Integration of continuous seismic profiling in geotechnical investigations off the Belgian coast

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Dr. J. P. Henriet, R.U.G., Laboratorium voor Aardkunde, Gent.

Dr. A. Bastin, Haecon N.V., Gent.

Ir. J. De Rouck, Haecon N.V., Gent.

ABSTRACT

Continuous seismic profiling using boomer, sparker or pinger sources has gained widespread use in marine site investigations.

At a reconnaissance stage, a grid of continuous seismic traverses with adequate orientation and mesh size is able to yield a coherent picture of the structural conditions of subsurface, allowing the definition of areas of main prospective interest. In the early stages of detailed site investigations, seismic profiling forms an efficient tool for the planning of high-cost offshore drilling and penetration testing programs.

Keys to success in seismic data acquisition are a matter of careful balancing and matching of source/receiver parameters with the marine and geological environment and with the geotechnical penetration/resolution requirements. In many cases, sea state conditions are critical.

Seismic work is mostly rewarding when used in multiple attack-mode, in conjunction with other exploration efforts. It provides the lateral exploration power which point investigations like boreholes lack. On the other hand, borehole data, seabed coring and penetration testing provide the necessary clues for identification of observed seismic events and for raising any ambiguity, inherent in the seismic method.

The vertical time dimension of seismic profiles can be converted into depth by suitable borehole control and seismic velocity models, compiled from refraction data and well shooting.

A comprehensive geotechnical survey for the offshore extention of Zeebrugge harbour illustrates some possibilities and limitations of seismic profiling in Belgian offshore areas and proves a striking example of its succesfull integration in geotechnical investigations.

INTRODUCTION

Seismic reflection profiling could be regarded as a downward extension of the common bathymetric echo-sounding technique. Operating at lower frequencies allows the penetration of an acoustic signal into the subsoil and the recording of echoes from layers at depths of tens, hundreds or thousands of meters. The deeper penetration range is within the achievements of the highly sophisticated multi-channel reflection surveys, used in oil and gas exploration. The shallower, single-channel seismic profiling technique has turned out a standard procedure in most types of marine engineering site surveys.

Early seismic investigations in the Belgian offshore area have been carried out by HOUBOLT (1968) and BASTIN (1970, 1974). HOUBOLT studied the recent sediments of the southern bight of the North Sea as a possible model for the interpretation of fossil sand bodies, which are known as potential oil reservoirs. BASTIN worked out a first coherent picture of the subsurface extension trend of the tertiary sequence into the Belgian offshore area.
Further sporadic investigations have been carried out, but most of these have not been reported in literature.

The decision to develop the outer harbour of Zeebrugge, which involves the construction of an LNG-terminal and entails the dredging of approach channels and the protection of the east coast, has formed the incentive for an application-oriented seismic survey, integrated into a marine engineering investigation program.

This paper briefly outlines the principle of seismic profiling and its integration into the engineering survey scheme and discusses, with a few examples, some possibilities and limitations of shallow seismic profiling in Belgian coastal and offshore areas.

ELEMENTS OF REFLECTION SEISMICS

Basically, the seismic reflection method depends on the generation and detection of acoustic waves. Acoustic signals are initiated at a sound source with a high firing rate and the echoes from the seabed and from discontinuities in the underlying sediments are recorded in a continuous way along the track of a survey vessel. The time elapsed between the initiation of the pulse and the detection of a particular echo yields the depth to the reflecting interface, provided the acoustic velocity in the transmitting media is known.

In marine surveys, one is primarily concerned with longitudinal or pressure waves. The velocity of such waves is a function of the bulk modulus, the rigidity (or shear) modulus (which can be expressed in terms of Young's modulus and Poisson's ratio) and the density of the transmitting media.

Reflection of part of the propagating acoustic energy takes place at boundaries between layers with different acoustic impedance, i.e. the product of wave velocity and density of the layers. It should be realized that such boundaries between media of contrasting density and/or elastic properties will not necessarily always correlate with prominent boundaries in borehole logs or geomechanical tests.

Important characteristics of a seismic signal are its bandwidth, frequency content and energy. The bandwidth is the main factor controlling the pulse length and hence the possibility of resolution of short-spaced reflectors.

The frequency content and, to a lesser extent, the energy are the main factors controlling the depth penetration. The energy radiated within the suited bandwidth must be sufficient to overcome the ambient noise level at the target depth, neither more nor less.

It should be borne in mind that these three factors are not independent. For example, the propagation of an acoustic signal in a sediment is characterized by a progressive loss of higher frequencies due to absorption, a mechanism caused by solid friction associated with the particle motion in the waves. A good penetration is hence relying on the lower-frequency content of the signal. However, frequency loss by absorption progressively reduces the bandwidth of the signal and hence increases the pulse length, causing a loss of resolution. As such, penetration and resolution unfortunately are mutually counteracting properties, which have to be carefully balanced to meet the specific requirements of any particular survey.

SEISMIC SOURCES AND RECEIVERS

The principal components of a seismic profiling system are the source transducer with its primary energy source and a trigger unit, the receiving transducer, a signal processing unit (filter, amplifier) and the recording unit (paper recorder, analogue tape recorder).

Currently available sources for high-resolution surveys are pinger probes, boomers and sparkers. A merely indicative review of some general performance characteristics and of some constructors, compiled from LEENHARDT (1972), BURTON (1976), LE TIRANT (1976), QUILLIN & ARDUS (1977) and constructor's data sheets is shown on table 1.

Pinger probes generate an acoustic pulse by the oscillation of magnetostrictive (or piezoelectric) transducers, activated by a discharge of electrical energy. The pulses are of fairly low energy and have a dominant frequency between 2 and 8 kHz. Penetration is low but benefits from the focusing of the energy into a beam, pointed at the seabed. The transducers are hull-mounted, towed in a "fish" behind the survey vessel or mounted on a bottom-towed sledge (Sonia).

