

# An overview of key developments in seismic reflection techniques for geotechnical applications

**Dr Rod Eddies**, technical director, Fugro Aperio

**R**eflection seismology, or seismic reflection, is a sophisticated and powerful method of geophysical investigation that has become a cornerstone of the hydrocarbon exploration industry and of earthquake investigation. The technique, which is used both onshore and offshore, enables imaging of geological stratigraphy and structure to depths of several kilometres, and has been fundamental to the mapping of much of the world's hydrocarbon reserves.

Arguably, seismic reflection is the geophysical technique that has been subject to the most research and commercial development effort over the past 90 years. Modern seismic surveys can measure multiple components of the seismic wavefield through thousands of receivers, and seismic data processing has become so specialised that processing specialists may develop expertise in processing either in time or depth.

Seismic reflection moved from depth versus distance profiles (2D) to area versus depth data blocks (3D) in the 1980s. Today, multi-component (multiple seismic wave types) and time-lapse (4D) investigations to monitor hydrocarbon extraction and CO<sub>2</sub> sequestration management are commonplace.

The need to investigate to greater depths for geotechnical applications is coupled with increasing subsurface information requirements associated with major infrastructure construction projects, such as bridges and dams, nuclear power and waste facilities, geothermal/groundwater exploration, carbon sequestration and natural gas storage.

The pace of change of development in seismic reflection for the shallow subsurface (<500m) for geotechnical and geological investigation has been somewhat more lethargic than in the oil and gas sector over the past few decades, reflecting the different levels of resourcing available between the hydrocarbon and geotechnical sectors.

However, over the past two decades there has been a significant

number of technical developments. The rapid improvement in computing power, plus more sensitive recording hardware, has meant that some of the approaches used in hydrocarbon work can be scaled for geotechnical applications. Powerful vibratory sources can be tuned to site conditions to optimise resolution and depth of penetration. Software is now available that can apply powerful data processing and enhancement algorithms – such as deconvolution and time and depth migration – to relatively shallow data.

One of the key challenges of the shallow subsurface is the presence of noise. Land seismic receivers (geophones) in general measure the velocity of ground motion when the ground is displaced by a seismic event. The same receivers will be sensitive to both ambient ground motion and airborne acoustic noise, and to ambient electrical fields, all of which may be found in abundance within industrial and urban sites.

Ground geophysics experts understand that the sites where clients wish to determine subsurface characteristics are not confined to quiet agricultural areas, but include more demanding, busy industrial or urban sites.

Of course, other geophysical methods are available, but most have pitfalls, to a greater or lesser degree, in busy environments, meaning that signal-to-noise levels may not be sufficient to extract meaningful information of geological or engineering significance, particularly at depths of more than 30m.

Seismic reflection involves generating a ground disturbance at, or near, the surface (see Figure 1). The disturbance propagates into the ground and, under certain circumstances, is reflected back to the surface for detection and subsequent recording. It undergoes modification through several processes on its journey, including frequency-dependent attenuation,

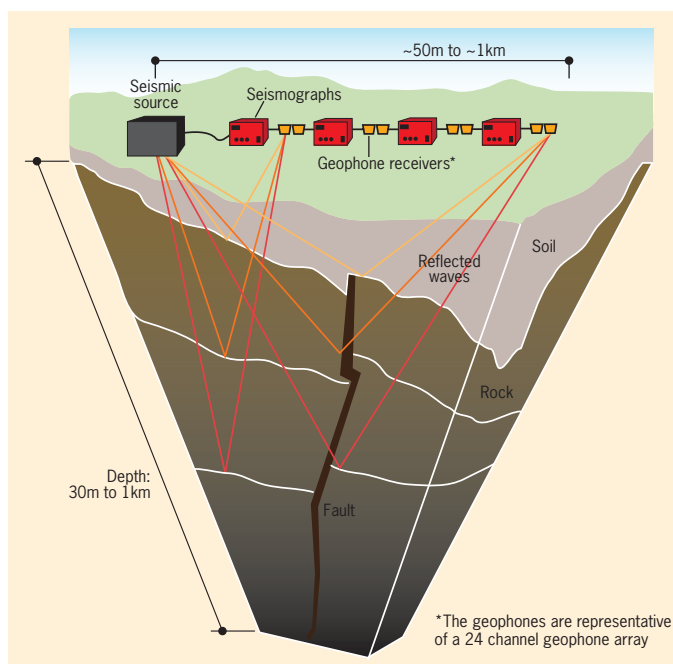
wavefront spreading, diffraction and reflection, all of which reduce the amplitude and frequency content of the transmitted signal. Seismic recording equipment has a very good dynamic range for such faint signals.

