Application of reflection seismology to foundation investigations at A5 Pont Melin Rûg, North Wales

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Abstract

A modern road bridge across the Afon Alwen is proposed to replace the existing A5 Pont Melin Rûg, a masonry arch structure built in 1792. However, progress on engineering design has been hampered by problematic ground conditions caused by a previously unrecorded, 40–50 m thick sequence of soft to very soft glaciolacustrine silts (Rûg Silts). The remarkable depth of the Rûg Silts and the need to locate a foundation stratum for the proposed new bridge prompted the application of geophysical techniques. A high-resolution seismic reflection survey was performed to image the subsurface conditions at the proposed bridge site to a depth of 100 m below ground level and provide a comprehensive understanding of the geological profile. The seismic survey successfully delineated the bottom of the Rûg Silts, identified a basal unit of very dense, heterogeneous glaciofluvial gravels and delimited bedrock of Silurian Nantglyn Flags. Subsequently, a single deep borehole confirmed the findings of the geophysical survey and importantly, the investigations proved a possible foundation horizon for the proposed new bridge at a depth of 45.80 m in the basal gravel unit. The seismology provided the largest and most continuous source of geological information across the site and consequently had the greatest influence on the deliberations on foundation selection and optimization. This case history illustrates the benefits of using reflection seismology in areas of complex glacial geology. It also demonstrates the benefits of geophysical investigations to geotechnical assessments of local ground conditions.

Keywords: case history, engineering properties, geophysics, highways, site investigation

Pont Melin Rûg is a strategically important road bridge over the Afon Alwen in upland North Wales. It lies some 2 km west of Corwen and National Grid Reference SJ 051436 applies (Fig. 1). Most highways through the steep terrain of the North Wales massif exploit rocky mountain corridors provided by river valleys. However, to the west of Corwen, the A5 and A494 trunk roads merge to form a single 2.2 km stretch of highway, including Pont Melin Rûg, that traverses an exceptional area of flat pasture land. This pastoral vale occupies a broad horizontal floodplain that forms a striking geomorphological feature in sharp contrast to the surrounding mountainous landscape (Fig. 2).

The bridge at Melin Rûg is narrow and humpbacked and the approaches feature sweeping curves and tight radii bends with poor forward visibility. In addition, awkward junction configurations on both sides of the bridge are accident cluster sites. Accordingly, a scheme is being considered to construct a new bridge and straighten the highway alignment. The preferred option involves an off-line improvement, some 30 m upstream of the existing bridge. However, it requires a substantially longer bridge in order to cross a wider stretch of the Afon Alwen at an oblique orientation.

Preliminary ground investigations at the proposed bridge site encountered a remarkable sequence of grey, soft to very soft silts (Rûg Silts) that proved doubtful for modern bridge foundation purposes. Moreover, boreholes failed to reach the base of the silts and so the deeper ground conditions remained uncertain and nothing was known about the rockhead geometry. Accordingly, a seismic survey was commissioned to gain a comprehensive understanding of the geological profile at the site and importantly, to search for a foundation stratum for the proposed new bridge.

This paper presents a practical case history of a high-resolution seismic reflection survey designed to investigate the problematic ground conditions. The geophysical fieldwork was undertaken during January 1999. The paper also describes the unusual glaciolacustrine sediments that were discovered during the engineering geology investigations and presents the first published record of Llyn Edeirnion, the glacial lake in which these deposits accumulated.

Historical background

According to the historic records, the Chester based architect Joseph Turner designed Pont Melin Rûg to replace an earlier bridge that had fallen into a state of disrepair. Work on the bridge started in 1790 and was substantially completed by late 1792. It is a three-span, segmental, circular masonry arch bridge with random masonry spandrels and wing walls (Fig. 3). The central arch spans 15.55 m and the side arches span 11.75 m. Width between parapets measures 6.3 m. Both