SEISMIC SOURCES FOR MARINE ENGINEERING SURVEYS

Performance characteristics	Some constructors
PINGER PROBES	
power output (J/pulse) : 0.2-5 firing rate (sec^{-1}) : up to 20 frequency band (kHz) : 1-12 resolution (m) : 0.1-1 penetration (m) : 2-30	CESCO (Sonia), EDO WESTERN, EG & G, ORE, RAYTHEON RTT, THOMSON CSF, etc.
PRECISION BOOMERS	
power output (J/pulse) : 100-300 firing rate (sec^{-1}) : 2-6 frequency band (kHz) : 0.4-14 resolution (m) : 0.2-0.4 penetration (m) : 30-80	EG & G (Uniboom) (catamaran or deep-tow), HUNTEC (catamaran or deep-tow)
LIGHT-DUTY MULTI-ELECTRODE SPARKERS	
power output (J/pulse) : 100-1000 firing rate (sec^{-1}) : 2-4 frequency band (kHz) : 0.1-5 resolution (m) : 2-4 penetration (m) : 50-200	EG & G (Sparkarray), IFP-GEOMECANIQUE, NOVA SCOTIA RESEARCH FOUNDATION (also deep-tow), etc.

Table 1.

Boomer sources operate by the electromagnetic repulsion of a metal plate, spring-loaded against an insulated coil,when electrical energy is discharged through the coil. Precision boomers such as the EG & G Uniboom or the HUNTEC boomer have a special design eliminating spurious oscillations, which ensures a broad-band, sharp signal. Operating in the 100-500 joule/pulse range, they offer a good compromise between resolution and penetration for many shallow targets.

Precision boomers are either surface-towed (catamaran) or built in a deep-tow body, which has the major advantage of being decoupled from sea wave motion.

Sparkers generate acoustic pulses by the explosive formation of steam bubbles, resulting from the discharge of electric energy between electrode tips in the sea. The required high-voltage is stored in capacitor banks, similar to those used for driving boomer transducers. The penetration of sparker systems is generally superior to that of precision boomers, but oscillation of the steam bubbles can increase the pulse length, causing a loss of resolution. Multi-electrode arrays ("combs") generate shorter pulses with increased peak pressure. Deep-tow sparkers are also available (NOVA SCOTIA RESEARCH FOUNDATION). Besides, a pinger probe can be run concurrently with a sparker system, causing but negligible interference (cfr. oblique parallel lines on the sparker record on top of fig. 4).

Further sources such as the air gun (BOLT) or devices using explosions of gas mixtures in small elastic sleeves (the EXXON Mini-sleeve Exploder, a little brother of WESTERN GEOPHYSICAL's Aquapulse) are better suited for deeper surveys (down to 1000 m) with lower resolution requirements.

Common acoustic receivers are hydrophones, which convert pressure variations into electric signals, usually through a piezoelectric (or magnetostrictive) device. Grouping of hydrophones into a buoyant streamer cable or "eel" increases the signal-to-noise ratio. In pinger probes, generally the same transducer is alternately used as source and receiver.

After a preliminary filtering with a band pass selected to suit the type of acoustic source and the resolution/penetration requirements of the survey, the signal from the hydrophone array is amplified (time-variant gain or automatic gain control) and fed into the recording unit.

Seismic recorders for single-channel surveys have some similarity with echo-sounding recorders. Signal traces from successive shots are juxtaposed on a paper chart, driven by a drum system. Echoes from a same stratum on successive sweeps line up into prominent reflection bands, composing a facsimile profile of the subsoil, however distorted both in the horizontal dimension (variations in the ship's speed) and in the vertical one (variations in acoustic velocity in the subsoil). Parallel analogue recording on magnetic tape, allowing later replays of seismic sections using a variety of signal processing techniques, is extremely useful.

SURVEY OUTLINE AND RELEVANT BACKGROUND

The global area of investigations off the eastern Belgian coast extends between longitudes 2° 45' east and 3° 25' east and between latitudes 51° 17' north and 51° 34' north (fig. 1).

From the geological point of view, this area belongs to the southern rim of the North Sea basin. Tertiary sandy and clayey layers of eocene and oligocene age, striking north 50° west and dipping 4 m per km north-east, are subcropping below a quaternary, mainly sandy cover which reaches a thickness of 30 m at the coast and progressively thins out in seaward direction. The surface of unconformity at the base of the Quaternary locally shows marked relief features, in many cases related to differential erosion of the tertiary beds. The outer harbour of Zeebrugge straddles the boundary between the mainly sandy lutetian layers (middle-Eocene), subcropping to the south-west, and the bartonian clays (upper-Eocene), subcropping to the north-east.

The general geotechnical investigation program, carried out on behalf of the Ministry of Public Works, involves reconnaissance, semi-detailed and detailed investigations in the harbour extension area, the area spanning the possible options for the approach channels and the near-shore area east of Zeebrugge, which will require special protection works.

In its reconnaissance stage, the geotechnical investigation for the outer harbour consisted of the following consecutive phases : seismic profiling (75 km, fig. 1A), offshore cone-penetration testing, offshore drilling with associated laboratory testing of disturbed and undisturbed samples (classification tests, stress and deformation tests) backed by parallel onshore cone-penetration testing and drilling. Subsequent detailed investigations involve additional drilling and cone-penetration testing, pressiometer testing, borehole logging and laboratory testing.

The fundamental grid for the reconnaissance survey in the harbour area is shown of fig. 1B. Average drilling and geotechnical testing depth amounts to about 30 m below seabed, with a few additional offshore and onshore deep boreholes ranging between 65 and 100 m below seabed or soil level.

The approach channel area and the eastern near-shore area have been covered by a seismic survey (345 km, fig. 1) and an associated program of vibrocoring and offshore drilling. The total number of vibrocores amounts to about 250. Sediment transport investigations involved radioactive tracer studies and bottom sediment density determinations.