The propensity for the subsurface to reflect seismic waves generated at the surface is based upon the presence of boundaries across which there is a contrast in acoustic impedance (seismic velocity x density). The stronger the contrast, the stronger the reflectivity of the subsurface. In the context of the shallow subsurface, impedance contrasts are typically found at the base of weathering, at the top of the saturated zone and at lithological boundaries.

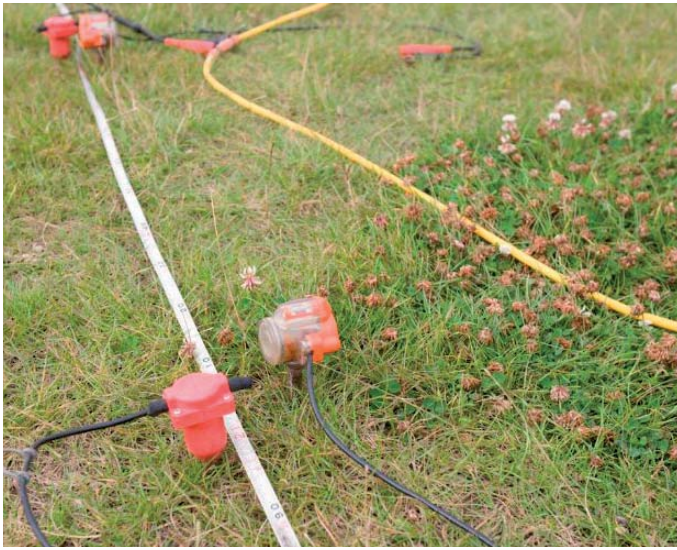
Seismic surveys need to be carefully planned to achieve maximum benefit at reasonable cost. Consideration needs to be given to the seismic source, particularly its power and frequency content. Like many other methods, such as ground penetrating radar (GPR), using high frequencies improves resolution but low frequencies may be required to achieve the desired depth penetration.

In general, shallow land seismic surveys deploy a single source but multiple receivers. Each receiver is a sensitive geophone or combined group of geophones (see Figure 2) that will send its incoming signal for recording to a digital seismograph. Careful positioning of source and receiver locations is critical to shallow investigation work – real-time kinematic (RTK) positioning systems are used to fix survey geometry to within 100mm.

Another key consideration is how many receivers to deploy (preferably in a straight line for 2D work, but not necessarily), and over what distance. To properly image deeper targets, the distance between seismic source and furthest receiver needs to be equivalent to at least the target depth. Hence imaging to 300m depth is not realistic within the confines of a tennis court. To image shallow targets, receiver intervals need to be kept small but this has a trade-off in terms of the number of receivers



**Figure 1: Seismic reflection involves generating a ground disturbance at or near the surface**



**Figure 2: Geophone receivers at the surface recording P-waves (left) and S-waves (right).**



**Figure 3: Higher power impulsive source (accelerated weight drop) on an industrial site.**

and associated recording channels required per line-km, labour costs and overall productivity.

Some survey design parameters can be considered from the comfort of the office but, arguably, the critical part of seismic survey design is a field trial of design parameters commonly known as a walkaway-noise test. This is an essential element of a phased investigation approach that manages technical and commercial risk for the client. At the start of a project, testing of different source-receiver configurations and recording parameters can make very significant improvements to both field logistics and to the final image of the subsurface.

The choice of seismic source is critical to land investigation. In the past, the use of explosive sources was commonplace, but developments in vibrating sources have made the use of seismic reflection in sensitive environments much more straightforward.