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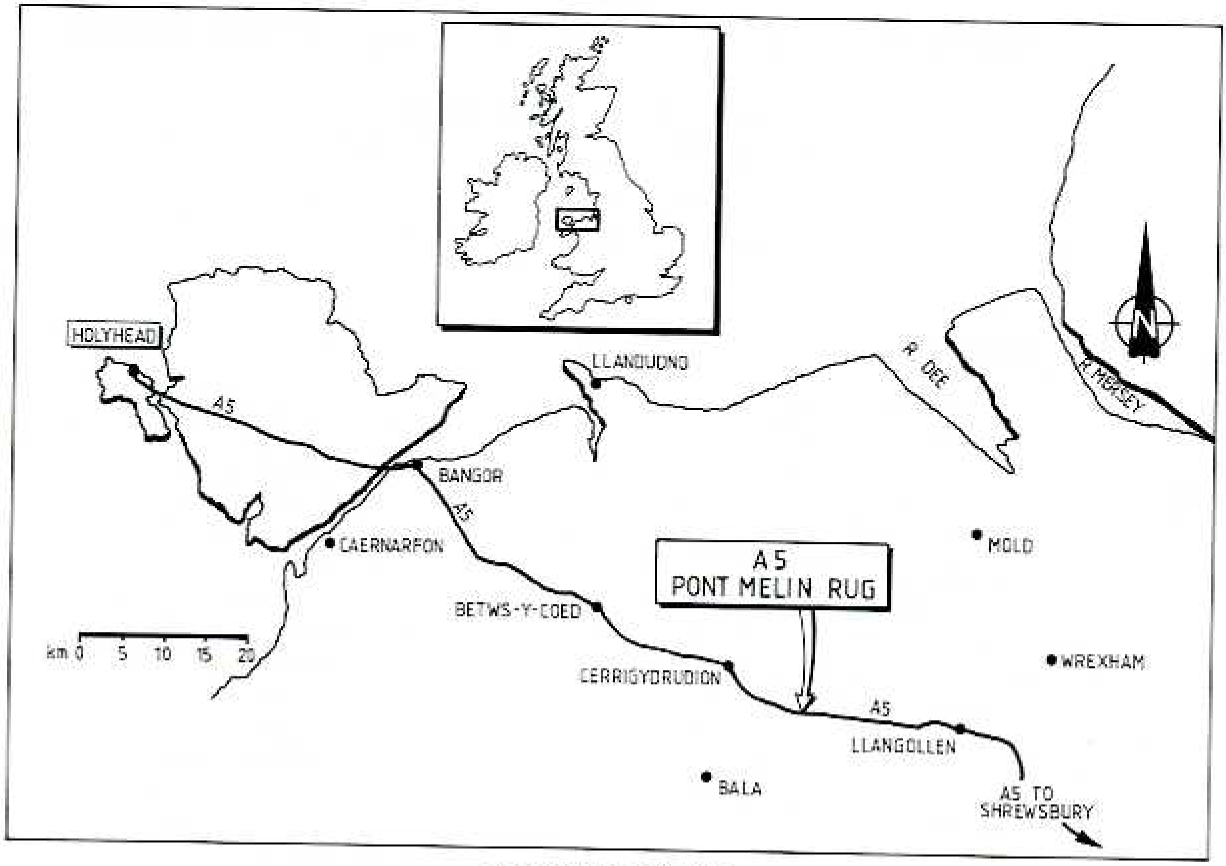

Fig. 1. Orientation map.

abutments and piers are thought to be founded on shallow alluvial gravels within the tract of the Afon Alwen.

The Act of Union between the two parliaments of Great Britain and Ireland in 1800 led to considerable increase in travel between London and Dublin. To ease the journey, the father of engineering, Thomas Telford was commissioned to design and construct the A5 Holyhead Road across Wales. Telford incorporated a host of innovative features in his road design but a prime objective was to enable stagecoach horses to easily and rapidly trot over the whole road at an average speed of 13 km/h. Around 1820, Telford developed his A5 route to the west of Corwen and incorporated the existing county-built bridge at Pont Melin Rûg into his road scheme.

Not surprisingly, Pont Melin Rûg is designated an Ancient Monument albeit with only a Grade II listing. It is widely acknowledged as a structure of considerable visual appeal and architectural significance. At the present time, traffic flow across the bridge averages almost 8000 vehicles per day.

Geological setting

The regional geology was described by Anonymous (1993) and Smith & George (1961) and Quaternary aspects were discussed by Campbell & Bowen (1989). In addition, Rowlands (1979) described glacial and geomorphic features in the area between Bala and Corwen to the SW of Melin Rûg.

Bedrock in this part of the Welsh Uplands comprises sedimentary strata of Lower Palaeozoic age. In the vicinity of Melin Rûg these consist predominantly of a monotonous sequence of siltstones and mudstones of the Nantglyn Flags of Silurian (Wenlock) age that generally dip at moderate angles southeastwards.

The landscape architecture of the district was created during the Pleistocene (Late Devensian) glaciation. The valleys of the Afon Alwen and the neighbouring Afon Dyfrdwy originated as U-shaped glacial troughs associated with tributary glaciers from the Meirionnydd Ice Cap. The floor of each glacial valley is deeply incised and overlain in places by heterogeneous glacial deposits. A drumlin field about 1 km SW of Melin Rûg features a series of drumlins oriented NE–SW that indicate an essentially northeastwards direction of former ice movement across the region. Elsewhere in the district, glacial sand and gravel deposits form hummocky features associated with kame and kettle topography and mixed glacial deposits locally drape the flanks of the valleys.