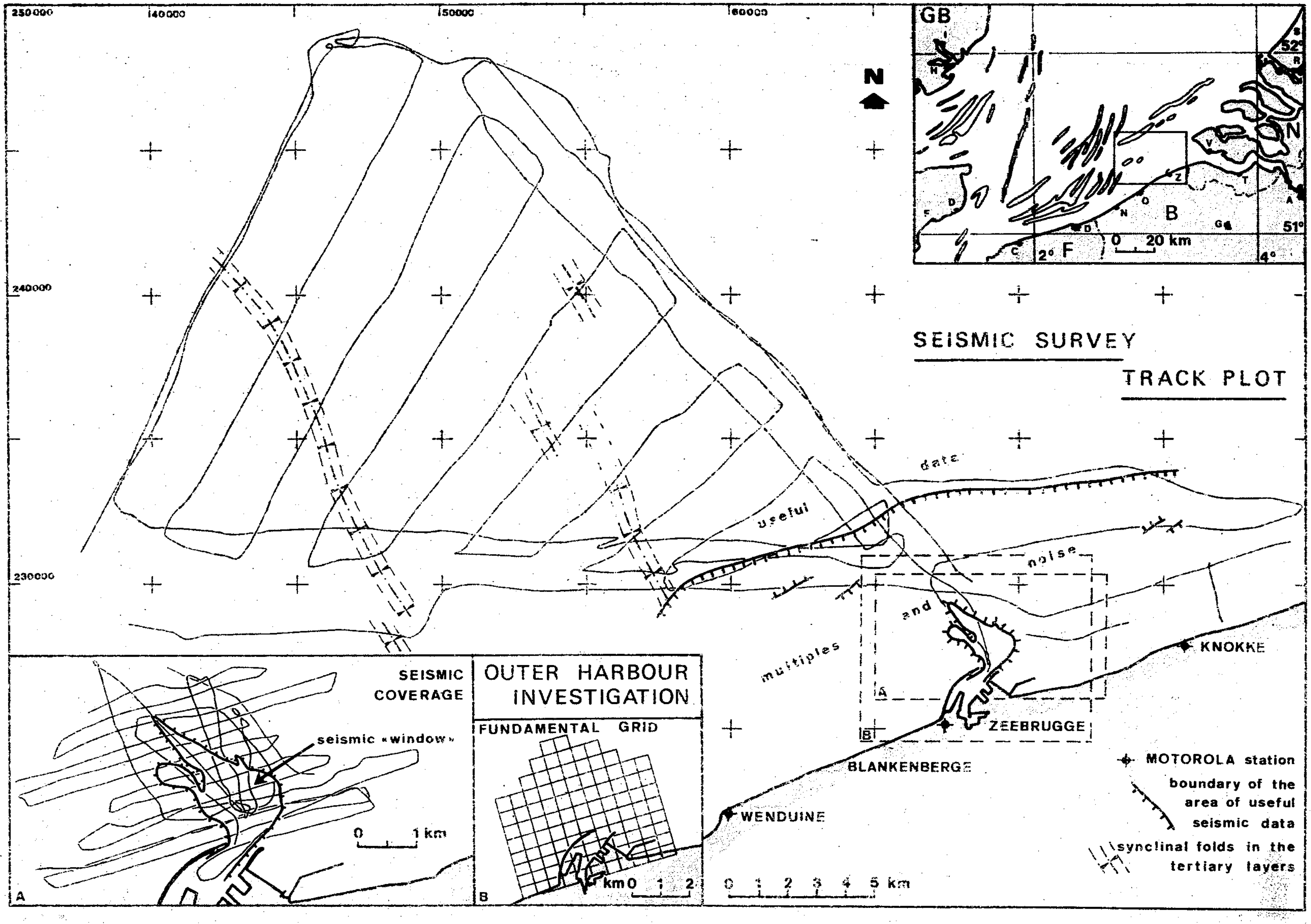

Fig. 1 General map of the survey area, with seismic track plots and fundamental grid of the outer harbour investigations.

The geophysical survey has been carried out in April 1977. The survey vessel was equipped with an EG & G 300 joule Uniboom, multi-electrode sparker and an EDO-WESTERN pinger profiling system (fig. 2). Following a period of trials with negative results of the pinger system, it was decided to utilise the Uniboom system only for the actual survey. The receiver consisted of an 8-hydrophone array in a streamer cable, towed 30 m astern of the mast, on which the positioning antenna was fixed. The Uniboom system was used in conjunction with an EG & G 255 Engineering Survey Recorder, with time-variable gain, and an additional active band-pass filter.

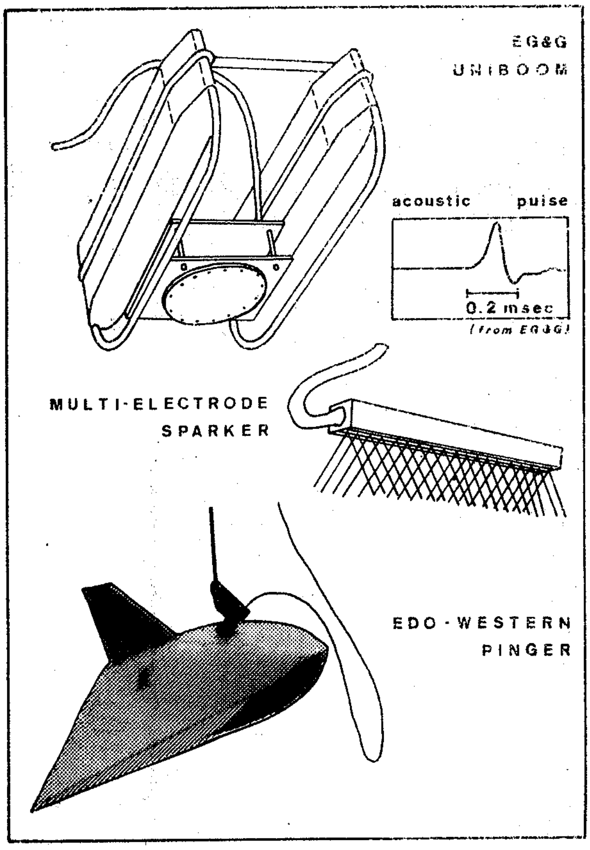

Fig. 2 Seismic sources tested in the Zeebrugge survey.

Prevailing weather conditions were reasonably good, sea state being slight to moderate, a prerequisite for satisfactory surface- tow Uniboom results. Towing speeds were usually 4-8 knots, dependent on tides and sea state.

A MOTOROLA Mini-Ranger III system was used for position fixing, with four reference stations established at Oostende, Wenduine, Zeebrugge and Knokke. Depending on the position of the vessel, the two stations giving optimal circle intersections were selected for position fixing. Locally, problems were caused by temporary black-out phenomena of one or several ranging stations, even in the line of sight.

Sediment velocities, required for the interpretation of the seismic sections, have been gathered indirectly by correlation with offshore borehole logs and cone-penetration soundings, using plausible assumptions about the possible position of reflecting interfaces in these logs, or by direct onshore measurements with seismic refraction profiles (CHERLET 1978) and seismic borehole calibrations.

Borehole calibrations, developed from the "well shooting" technique in oil exploration, yield a continous velocity/depth function of the subsoil (fig. 3). Acoustic waves generated by hammer impacts at the soil surface are directly recorded with a well hydrophone at regular depth intervals in the borehole. The measured one-way travel time of the acoustic wave, corrected for the slant travel path, yields the interval velocities of the different layers. Both refraction profiles and borehole calibrations have been carried out with a BISON 1570 B Signal Enhancement Seismograph.