Some land sources are impulsive and create a pulse of a few milliseconds. These include accelerated weight drop instruments and explosive, pneumatic or electrical sources deployed in boreholes (see Figure 3). Other sources are swept-frequency, usually a plate coupled to the ground (vibroseis) that vibrates at a time-variant frequency, usually from low (5-15Hz) to high frequency (300-500Hz) over a period of five to 30 seconds (see Figures 4 and 5).

For vibroseis work, accelerometers measure the motion of the baseplate and reactive mass (downforce or input signal) mounted to the vehicle to enable the seismic signal to be extracted from the complex received signal, a process known as cross-correlation. Once a raw vibroseis record has been cross-correlated, the result looks very similar to a record acquired using an impulsive source, like an explosive charge (Figure 6 overleaf).



**Figure 4: A high frequency vibroseis seismic source capable of transmitting compressional and shear wave energy used for investigations down to 50-100m.**

Very shallow surveys (<50m depth) require sources to generate high frequencies in excess of 150Hz to resolve fine detail and, from a processing perspective, to discriminate refracted from shallow reflected energy. As the required depth of investigation increases, power and lower frequencies, below 75Hz, become important. Vibroseis trucks with several hundred kN of downforce are frequently used to image beyond 1km depth, but also have the resolving power (high frequencies and bandwidth) to determine near-surface structure (see Figure 5).

The timing of the source impulse is just as important as the source characteristics, in that errors in “time zero”, to which all seismic data are referenced, are problematic to correct following acquisition. The walkaway-noise test presents a good opportunity to confirm the proper function of the source trigger device, often a sensitive piezoelectric device attached to the source to record the moment of impact on the ground.

In seismic reflection investigation, the wave types that are of key interest are known as body waves – waves that behave in a predictable way through elastic wave theory and that propagate through the interior of solids. These waves are known as P and S, or compressional and shear, or primary and secondary waves.

One of the more unpredictable elements when undertaking land

seismic investigation is the presence of low frequency, unwanted energy known as “ground-roll”. When a disturbance is initiated close to the ground surface, only about a third of the energy will propagate as body waves and less than a tenth as compressional waves. The remainder will propagate as slowly decaying and slowly propagating surface waves (largely Rayleigh waves, a combination of P and vertically polarised S waves) with high amplitudes that may swamp the seismic record with unwanted signal (see Figure 7). This ground-roll, however, contains information about the stiffness of the subsurface, and is the key component for surface-wave methods that measure ground stiffness, including multichannel acquisition of surface waves (MASW), the continuous surface wave method (CSW) and the spectral analysis of surface waves (SASW) method.

The walkaway-noise test, which usually takes one to two days, can be used to characterise the ground-roll and design the survey geometry to minimise its effect. Quite often this can be achieved by offsetting the seismic source from the receiver array and/or adequately sampling the ground roll with sufficiently closely spaced receivers. Ambient seismic and electrical noise can also be assessed prior to full commitment to a major field investigation (see Figure 7). >>

# TECHNICAL NOTE

» Another source of unwanted, but highly predictable, noise is the air-wave produced by the seismic source that propagates in air at about 330m/s (Figure 7). Typically, this needs to be surgically removed from the data during data processing as it usually has a broad spectrum and is not easily removed by simple band-pass filtering, or it is removed by sophisticated algorithms that can filter events with specific velocity characteristics (called “frequency-wave number of FK” filtering). A further complication is the presence of refracted and guided waves from the base of, and within, the weathered layer (Figure 7). Again, these often need to be removed during processing.

It is generally accepted that one of the key challenges to investigating the very near surface is the ability to discriminate between earlier refracted arrivals and (slightly) later reflections (Figure 7). In general, refracted arrivals and guided waves that can propagate in near surface layers can mask shallow reflections.

Very short receiver intervals and high source frequencies can help to differentiate in this regard. The presence of shallow groundwater is helpful, as shot and receiver coupling to the ground may be enhanced. Water has a very high “Q” value, or quality factor, meaning that seismic energy propagates with little intrinsic attenuation, particularly at lower frequencies (helping whales to communicate).