During deglaciation, meltwater from the decay of the Meirionnydd Ice Cap also flowed northeastwards and deposited glaciofluvial sands and gravels. The valley of the Afon Alwen provided one of a series of major meltwater escape routes associated with the ice-cap.

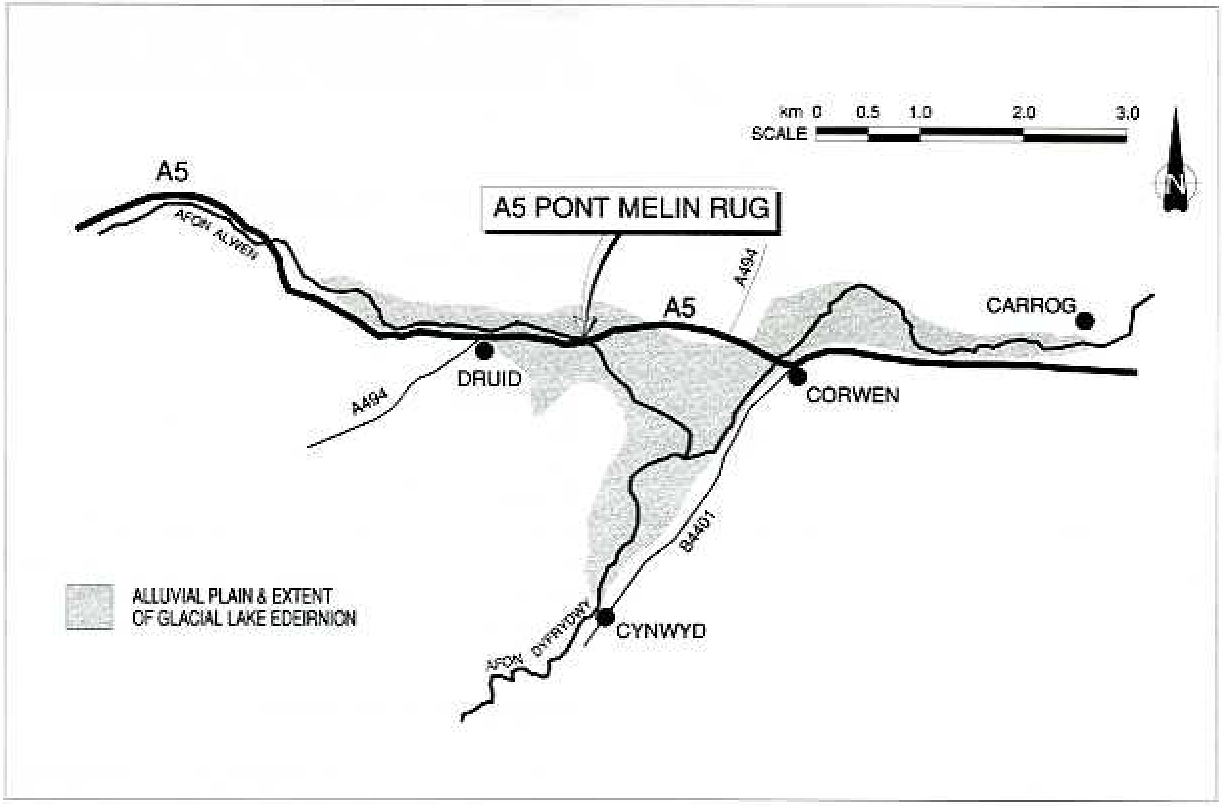

Fig. 2. The distribution of alluvial flats overlying Rûg Silts and the estimated extent of glacial Lake Edeirnion.

Fig. 3. View of Pont Melin Rûg.

Also during deglaciation, a glacial lake of large dimensions developed where the former ice streams of the valleys of the Afon Alwen and Afon Dyfrdwy were confluent. Borehole data around Corwen demonstrates that the glacial lake ("Llyn Edeirnion") occupied at least 10 km^2. Its surface extent probably coincided with the area of flat pastureland at elevation 130–140 m AOD that lies between Carrog, Corwen, Cynwyd and Druid (Fig. 2). Recent alluvium conceals the entire glacial lake basin and it will require specialized subsurface investigations to delineate its exact boundaries. The siltation of glacial Llyn Edeirnion produced the thick sequence of rhythmites referred to herein as the Rûg Silts.

Elsewhere in North Wales, Tinsley & Derbyshire (1976) have described a glacial lake at Llyn Peris and Seddon (1962) discussed lake deposits at Llyn Dwythwch and Nant Ffrancon. In addition, laminated clays have been reported by Warren *et al.* 1984 at Pont Glan y Wern in the Vale of Clwyd and at Dyto in the Conwy Valley. However, as far as can be determined, no previous record exists in the published literature of the impressive and remarkably uniform sequence of Rûg Silts that accumulated in glacial Llyn Edeirnion.