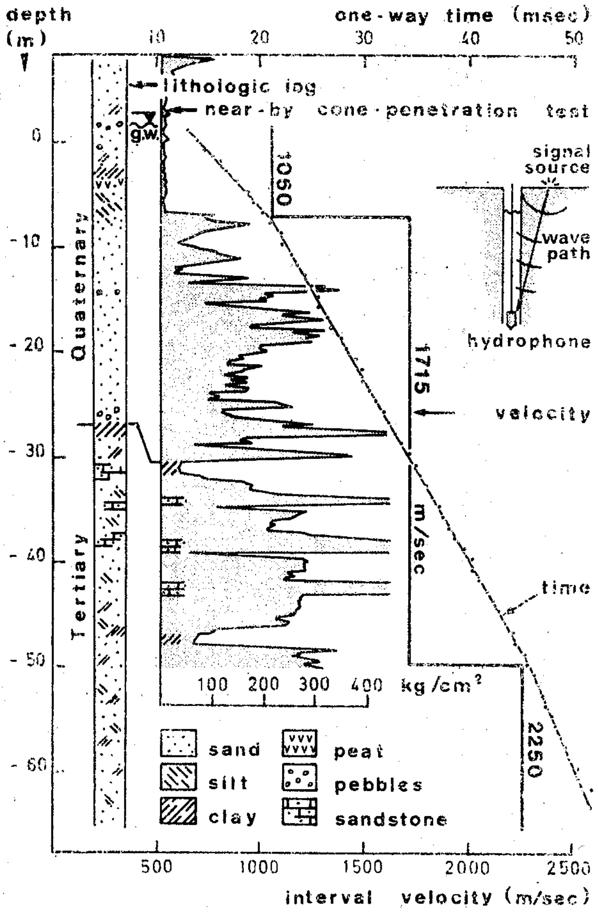

Fig. 3 Correlation of the travel-time curve and the derived interval-velocity curve of a deep calibration well with the lithological borehole log and a neighbouring cone-penetration curve.

DATA ANALYSIS

In the outer survey area, a large amount of good quality data was obtained. Locally, useful information spanned the whole record depth of 100 msec, corresponding with 80 to 90 m. However, within a belt extending about 7 km from the shoreline, whole sweeps of multiple reflections (waves which have been reflected more than once) masked any subsoil information.

The transition between areas with and without useful seismic data is generally sharp and noisy. This limit, shown on fig. 1, approximately fits the -8 or -9 m seabottom isobath. In the harbour area, the seismically opaque area is sharply interrupted by a window with excellent data quality (fig. 7). Its boundaries (fig. 1, 1A) also roughly fit the -8 to -9 m isobath.

It is perhaps relevant to observe that in the subsoil of the coastal plain, the limit between pleistocene and holocene deposits is an erosion surface at about -8 m (DE BREUCK, DE MOOR & MARECHAL 1969), which is locally marked by thin peat layers. Moreover, most vibrocores taken within the limits of the opaque area show small peat inclusions or lamellae. It is tempting to speculate that organic matter is playing a substantial role in the acoustic shielding of part of the near-shore subsoil, but maybe other factors are interacting too.

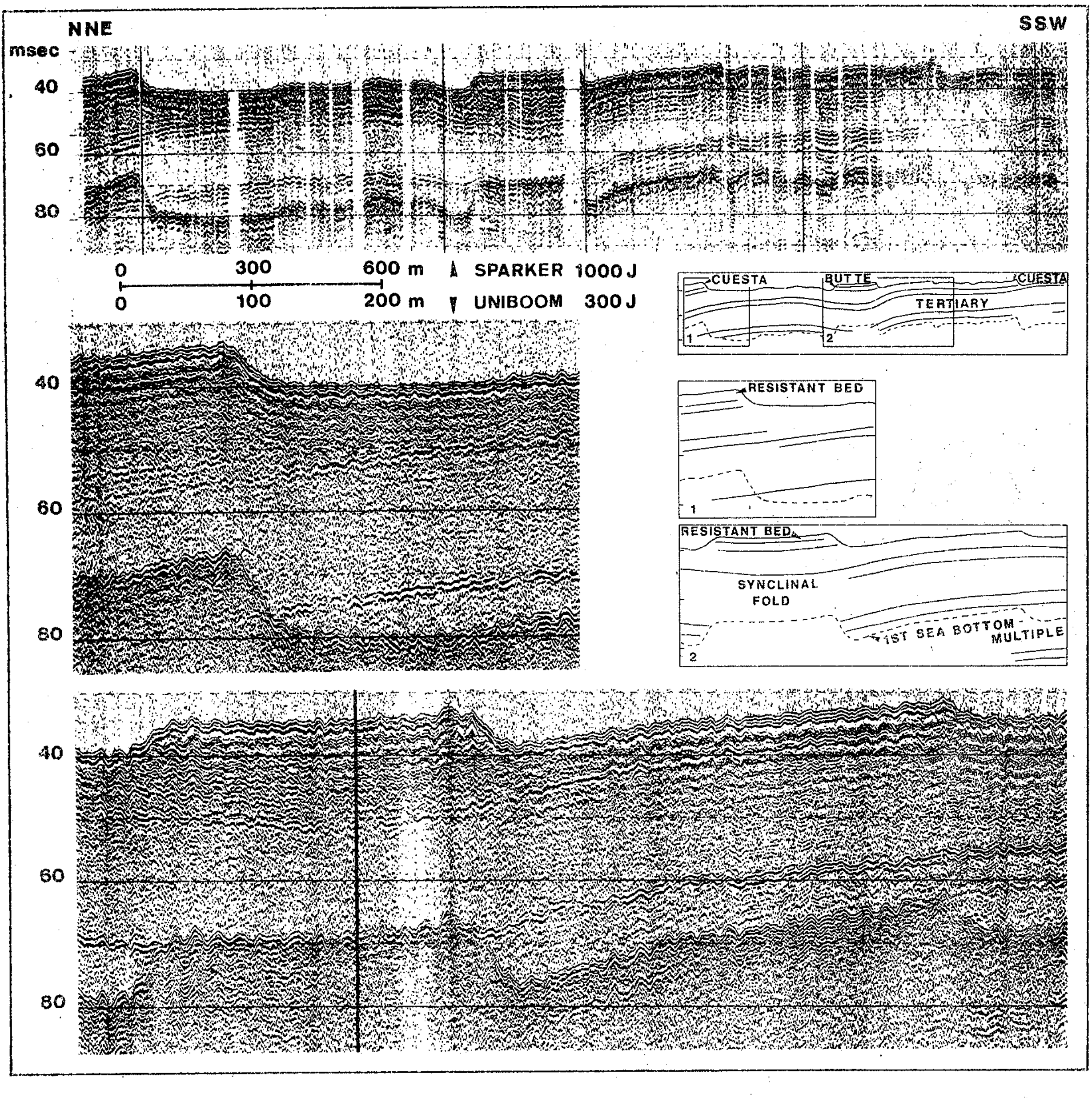

Fig. 4 Concurrent sparker and Uniboom profiles over an outcropping, gently folded tertiary sequence.