It is widely known that the near surface will attenuate propagating signals much more rapidly given unsaturated, compressible conditions, and the top of the saturated zone may present a very strong reflective interface.

One of the key objectives when working in noisy environments is to generate sufficient signal relative to the various sources of ambient noise. During data acquisition, the source signal might be repeated a number of times (typically two to 15) to reinforce that part of the signal that is coherent, and reduce the part that is random. Surface seismic sources can produce repeatable noise that is not effectively cancelled by signal stacking and must be dealt with by more sophisticated techniques.

The combined attenuation and reflectivity characteristics of the ground (broadly called the “earth filtering effect”) may mean that very little signal gets to the target depth, and a lack of impedance contrast at depth may mean little or no reflected energy returns to the surface to be detected. In a recent investigation, an input spectrum of 10 to 250Hz yielded a received signal spectrum with an absence of significant



**Figure 5: Swept-frequency seismic source (vibroseis) used for seismic surveys from tens of metres to beyond 1km in depth.**

frequencies above 60Hz due to a highly attenuating near surface layer. Hence, seismic reflection, like other geophysical techniques, would not be recommended for certain sites or target types, highlighting the importance of the walkaway-noise test for sensible acquisition parameter design.

Another way to build signal at the expense of noise is embodied within one of the underlying principles of seismic reflection investigation: the common mid-point (CMP) concept. Subject to certain limitations of geometry and seismic velocity, we can identify a reflecting point in the subsurface that is halfway (in a lateral sense) between a source and receiver. In the case of a single source and receiver geophone located  $x$  metres away, the CMP will be located at  $x/2$  metres from the source in the subsurface. By moving both source and receiver outwards the same distance from the surface projection

of the CMP, and repeating the source, the reflecting point or CMP remains at the same location.

In survey designs, a system of source and receiver positions can be set up such that any specific point is sampled many times by different source-receiver geometries, the number of repeat samples being referred to as the “fold” of the data. Data processing can then significantly improve signal to noise levels by “stacking” all or some of the records sharing the same CMP.

Before acquiring several line-km of high resolution data for a site in 2008 and 2009, Fugro Aperio carried out extensive walkaway-noise testing at an industrial site characterised by very strong ambient ground motions and electrical noise, all within the frequency band of most suitable seismic sources. To achieve sufficient signal-to-noise, each source location required 10 to 15 repeated “shots”, and the

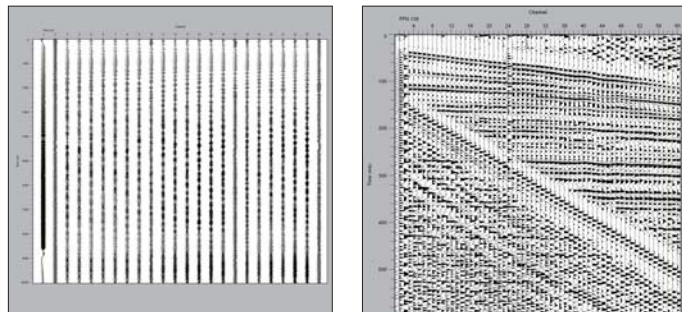
maximum number of separate source-receiver pairs for each CMP was 48 (fold), meaning that each reflecting point was frequently sampled more than 700 times.

Data from the site is shown in Figure 8, where faulting with vertical offsets of about 5m or less was successfully imaged at a depth greater than 150m. Maximum depth penetration was about 300m.

Significant spatial oversampling and fastidious walkaway-noise tests are key factors in the successful use of seismic reflection in noisy environments, and field quality control of raw records is essential. Following a shot or vibroseis sweep, the resulting signal can be displayed on a field PC as a series of seismic traces displayed channel-by-channel as a function of offset from the source (shot record). Noise, dead channels, reverse polarity cable sections and reflector presence can all be monitored during a seismic investigation to allow prompt corrective action where appropriate.