At Melin Rûg, the present day floor of the Alwen valley has a veneer of alluvium associated with the contemporary river drainage. A variable spread of silts, sands and gravels typically ranges up to several metres deep. *In-situ* rock and drift relationships are illustrated diagrammatically in Figure 4.

Rûg Silts

The Rûg Silts are soft to very soft, becoming firm with depth, grey, thinly laminated, clayey, slightly sandy SILT with numerous medium greyish brown, sandy partings and lenses, and occasional thin bands (1–5 mm thick) of soft, pale grey clay. The bedding in the laminated deposits is subhorizontal.

Moisture contents range from 15 to 36% with no particular relationship discernible between moisture content and depth. The material is almost invariably non-plastic and liquid limits range between 18 and 41. Particle size distribution falls predominantly within the

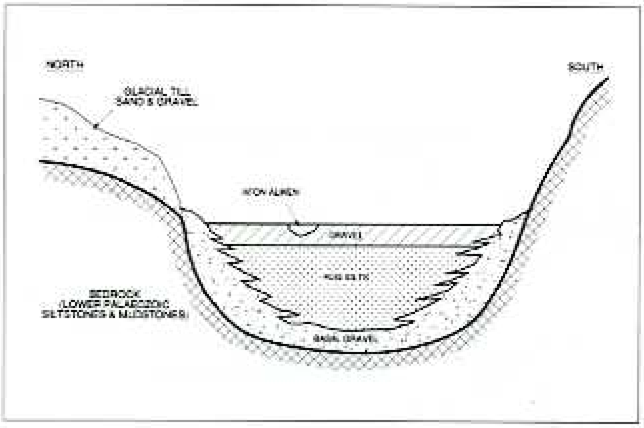

Fig. 4. Rock relationships diagram (not to scale).

Table 1. *Representative engineering properties of Rûg Silts.*

Property	Median value
Moisture content	25 %
Plasticity index (PI)	5
Liquid limit (LL)	30
Mean silt content	72 %
Mean clay content	24 %
Average bulk density	1.965 Mg/m^3
Typical 'N' value	4
Undrained cohesive strength (Cu)	50 kPa
Undrained shear strength (C)	15 kPa
Effective stress strength parameters	$c'=0$, $\varphi'=24°$
Coefficient of volume compressibility (m_v)	0.05 m^2/MN
Coefficient of consolidation (c_v)	100 m^2/y
Cone penetrometer resistance (qc)	1.80 MPa
Cone penetrometer, sleeve friction (fs)	0.05 MPa

fine sand to fine silt range with between 62 % and 100 % finer than 425 μm. In addition, weak trends exist of increasing clay content and decreasing fine sand content with depth. Salient engineering properties of the Rûg Silts are summarized in Table 1.

Dutch Cone Penetrometer testing of the Rûg Silts to depths approaching 40 m revealed a restricted range of variation of cone resistance and sleeve friction, with very low penetration resistance and low friction values throughout the whole thickness of material penetrated. Based on the penetrometer results, the allowable bearing capacity of the Rûg Silts is only 48 kPa.

The Rûg Silts are glaciolacustrine rhythmites predominantly of the diatactic type. The sediment consists of rhythmically bedded rock flour that settled from suspension within the impounded glacial Llyn Edeirnion. Individual laminae reflect changes in the grain size and quantity of sediment as a function of fluctuating water and sediment discharge cycles over time. Neither pollen analysis nor radiocarbon calibration are yet available for the Rûg Silts. However, the rock basin within which the thick sequence of silts accumulated was probably produced by glacial overdeepening during the Late Devensian. Importantly, the sequence of Rûg Silts is of considerable interest for studies on Late Quaternary history and provides a unique opportunity for research on past environmental changes.

Seismic reflection survey

Introduction

The findings of the preliminary borehole investigations demonstrated a need for deep exploration along the proposed construction corridor to search for a foundation stratum for the proposed new bridge. It was also considered prudent to obtain information about the geology to a depth of some 100 m below ground level prior to undertaking any further drilling. Various geophysical methods were considered and high-resolution reflection seismology was judged to be the most appropriate for the site conditions in this instance.

Principles of operation

Seismic reflection surveying requires three components: a seismic source to generate the initial seismic signal, a series of geophone stations at the ground surface to detect the arrival of the reflected seismic signals and a signal enhancement seismograph to control the survey and to record the data. The seismic waves generated travel through the ground and are reflected back from sub-horizontal interfaces at depth. For each shot fired, the seismic data measured by the geophones are recorded by the seismograph. By producing a sequence of shots fired from different positions and recorded over different spreads of geophones sufficient data can be acquired that can be processed to form a complete seismic section.

