disadvantage of truck mounted systems is the mobility in terrain's with severe topography. The main advantage is the saving of field personnel and the increase in acquisition speed.

Figure F.1: The two survey areas in Switzerland. Data recorded in the Reuss Delta is characterized by shallow-(50-200 ms) to intermediate (200-700 ms) reflective energy, whereas the Suhre Valley data shows ultra-shallow (<50 ms) to shallow reflections.
Figure F.2: Comparison of the (a) pipegun (shot record), (b) pipegun (amplitude spectrum), (c) SISSY shotgun (shot record), (d) SISSY shot record (amplitude spectrum), (e) sledgehammer, with a vertical stack of 10 (shot record) and (f) sledgehammer (amplitude spectrum). The data is recorded in the Reuss-delta (Central Switzerland) with a geophone separation of 1.5 m. The shot records have not been processed and are trace normalized.
Figure F.3: Comparison of (a) pipegun (shot record), (b) pipegun (amplitude spectrum), (c) sledgehammer (shot record), (d) sledgehammer (amplitude spectrum), (e) accelerated weight drop (shot record) and (f) accelerated weight drop (amplitude spectrum). The data is recorded in the Suhre Valley (Northern Switzerland) with a geophone separation of 1.5 m. Shot records have been processed using spiking deconvolution and time variant spectral whitening, focussing on the very shallow reflection events (< 100 ms).
Figure F.4: Source comparison in the Suhre Valley (central Switzerland) with a geophone separation of 1.0 m; (a) pipegun, displayed with a band pass filter from 70-300 Hz, and (b) GGA Vibrator with a 10 s sweep from 70 to 300 Hz. Both records are processed using time-variant spectral whitening with corner frequencies of 70 and 300 Hz.
Abstract
Geotechnical and geophysical techniques have been combined to determine the elastic parameters of a series of lacustrine clays at a location where series of highway underpasses are to be constructed. Piezocone penetrometer and triaxial tests on borehole core samples allowed variations of the soil structure and the shear modulus $\mu$ over a range of larger strains to be measured. The small-strain behavior of $\mu$ was established from seismic measurements. Extremely low $\mu$ values of less than 50 MPa and Poisson's ratios near 0.5 for small strains were found. Together with experience gained from the first construction phase, these results will be used to optimize the design of construction process.

G.1 Introduction
In the framework of a highway underpass construction project in northern Switzerland, a variety of seismic and geotechnical experiments have been conducted. The principal objective of the investigations was to determine the elastic properties of a series of lacustrine clays within the 0-28 m depth range. Of particular interest was the...
behavior of the shear modulus \(\mu\) at small strains, which is required for optimized construction of the underpass side-walls.

Geotechnical measurements (e.g., using standard triaxial testing of undisturbed borehole samples) provide estimates of the shear modulus. Such estimates are only derived from specific points in the subsurface and they may suffer from significant inaccuracies in the small-strain domain (\(\varepsilon < 10^{-3}\)). In contrast, seismic measurements sample large subsurface volumes and provide reliable estimates of \(\mu\) as \(\varepsilon\) tends to zero. These latter estimates are determined indirectly via measurements of travel-times and measured or assumed density distributions. We demonstrate that combined applications of geotechnical and geophysical techniques can benefit the design process by supplying improved information on the relevant soil stiffness.

We had access to a 28 m deep borehole in the highway underpass area (Figure G.2e). Core samples were tested under triaxial stress conditions in a geotechnical laboratory. Adjacent to the borehole, piezocone penetrometer testing was used to delineate vertical changes of the soil strata. Small-strain estimates of the elastic parameters were obtained from a seismic surface-to-borehole transmission experiment.

G.2 Geotechnical Measurements

Results from the piezocone penetrometer tests are depicted in Figure G.2d. They show fluctuations with depth of the total pressure at the tip \((q_T)\). Highly variable values between 14 and 25 m depth indicate changes of soil properties. Triaxial testing of lacustrine clay samples collected between 5 and 15 m depth allowed the shear modulus to be determined for a range of strains between \(4 \times 10^{-5}\) and \(10^{-1}\). As shown in Figure G.2, \(\mu\) values for \(\varepsilon \leq 10^{-3}\) were highly scattered (note that \(\mu\) values were normalized by the overloading pressure \((p_u)\) to compensate for the different sample depths). This scatter was the result of inherent limitations of standard triaxial devices at small strains. Besides large fluctuations of \(\mu\) in the small-strain domain, we judge that the estimated \(\mu\) values are systematically too low due to bedding errors (i.e., effects of slight mis-orientations of the samples in the triaxial apparatus (e.g., Clayton et al., 1995).

G.3 Acquisition, Processing and Inversion of the Seismic Data

Seismic energy was excited at the surface along a 40 meter long profile that extended from the collar of the borehole. Seismic waves were recorded with a 3-component seismometer clamped to the borehole wall at various depths. Shot and receiver spacings were both 1 m. Since determination of shear modulus was the primary objective of the study, generation of sufficient shear-wave energy and 3-component recordings of the waveforms were essential.

A sketch of the seismic source is shown in Figure G.3. It consists of 3 solid steel plates welded together to give a rugged structure with a triangular cross-section. Spikes attached to the base plate ensure good coupling to the ground. Hammer blows on the left and right plates can be represented by force vectors. Addition of the two vectors yields a
vertical point source and seismic records dominated by P-wave energy, whereas subtraction of the vectors simulates a horizontal force and seismic records dominated by S-wave energy.