The type of information which merges from seismic profiles, the quality of the data and their relevance for geotechnical investigations are best illustrated by a few selected examples.

CASE 1

The section displayed on fig. 4 has been shot with the 1000 joule sparker during the initial trials and subsequently with the 300 joule Uniboom system, which achieved a better resolution. In the area under interest, quaternary deposits are thin or absent and the seabottom morphology forms the expression of the subbottom structure of tertiary age. Differential erosion of the gently inclined strata has formed small cuesta's, with a gentle slope on one side, conforming with the top of the resistant bed that forms it, and a steep slope on the other side, formed by the outcrop of the resistant bed.

The core of the synclinal fold is topped by a small butte or isolated erosion remnant, bounded by steep scarps on either side.

These small cuesta's and the variations in mechanical properties of the seabed which they reflect may be of importance for dredging works. However, they are shown here not the least because they form nice small-scale models of the large tertiary clay cuesta's, which have been encountered a short distance off Zeebrugge, buried under a quaternary cover.

The small, trough-like synclinal fold which merges on the profile is quite remarkable by its extension : it could be followed for a distance of 15 km through many profiles (fig. 5), with a constant width of 500 to 700 m and an amplitude of 5 to 10 m. It shows a local offset of the axis in the south and is paralleled to the east by shorter, similar folds (fig. 1). These elongated folds possibly reflect deformations in the deeper substratum.

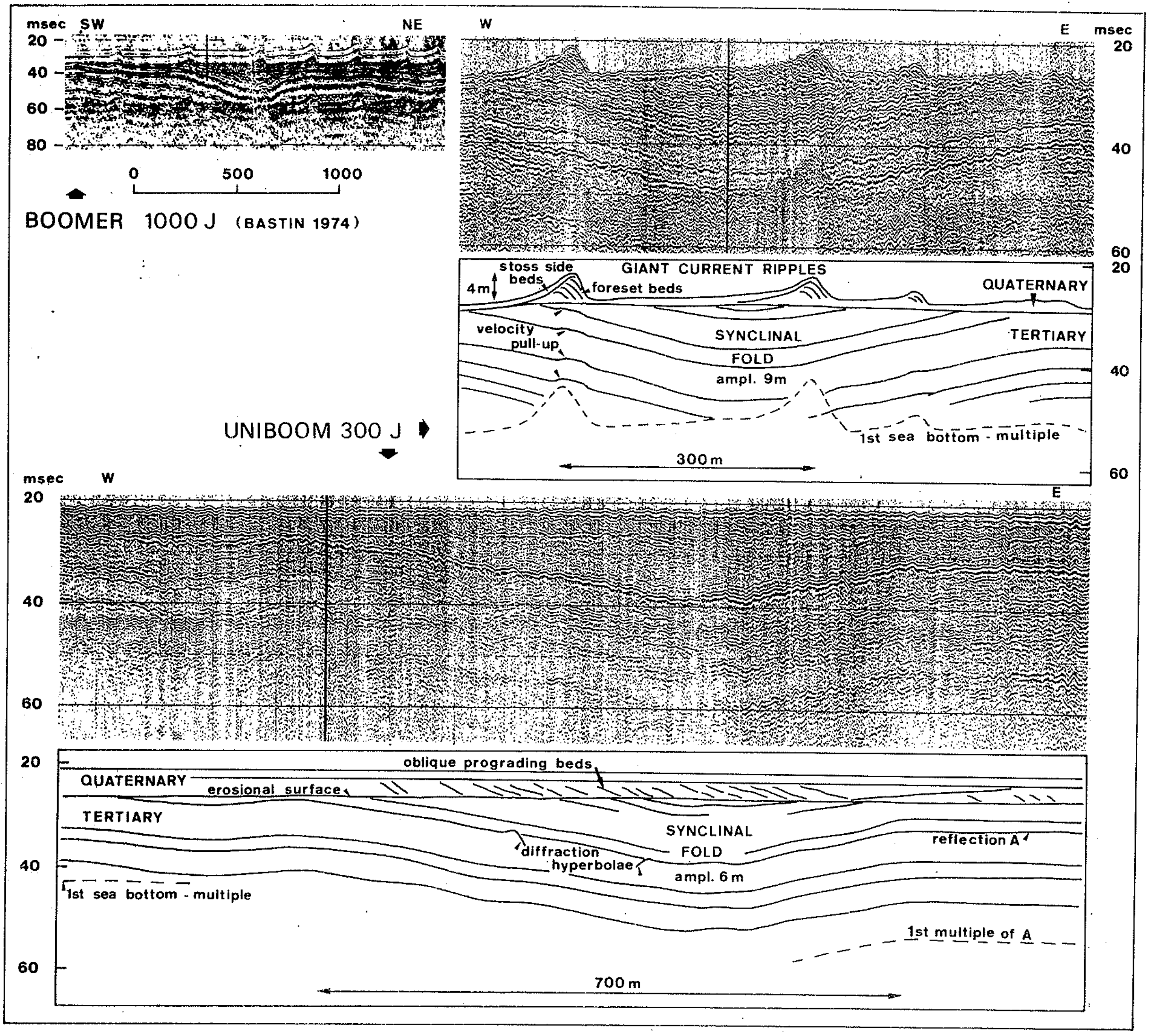

Fig. 5 An early boomer section and present Uniboom profiles over an area with a thin quaternary cover, locally modulated into giant current ripples.

CASE 2

The area crossed by the seismic traverses shown on fig. 5 has a clearly defined thin cover of quaternary, mainly sandy sediments. Compared with the 1000 joule boomer section shot in the late sixties (BASTIN 1974), the improvement in resolution is obvious.