As the time at which the source was fired is known (recorded by the seismograph) the time it takes for the seismic waves to travel into the ground and then back to the surface to be detected by the geophones can be measured and stored on the seismograph. The reflected data detected at each geophone are measured as a function of travel-time and are displayed as a single trace. A panel of geophones will give rise to a sequence of traces.

Seismic reflection profiling requires specialized computer processing to correct the data for a series of geometric distortions and to improve the signal-to-noise ratio. The ultimate product from seismic reflection profiling is a stacked seismic section.

If the velocity for different horizons can be deduced (using complex velocity analysis computer routines) and the Two-Way Travel-Time (TWTT) for the seismic section is known (recorded by the field survey) then the travel-time information can be translated into depth

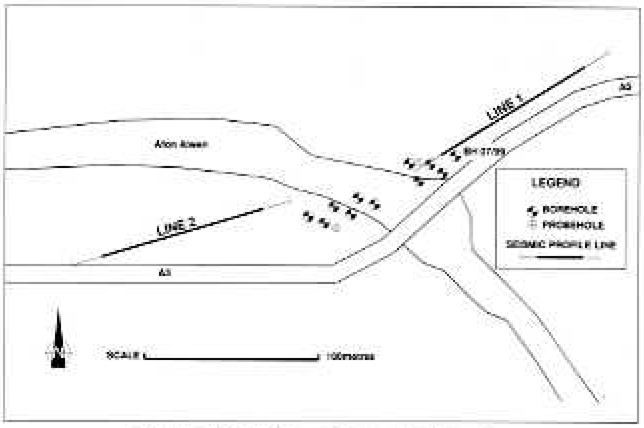

Fig. 5. Site plan and survey layout.

Fig. 6. Setting out Line 1. View looking westwards. Pont Melin Rûg on the left of the picture.

sections. Further information on reflection seismology is provided by King (1992) and Reynolds (1997).

Field techniques

The layout for the seismic reflection survey at Pont Melin Rûg comprised two seismic lines (Lines 1 & 2) each 75 m in length on either side of the Afon Alwen and as close as possible to the centre line of the proposed new route (Fig. 5). The Afon Alwen is a fast-flowing river and so seismic surveying was not continuous across the river partly for logistical reasons but also because of the high noise levels generated by the turbulent water flow conditions.

An ABEM Terraloc Mark 6, 24 channel, high-resolution seismograph was employed and a total of 48 geophones at 2 m intervals were used per spread (Fig. 6). The seismic energy source used to generate the sound waves consisted of a buffalo gun that fired blank 8 gauge cartridges vertically downwards at a depth of about 0.8 m in the ground. Seismograph triggering was initiated by contact closure between a hammer and the firing pin on the buffalo gun (Fig. 7).

The optimum offset configuration was deployed. Initially, the most appropriate horizontal offset distance between the seismic source and the geophone array was established that allowed the refracted arrival from the base of the alluvial overburden to be differentiated from the reflected arrival from the first principal geological interface at depth (Fig. 8). An optimum offset of 32 m was determined using a walkaway test. This involved firing a series of shots at different separation distances between the seismic source and the geophone group. The seismic record yielding the best quality data was selected by visual inspection.

Fig. 7. Triggering the buffalo gun seismic source.

For the main production survey, individual shots were fired at 2 m intervals along each line into an array of 24 geophones per shot. The short spacing of only 2 m ensured that the sound waves were effectively normally incident and so the effects of dip-moveout may be considered insignificant.

The optimum offset distance was maintained by addressing each set of geophones incrementing by one geophone interval each time using the rollalong switch box. This addressed 24 geophones out of the 48 connected to the system and simply allowed the selection to be done by the system operator instead of the physical relocation of the geophones after each shot. This process of 24-channels per shot and moving the spread along by one increment between shots facilitated collection of a considerable amount of data.

Data processing procedures

Each shot fired produced a shot record consisting of 24 traces with each trace corresponding to the signals recorded from each geophone on the spread.