Component rotation was performed prior to the picking of the P- and S-wave onsets. As indicated in Figure G.3, the new coordinate system is oriented such that one component is perpendicular to the incident P-wavefront (normal component) and one component perpendicular to the plane of the shot profile (transverse component). Effects of the component rotations are illustrated in Figure G.4. Signals from the left and the right blows on the normal component seismograms should be almost identical, which is indeed the case (Figure G.4a). Addition of the two normal components (Figure G.4b) results in an improved signal-to-noise-ratio that simplifies picking of the first-arriving P-wave.

The transverse components (Figure G.4c) exhibit a polarity reversal for wave-trains between 75 and 100 ms. Such a reversal identifies this seismic phase as an SH-wave, which is expected to be perpendicularly polarized to the profile line. Note that later phases at about 100 ms are polarized in the direction of the profile-borehole plane. They are probably Rayleigh waves. Subtraction of the "left" and "right" transverse components (Figure G.4d) reveals the first arriving SH-wave train unambiguously.

A total of 962 P- and 397 S-wave onsets were picked from the recorded seismograms. They were inverted for P- and S-wave velocity-depth functions, which were parameterized as a stack of 15 layers with fixed thicknesses. This inversion problem is only weakly non-linear and can be solved with a damped linearized inversion scheme (e.g., Menke, 1989). A variety of markedly different initial models were employed to test the stability of the inversion. All inversions converged to the velocity-depth functions shown in Figures G.1a and G.1b.

Near-surface P-wave velocities (Figure G.1a) are about 1200 m/s. At a depth of 4 m the velocity increases to 1500 m/s. Velocities gradually increase to about 1700 m/s at 28 m depth. S-wave velocities (Figure G.1b) within the uppermost 8 m are approximately 150 m/s. Below 15 m depth they are in the range 250-300 m/s.

From the velocity-depth functions in Figures G.1a and G.1b very high Poisson’s ratios of 0.480 - 0.495 and extremely low shear modulus values μ of 45-150 MPa (Figure G.1c) were derived. Estimates of μ are based on a density of 1800 kg/m³, which was estimated from borehole samples.

**G.4 Interpretation**

Depth-dependent properties determined from the piezocone penetrometer (Figure G.1d) and seismic measurements (Figure G.1e) correlate well with the stratigraphic column derived from the borehole cores (Figure G.1e). The uppermost 15 m consist mainly of normally consolidated lacustrine clays. These sediments are expected to exhibit low $q_T$ and low μ values. Silty sands with gravely inclusions are found between 15 and 22 m. They show increased $q_T$ (Figure G.1d) and μ values (Figure G.1e).
Between 22 and 25 m the lacustrine clay units reappear, with an associated decrease of $q_T$. Unfortunately, the seismic data provide not enough resolution to resolve this rather thin clay layer. At about 25 m depth a moraine layer, which consists of coarse sands and gravel, is found.

Lacustrine clays between 3 and 15 m and 22 and 25 m depth are the critical units for highway underpass construction. Therefore, it is important to constrain their shear modulus over a large range of strains. As shown in Figure G.2, the triaxial measurements could only delineate the $\mu$ versus $\varepsilon$ relationship for $\varepsilon > 10^{-3}$. Including an average seismic shear modulus for the lacustrine clays (Figure G.1c) as $\varepsilon$ tends to zero allowed us to identify a range of possible $\mu$ versus $\varepsilon$ functions (dotted area in Figure G.2).

**G.5 Summary and Conclusions**

Using geotechnical and geophysical techniques, we have attempted to characterize elastic soil parameters in an area of a planned highway underpass construction. Analysis of piezocone penetrometer data, borehole cores and seismic transmission measurements revealed layers of lacustrine clays from 3 to 15 m and from 22 to 25 m depth. Triaxial testing with borehole samples and inversions of the seismic data yielded very low shear moduli of less than 50 MPa. Consequently, special efforts will be required to limit deformations of the underpass construction.

Integration of triaxial and seismic data was critical for estimating the behavior of the shear modulus over a range from small to large strains. Information obtained from the different methods is complementary. Since both measurements are straightforward and can be performed quickly, the proposed approach can be carried out in a cost-effective manner.

**Figure G.1:** (a) P-wave velocity-depth function. (b) S-wave velocity-depth function. (c) Shear modulus as derived from seismic measurements. (d) Total pressure at the tip ($q_T$) of the penetrometer device. (e) Geological profile from borehole cores.
Figure G.2: Strain-shear modulus relationship. Different symbols connected with thin lines represent the $\mu$ versus $\varepsilon$ relationships for individual borehole samples. Small-strain limit determined from seismic data is indicated by heavy solid line (mean) and two heavy dashed lines (standard deviation). Dotted area delimits the range where possible $\mu$ versus $\varepsilon$ functions are expected to lie.

Figure G.3: Schematic overview of seismic experiment. Expanded view shows the source, the force directions of the hammer blows ($F_L$ and $F_R$), and the resulting force vectors for added and subtracted signals.
Figure G.4: Examples of seismograms recorded at 10 m distance and 4 m depth. Panel (a) shows the normal-component seismograms from the “left” and “right” hammer blows (see Figure G.3), whereas (c) shows the equivalent transverse-component seismograms. Addition of the normal components in panel (a) are depicted in panel (b). Subtraction of the transverse components in panel (c) are shown in (d).