A further factor that has a significant influence on final data quality is the determination of those effects that are often not related to the target depth, but associated with near surface seismic velocity variations, known as static effects, or just “statics”. For example, the weathering layer is typically characterised by low velocity media of variable thickness. Lateral variations in weathering layer thickness can cause apparent “structure” on deeper reflections, because of the longer time required for seismic energy to propagate through a slow layer.

These effects can be drastically reduced by determining the near-surface velocity structure (refraction statics) as part of a reflection



**Figure 6: An uncorrelated vibroseis shot record representing the convolution of many different sinusoidal frequency components and the reflectivity of the subsurface (left). Each trace/channel represents the recorded signal at a single geophone. The raw vibroseis record is then processed by correlating channel 1 with the remaining channels. The result is a correlated vibroseis shot record – in this case, very high quality data showing a number of highly coherent reflectors to a depth of about 500m to the right of a very strong airwave event running from top left to bottom right (right).**

survey or through a separate seismic refraction survey. Similarly, differences in elevation between sources and receivers are accounted for by correcting to a fixed or floating datum (datum statics).

Having set the survey design parameters, a seismic reflection survey usually proceeds by setting out a large number of geophones (typically corresponding to <100 to >1,000 data channels) and then deploying the seismic source at fixed intervals. Typically, this might be 1-10m for shallow investigations.

Depending on the depth of interest and channel count, linear progress of 400m to greater than 1km a day is achievable. A single seismograph may record the incoming signals, but modern instrumentation is also available in modular form, managing up to 24 data channels per seismograph as part of a chain of data processors linked to a PC-based recording system.

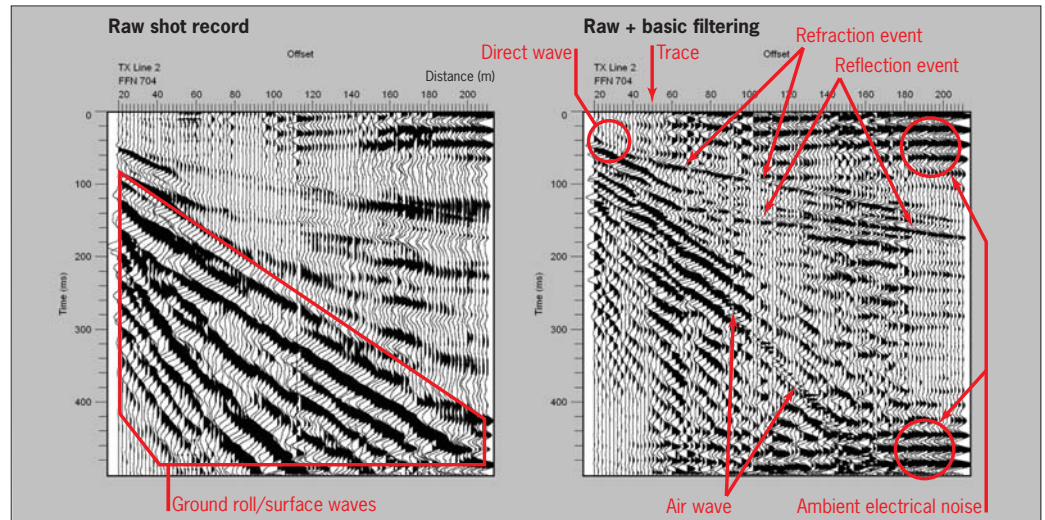
The signal received by the seismograph is recorded in digital format usually compliant with standards established in the hydrocarbon industry, such as SEG-2 and SEG-Y.

As with acquisition, data processing of shallow seismic data presents significant challenges, including proper recognition of refracted energy, correction of source output variation (shot coupling to the ground) and signal extraction from noise.

Modern processing software for shallow applications is largely scaled down from oil and gas applications, but the processing can be simplified to four key elements: signal deconvolution, velocity analysis, CMP stacking and migration.

Deconvolution is a mathematical process that attempts to improve the signal by making it sharper (spiking deconvolution) and to remove reverberations (predicted deconvolution) that may mask other features. The application of deconvolution may not be practical for shallow data in some circumstances because of changing source characteristics due to varying coupling conditions along a profile. Velocity analysis aims to derive the optimal distribution of velocity as a function of depth to improve the coherence of reflectors.