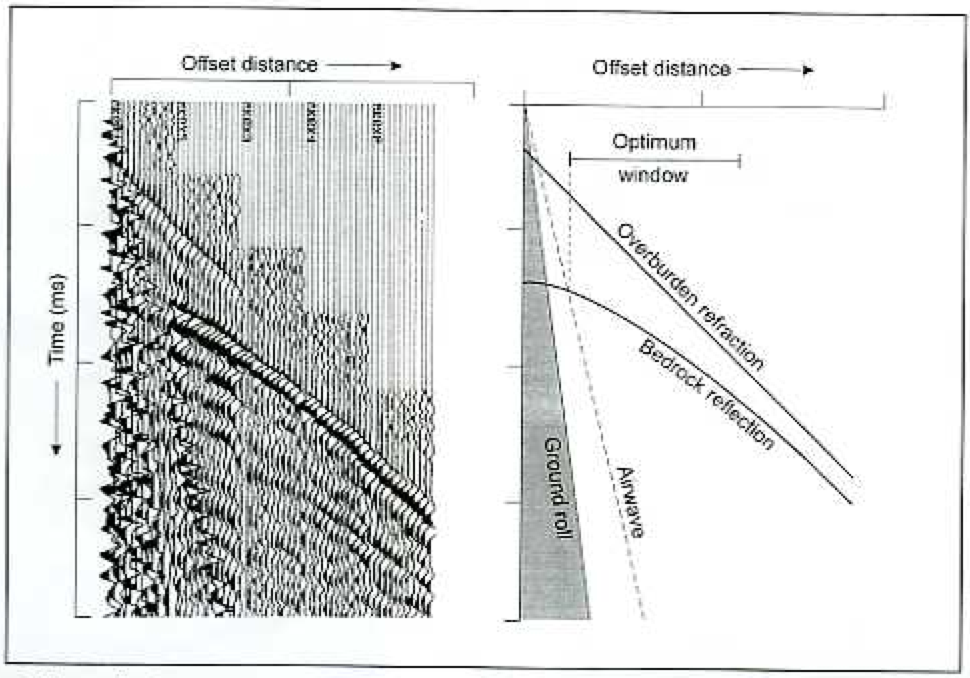

Fig. 8. Composite shallow reflection record (left) and corresponding time-distance graph (right) identifying the principal seismic events on the record (after Slaine *et al.* 1990).

Comparison of the seismic record (e.g. Fig. 9) with the model diagram (Fig. 8) allowed identification of the various components including the refracted arrival, the reflection events, and the airwave.

The data processing procedures convert the data from the shot record ray paths (Fig. 10a) to a Common Mid-Point gather (Fig. 10b). In the case of horizontal strata, the Common Mid-Point is equivalent to the

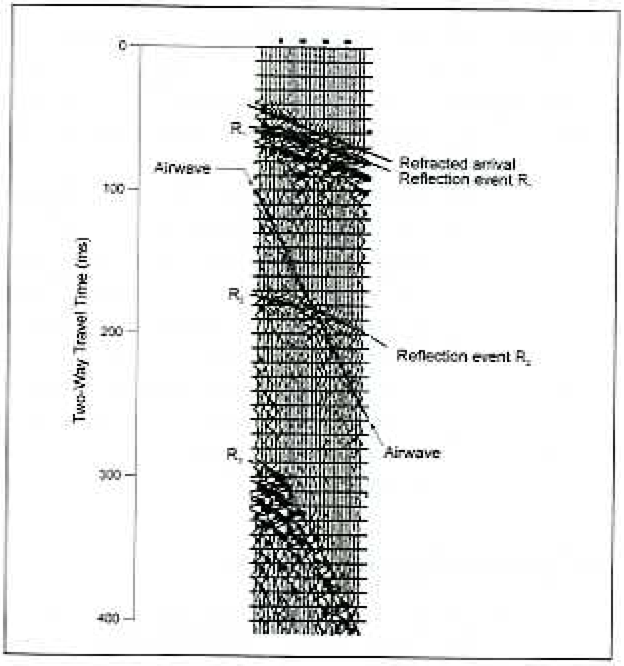

Fig. 9. Example of a shot record from Line 1.