The sand cover in the top section has been modulated by strong tidal currents into a train of well-developed, asymmetrical waves or ripples. Their internal structure, well visible on the precision boomer profile, bears the evidence of their mobility : the steep sloping foreset beds, which build up the main body of the sand wave are onlapped by the gently sloping stoss-side beds on the upcurrent side. The base level of the sand waves is well defined, allowing reliable sand-volume calculations.

The replacement of a sea water volume by a sand wave causes a local anomaly in the vertical velocity distribution in the section, resulting in small apparent elevations in the lower-laying reflections ("velocity pull-up").

In the lower section, the quaternary cover has a uniform thickness but also shows an internal structure with a sequence of oblique beds, prograding to the east. This type of planar cross-bedding, related to depositional conditions, turns out a useful diagnostic feature allowing the geometrical delineation of the sediment body.

In both profiles, the base of the quaternary deposits is sharply marked by the truncation of the inclined tertiary beds.

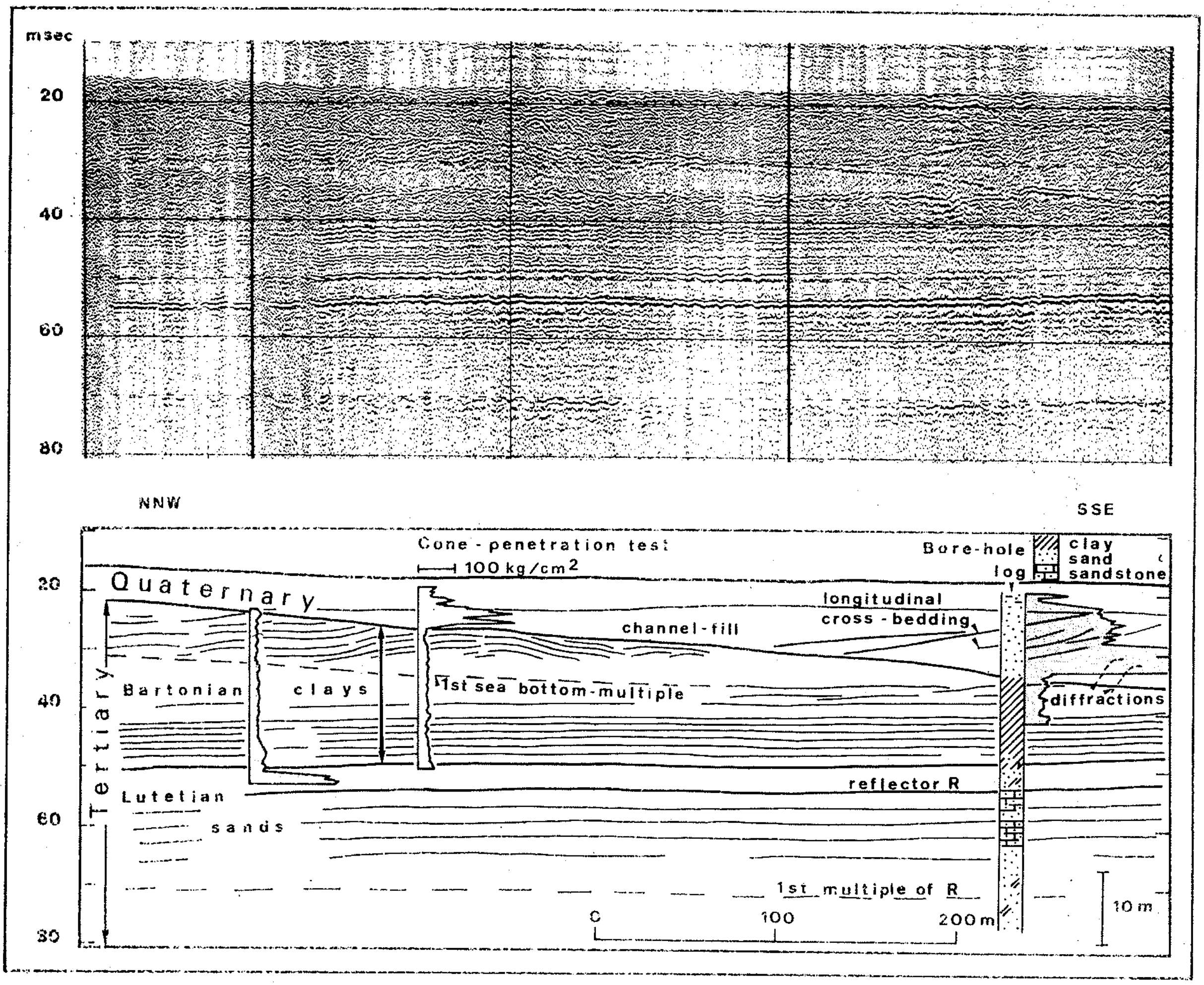

Fig. 6 An example of seismic interpolation between cone-penetration soundings and boreholes in an area with sloping erosion surfaces, buried channels and cross-bedding.

CASE 3

In areas with sloping erosional surfaces, buried channels and oblique sediment beds, seismic profiles are invaluable as interpolation tool between boreholes or cone-penetration soundings. In fig. 6, borehole logs and cone-resistance logs have been projected to their logical position on the seismic profile.

The seismic pattern of the tertiary sequence shown here, with a strong reflector (R) at about 55 msec and three characteristic intervals above it (described in case 4), forms an excellent marker sequence throughout the whole north-eastern part of the survey.

The channel with triangular cross-section, flanking the bartonian clay slope, has been recognised in several parallel profiles, each time with its characteristic cross-bedding in the flank facing the clay slope. This type of longitudinal cross-bedding (the beds running parallel to the current direction in the channel) is probably caused by the lateral shifting of the channel axis, in intertidal flats (REINECK & SINGH 1975).

Any interpolation carried out in such an area without the guide-lines of the seismic reflections would be of questionable reliability.

CASE 4

A critical problem of interpolation between distant boreholes and cone-penetration soundings is illustrated by fig. 7. The logs situated on either sides of a heavy-traffic lane, which impedes drilling-platform activities, are completely different. Fortunately, a seismic window, coinciding with the axis of the dredged channel, yields a very clear picture.