CMP stacking reduces the effects of uncorrelated noise, while the aim of migration is to improve the subsurface location of events expressed in the data to improve subsurface imaging. These elements are highly complex, but well understood by virtue of the R&D effort in the hydrocarbon exploration industry, and are used together to produce a final 2D



**Figure 7: A relatively raw shot record (left), and the same record with basic filtering applied to highlight the different seismic events within the record (right).**

seismic section (or 3D data block) that can be interpreted for geological or engineering significance (see Figure 8).

There are several key application areas where seismic reflection investigations are beneficial in the in the depth range from several tens of metres to more than 1km. For example, nuclear sites require detailed geological and geotechnical evaluation to meet IAEA guidelines; faulting that may undergo reactivation might represent a significant future risk to a nuclear facility.

Geotechnical investigations for large civil structures require structural and stratigraphic detail from significant depths. A well-executed geophysical investigation can target boreholes to maximise the efficacy and efficiency of a geotechnical investigation in a similar way to that in which offshore drilling locations are rationalised.

Relatively shallow CO<sub>2</sub> and natural gas storage requires

the determination of reservoir characteristics, including storage volume, spill points and sealing properties, which would benefit from knowledge of stratigraphy and structure determined by a seismic programme coupled with an optimised intrusive investigation.

In addition, major construction projects are not limited to seismically benign regions, so a seismic reflection investigation could form an integral part of a seismic risk evaluation.

The technical boundaries between offshore hydrocarbon exploration and onshore geotechnical and geological site investigation are becoming increasingly diffuse with the migration of expertise, acquisition hardware and processing algorithms into the shallow onshore environment. Inevitably, the value of the seismic information will drive the development of the technique for a particular application in a particular sector.

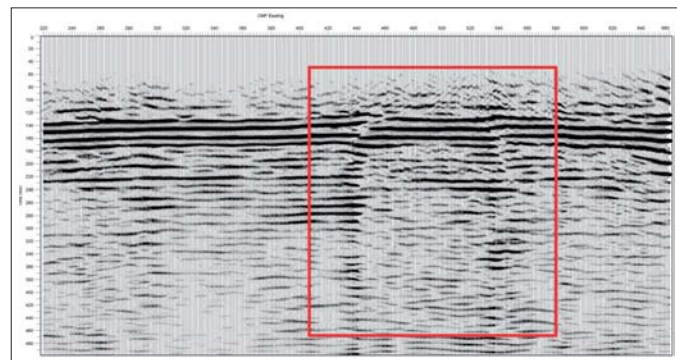
3D surveys are becoming more

commonplace for higher-value projects such as natural gas storage, carbon sequestration and seismic risk evaluation. Wireless, non-telemetric receiver technology, time synchronised by GPS satellites, may become more common, reducing the field effort associated with significant lengths and weight of cable. Channel count, as with land hydrocarbon exploration, is moving from hundreds to thousands. Increased data channels, combined P- and S-wave surveys, and the use of 2D/3D pre-acquisition modelling and post-acquisition wavefield imaging will place greater demands on processing power and algorithm efficiency. These may ultimately require clustered PC or Unix/Linux workstations rather than standalone workstations typically used for shallow work.

All of these capabilities are now available to the civil engineering industry from our colleagues in the oil and gas industry.

Good survey design with high fold and appropriate source power and bandwidth means it is possible to address the twin challenges of site-specific ambient noise and problematic variations in the seismic properties of the very shallow subsurface where our sources and receivers are physically deployed.

The seismic reflection method offers significant benefits in the geotechnical and geological characterisation of industrial and urban sites when we use all of the accrued knowledge of the past 90 years combined with the latest technical developments in acquisition and processing. Beyond a depth of about 30m, very few techniques can deliver the subsurface imaging capability of the seismic reflection technique.



**Figure 8: A final processed seismic section, where X-axis = distance, and Y-axis = (time) depth, showing a strong reflector from a limestone band at about 160m below ground surface and a fault block between approximate chainages 440m and 540m. Maximum depth of penetration was about 300m.**