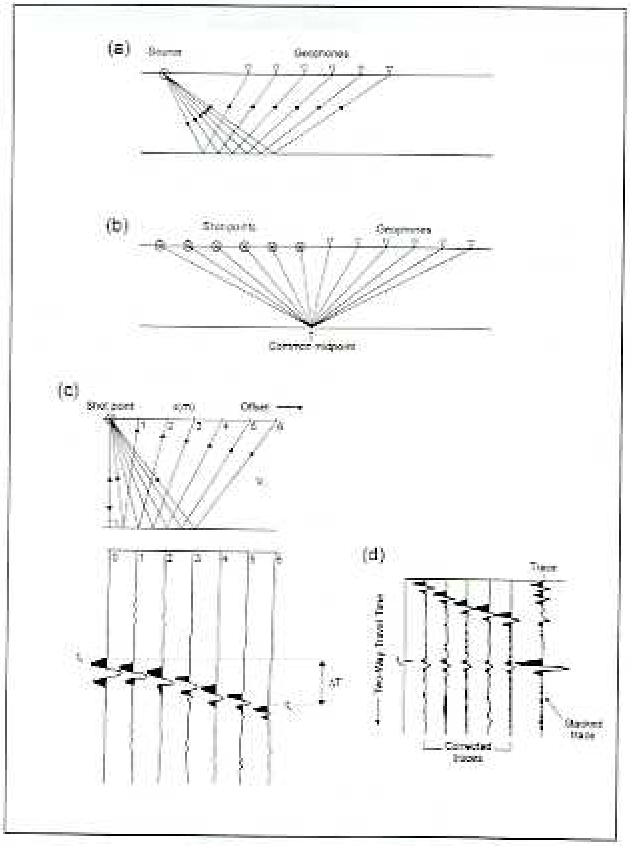

Fig. 10. (a) Shot record ray paths; (b) Common Mid (Depth) Point ray paths; (c) Normal Move-Out (NMO) geometry, ray paths and corresponding record; and (d) the NMO-corrected traces and the final stacked trace.

Common Depth Point (CDP) and always lies midway between the shot location and the geophone at which the data have been recorded. Having selected the source-receiver data from a sequence of shots for each CDP, a Normal Move-Out (NMO) gather is compiled (Fig. 10c). The Normal Move-Out correction requires the selection of an appropriate stacking velocity to correct for the time delay with increasing offset (Fig. 10c). Once the correct stacking velocity has been applied, the reflection events on each trace then line up at the same TWTT (Fig. 10d). The individual traces are then added together so that the coherent signals sum together to form a large signal whereas the incoherent noise tends to cancel itself out. Consequently, the signal-to-noise ratio is improved and the amplitudes of the coherent signals are increased by this process. From the NMO gather, one trace relating to a single CDP position is produced (Fig. 10d). This final stacked trace forms one of the many shown in the final stacked seismic section.

In addition to the above processes, the data were also enhanced by muting out dead traces from the shot records and filtering the data to reduce obvious noise and thereby creating the clearest patterns in the final stacked seismic section.

Results

Processing of the reflection data produced two stacked seismic sections (Lines 1 & 2) that were compared with the site investigation information (Fig. 11).

On both seismic sections the uppermost part of the sections appears transparent to seismic P-waves. This muted zone correlates with the laminated glaciolacustrine deposits of the Rûg Silts and the transparency indicates a high degree of homogeneity. The base of the Rûg Silts is designated R1.

The zone below R1 exhibits numerous strong reflectors. Well developed channelling patterns are discernible that have the appearance of infilled river channels. The unit is interpreted as dense to very dense, heterogeneous, glaciofluvial sands and gravels with some fine silt, clay and large boulders. The bottom of this unit, designated R2, corresponds to rockhead.

Line 1. Along Line 1, R1 ranges from TWTT of 50 ms in the east to 75 ms in the west. The basal gravel unit beneath the Rûg Silts (R1 to R2) is represented by a TWTT of about 40–50 ms. This basal gravel horizon comprises two parts: the western section contains a series of pronounced channel-like reflections and the eastern portion features prominent easterly dipping reflections of a more uniform character. These differences probably relate to variations in sedimentary facies associated with changes in the glaciofluvial regime.

Below R2, the monotonous bedrock sequence of Nantglyn Flags displays a generally featureless seismic signal.

Line 2. On Line 2, R1 ranges from TWTT of 78 ms in the east to 65 ms near the centre. The basal gravel unit beneath the Rûg Silts (R1 to R2) is represented by a TWTT of about 45–65 ms and comprises two parts: the majority of the unit contains a series of channel-like reflections similar to those in Line 1 but the western portion features a single deep channel structure infilled with layered deposits.

Below R2, a small number of discontinuous reflections in bedrock have extremely weak signatures.

Between Lines 1 & 2. Across the gap between Lines 1 and 2, R1 ranges from TWTT of 50 ms beneath the east bank of the river to TWTT of 78 ms beneath the west bank. Interpolating between the two seismic lines beneath the river suggests that the base of the Rûg Silts has a maximum depth equivalent to TWTT of 93 ms.

The basal gravel unit beneath the Rûg Silts (R1 to R2) is represented by a TWTT range of about 40–65 ms across the two seismic lines. Interpolating between the two seismic lines beneath the river suggests that the base of this unit has a maximum depth equivalent to TWTT of 134 ms.

Basal gravel unit. An appreciation of the thickness and continuity of the dense to very dense bands within the basal gravel unit are crucial for foundation engineering considerations and so detailed examinations were carried out on the seismographs for this horizon. Within the constraints on resolution inherent in seismic reflection surveying, certain observations appear apposite.