The seismic sequence shown has been identified by correlation wells and soundings, located within the window but outside the traffic lane. The strong reflections at 55 msec and below can be correlated with sandstone horizons in the top of lutetian sands. Above, a very diagnostic sequence of three intervals has been identified with bartonian clays. The lower interval is built up of a regular sequence of even, parallel reflectors, the middle one has a noisy random seismic facies, with a level of overlapping reflection segments at its base, while the upper one is characterised by a pattern of parallel, lobate or wavy reflections. On profiles trending north-east, these wavy reflections display a pronounced oblique prograding trend, stepwise cascading from the top of the interval down to the bottom. Comparison of this sequence with the known bartonian lithological sequence in north-eastern Flandern (JACOBS 1975) leads to the possible assumption that the lower interval includes the "a1" clay, that the upper interval in broad lines corresponds with the "a2" clay and that an intermediate sandy S2 level is either absent or represented by a clayey facies, fitting the middle interval.

The seismic section proves the extension of the thick bartonian clay sequence over a distance of at least 700 m from the easternmost borehole and hence narrows the locus of its western termination to a strip of less than 300 m. This termination is assumed to be a steep erosion scarp or cuesta front, against which the quaternary layers abut. Such a steep slope and the flanking, possibly heterogeneous quaternary deposits are of critical geomechanical importance. By saving a considerable amount of drilling and sounding, required for pin-pointing this critical area - at substantial risk for navigation in the traffic lane -, seismic profiling largely pays for itself.

CONVEYING THE RESULTS TO THE USER

The flow diagram on fig. 8 illustrates how the integrated results of seismic profiling, drilling, penetrometer sounding and vibrocoring have been distilled into readily usable formats.

After a first visual inspection of all seismic records, interpretation started with the picking of significant markers which were followed along the sections, checking line ties and loop closures. Time values for each picked horizon were digitized at suitable horizontal intervals and posted on profiles and maps. These documents, together with prior knowledge about subsoil, were used for the planning of subsequent drilling and penetrometer investigations.

Interpretation started for the harbour area, for reasons of technical priorities and because of the density and variety of correlation data. Velocity calibrations shed a new light on the vertical velocity distribution in the near-shore sediments. Velocities of 2000-2200 m/sec, formerly proposed for sediments of the southern North Sea (CURRY e.a. 1965, BASTIN 1974), proved valid below a level of about -50 m (fig. 3). Within the depth range of the marine engineering investigations, velocities between 1600 and 1750 m/sec yield better correlations. Integration of the borehole, penetrometer, seismic reflection and velocity-calibration data resulted in the design of an interpretation key, valid for the overall harbour area. Although the Zeebrugge seismic window is not directly linked with the outer positive area, the interpretation key elaborated in the harbour zone formed the very outset for the interpretation of the remote offshore regions, thanks to the identification of common seismic marker sequences.

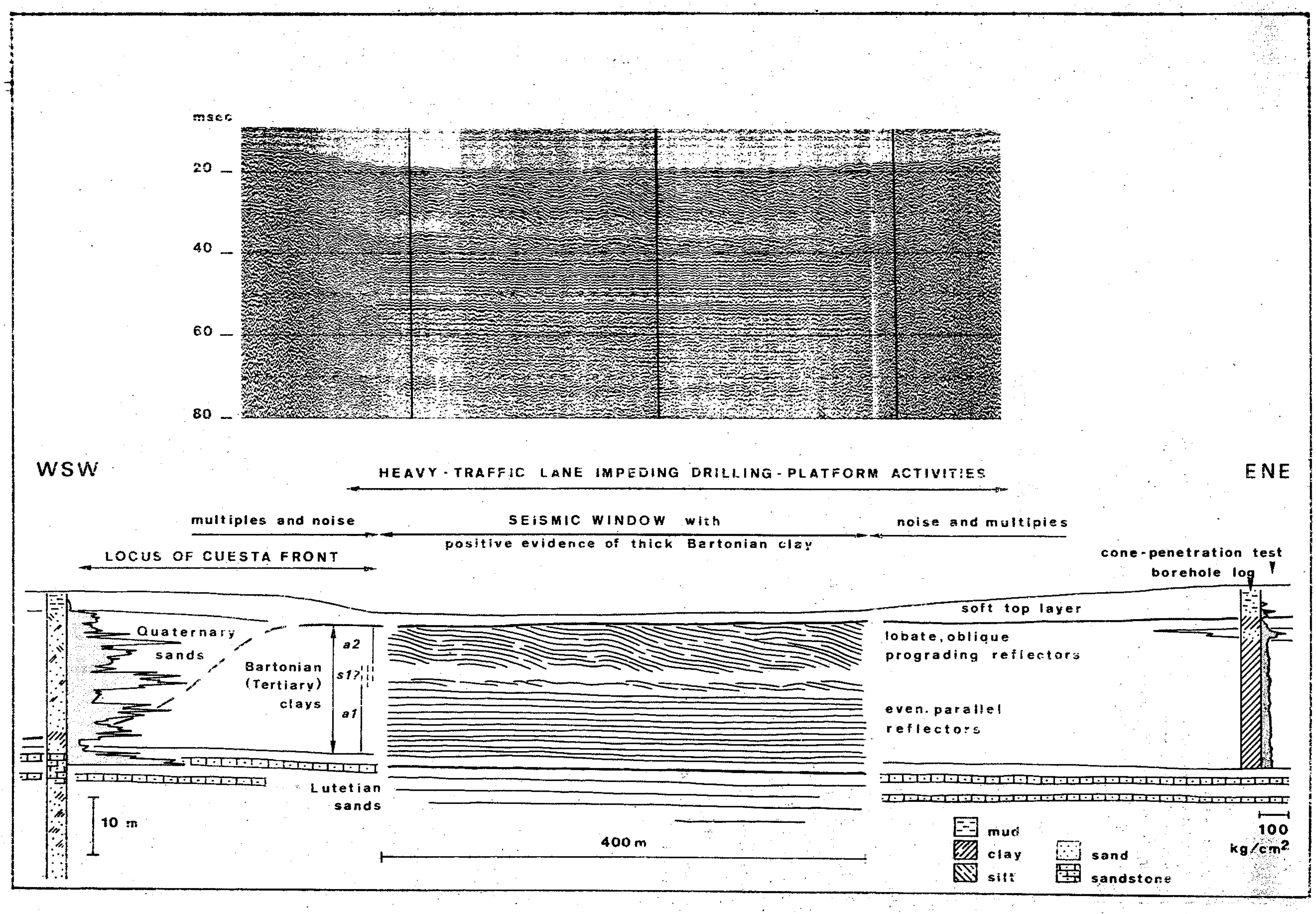

Fig. 7 Seismic profiling as an interpolation tool, bridging areas of difficult drilling-platform operations.