First, the seismic characteristics of the basal gravel unit are different for each line. Whereas on Line 1, the unit displays numerous, high amplitude, continuous reflections, on Line 2 it exhibits much more diffuse responses with disparate reflections (Fig. 12). In particular, the first main reflection on Line 1 appears comparatively sharp and distinct relative to that on Line 2. The strong events apparent on Line 1 as well as the subordinate areas of continuous high amplitude events that appear confined to the prominent channel feature on Line 2 are all probably associated with horizons of denser materials. The diffuse responses characteristic of Line 2 are taken to indicate greater heterogeneity and an upwards coarsening size distribution.

Secondly, lateral variations in reflection strength on Line 1 appear more pronounced than on Line 2. In addition, the seismic profile for Line 1 exhibits continuous high amplitude reflections that give way to complex, low amplitude events. These patterns comprise different responses to losses of energy and are probably due to

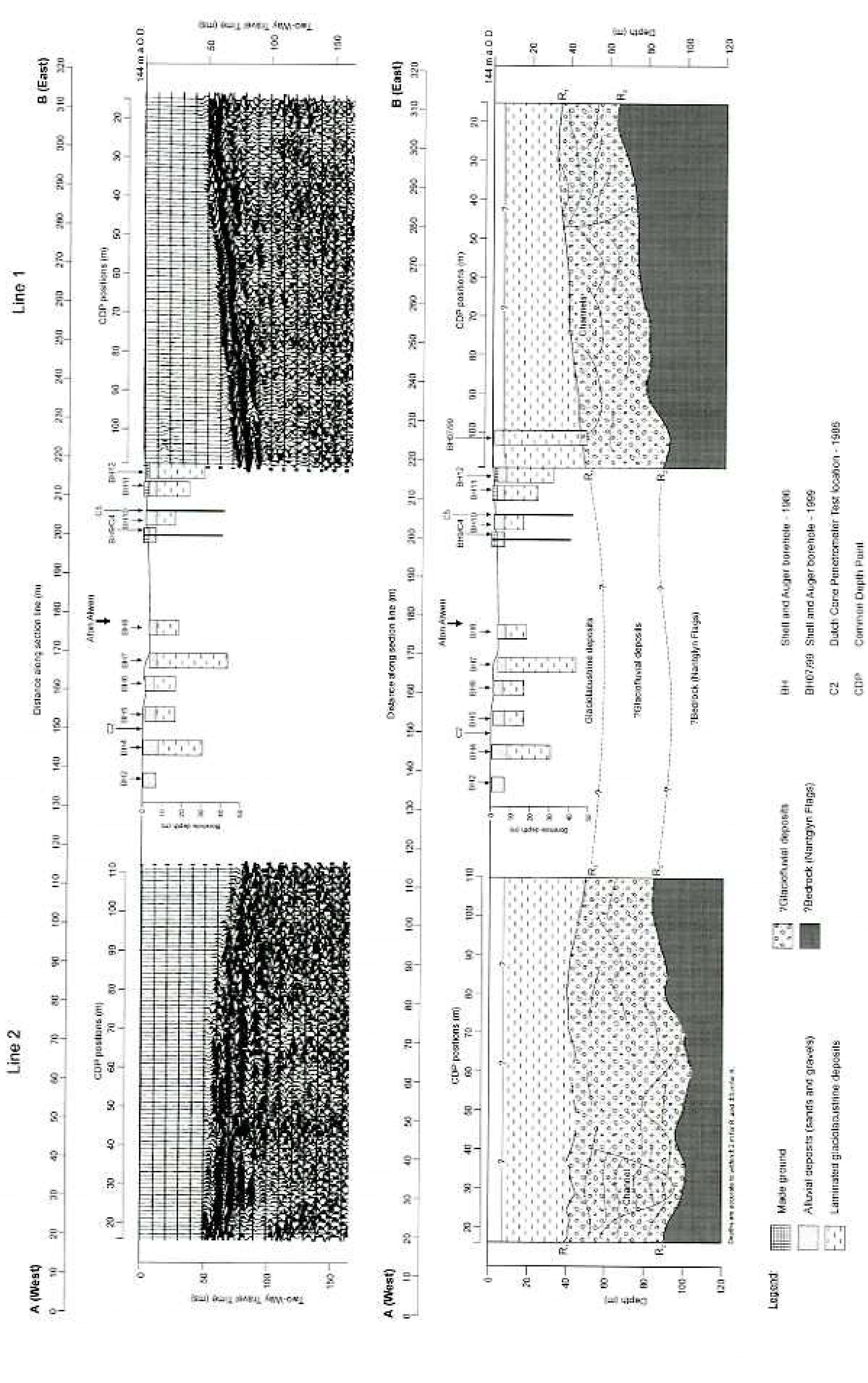

Fig. 11. Integrated interpretation of seismic reflection survey results and site investigation data.