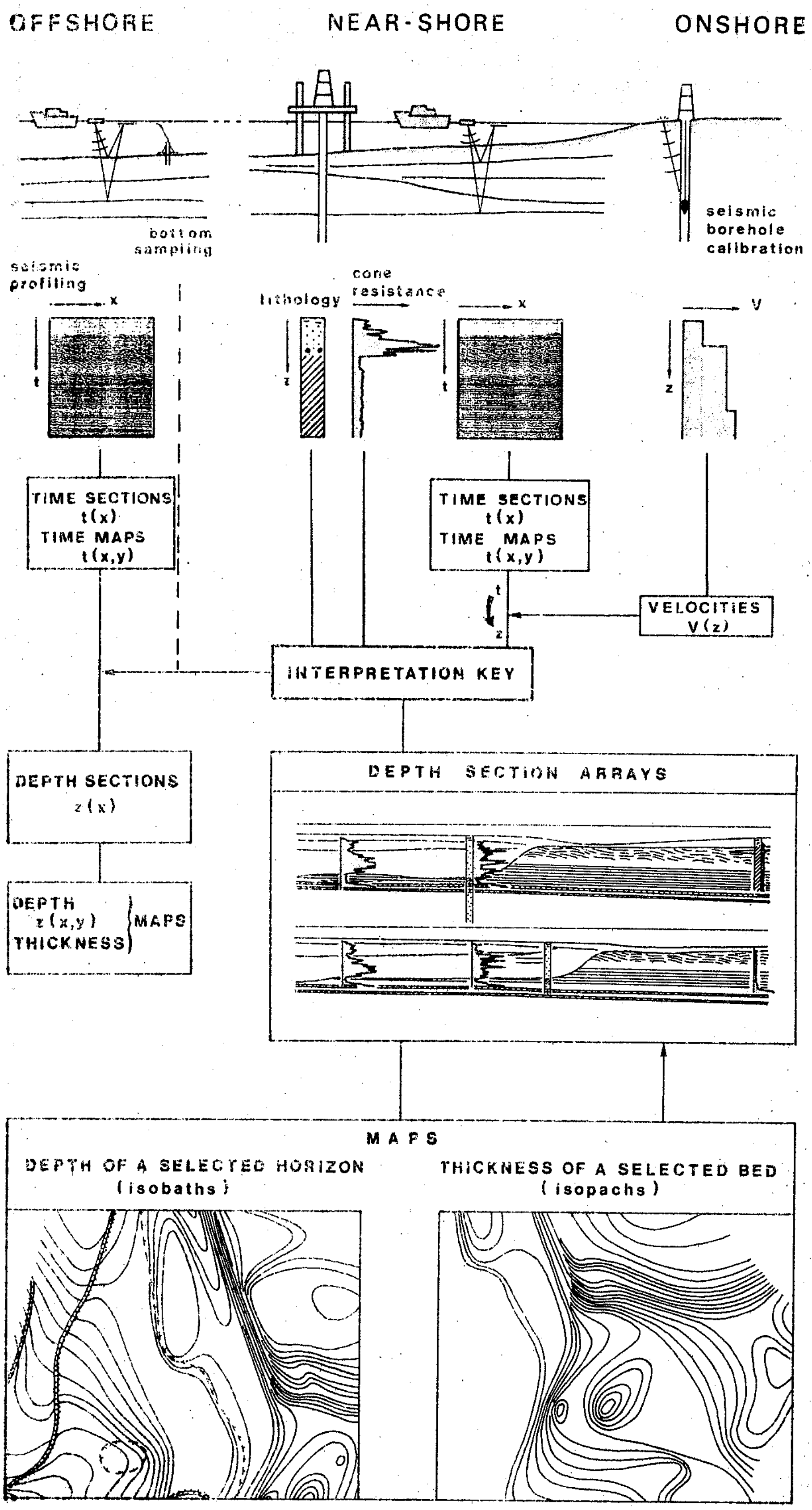

Fig. 8 General scheme of the interpretation flow of the integrated geotechnical and seismic data and presentation mode of the results.

Troughout the interpretation process of the harbour survey, the prime aim was a geologically plausible structural model, giving a best fit with all available data. For its elaboration and presentation, this model or part of it had to be projected on a set of orthogonal planes : vertical profiles along the lines of the fundamental grid (fig. 1) and projections of selected surfaces on horizontal planes under the form of isobath maps (fig. 8). The elaboration of the model required repeated iterations around the loop formed by these orthogonal projection planes, checking again all line ties and loop closures and paying attention to the necessary geological bias in any interpolation and smoothing process.

In a following stage, derived documents could be grafted on this rigid fundamental frame : profiles along the axes of the planned breakwaters, isopach maps showing thickness variations of any selected bed.

A possible drawback of the emerging set of fair-drawn profiles and contour maps is that they often appear definitive and convey an impression of finality. It is virtually impossible for the interpreter to incorporate any quantitative indication of the effects of alternative interpretation judgements. The user should be aware of this. Moreover, as more factual information becomes avaible with the subsequent detailed investigations, the model may have to be modified and updated at reasonable time intervals.

CONCLUSION

The combined use of seismic profiling with drilling and penetrometer testing in the survey off the eastern Belgian coast has proved a sound approach. Before any drilling started, the main structural trends could be appraised from the seismic sections. Subsequent drilling and cone-penetration sounding provided the clues for the identification of the seismic events which, in turn, guided the interpolation between soundings and drillings. Seismic profiles proved highly rewarding by partly filling the gap created by the main traffic lane, where platform operations implied substantial risks for navigation. However, the feasibility of the applied seismic technique could not be proved within the limits of a near-shore area, which has been partly delineated by the present survey.

As concerns the technique itself a few comments should be added. Signal sources and receivers have generally approached an acceptable state of art, aspecially in the precision boomer systems. However, considerable improvement is still to be expected from suitable forms of processing of recorded single-channel seismic data. Engineering seismics has not yet taken full advantage from the geophysical processing experience acquired in oil exploration.

Still too few engineering seismic operators are actually proposing elementary data processing packages. In the Netherlands, a common research program of Rijkswaterstaat, Rijksgeologische Dienst and SHELL achieved substantial improvements of single-channel reflections profile from the Brown Bank test area, by applying a few processing steps including heave compensation, bandpass filtering at various settings, time-variant gain corrections and deconvolution. Seismic operators who ignore such developments will make themselves uncompetitive, whenever project management is concerned with getting the most out of their survey data. Anyhow, the prime requirement of magnetic tape recording of all seismic data should become standard in any survey specification.

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