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High-resolution seismic reflection surveying at paved areas using an S-wave type land streamer

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Key Words: Land Streamer, woven belt, S-wave, seismic reflection survey, pavement

ABSTRACT

High-resolution S-wave reflection surveying has been successfully conducted on paved areas using a Land Streamer originally designed by the author. The main feature of the Land Streamer tool is the non-stretch woven belt on which geophone units are mounted to form a multichannel geophone array similar to a marine streamer. Because it is easily towed by a vehicle or by hand, the tool leads to high performance in field measurements and resultant cost-effectiveness of high-resolution reflection surveys. Although each geophone unit is coupled to the pavement through a metallic baseplate instead of being firmly planted in the ground, the Land Streamer tool provides comparatively clean data, unaffected by traffic noise even on the pavement. Thus, the tool is capable of expanding the opportunity for S-wave reflection surveys in urban areas where many surfaces are paved and traffic noise is severe.

A series of high-resolution S-wave reflection surveys on paved areas delineated detailed structures of surface layers shallower than 60 m, and proved the wide applicability of the tool to engineering, environmental applications, and earthquake disaster prevention projects.

INTRODUCTION

After the 1995 Hyogo-ken Nanbu Earthquake, which destroyed over 150000 buildings and took more than 6400 lives in Kobe City and its surrounding areas, active fault research has been systematically conducted throughout Japan to clarify the recent activities of individual faults and to estimate the potential for future activity of those faults. To this date, more than 100 major active faults have been studied by the Geological Survey of Japan, university research groups, and local government offices, and seismic reflection surveying has become one of the main survey methods for such active fault research in Japan. Reflection surveying plays an especially important role in the investigation of concealed faults beneath alluvial plains or in urban areas, where it is hard to recognize surface evidence of faulting because landforms may have been artificially modified. Conventional seismic reflection surveys using P waves are useful in delineating the relatively deep structure of such faults; however, such surveys are not as effective in imaging near-surface deformation resulting from recent faulting. Identification of deformed structures in near-surface sediments is the key to the interpretation of recent activity of a detected fault. High-resolution reflection surveys are essential for clarifying such detailed deformation structures in surface layers.

Delineation of near-surface structure and estimation of the geotechnical properties of surface layers are also important in site characterization to improve the earthquake resistance of man-made structures, because earthquake strong motion at a site is strongly influenced by near-surface ground conditions. Particularly in soft soil, ground motion is strongly affected by soil conditions such as the thickness of soft layers and their shear wave velocities. It is well known that soil conditions vary locally. Conventional drilling is inadequate to detect such local anomalies of soil condition as abrupt changes in soil layer thickness, or the occurrence of a buried channel. P-wave reflection surveys do not have enough resolution to image local anomalies. By contrast, S-wave reflection surveys possess sufficient resolution to identify local anomalies and detailed structure in surface layers. The advantage of using S waves is increased resolution because of their lower velocities and consequent shorter wavelengths compared with P waves in soft sediments. In addition, an S-wave reflection survey provides S-wave velocity structure, which is fundamental information that can be used directly to estimate the strong motion response of a target site.

High-resolution reflection surveying using S waves also contributes information to engineering and environmental studies. In particular, delineation of depth to a bearing layer overlain by unconsolidated surface sediments is essential for foundation design and for the evaluation of the potential for subsidence of soft ground. Because S-wave velocities are closely related to the geotechnical properties of sediments, an S-wave reflection profile can be interpreted in geotechnical terms as well as geologically.

The author has studied the high-resolution shallow seismic reflection technique using S-waves for engineering purposes and for active fault studies, and has demonstrated that it has the resolution to discriminate a vertical fault displacement of less than 50 cm (Inazaki, 1990). High-resolution surveys, however, tend to be influenced by surface conditions. Particularly in large urban areas, high-amplitude traffic and industrial noise might decrease the quality of seismic records, and the pavement also makes it difficult to plant conventional spike-type geophones in the ground. Moreover, high-resolution surveys inevitably require closely-spaced geophones and sources, which leads to increases in the number of crew members required and the time taken, and so to increases in survey cost. In response to these points, the author designed and produced a new tool — an integrated geophone array which could be easily towed on pavement, just like a marine streamer — and named it the "Land Streamer" (Inazaki, 1992). After continual refinement, production versions of the Land Streamer were manufactured and used in actual surveys for research into active faults (Inazaki, 1998; Inazaki, 1999) and for detailed imaging of near-surface structures (Inazaki, 2002).

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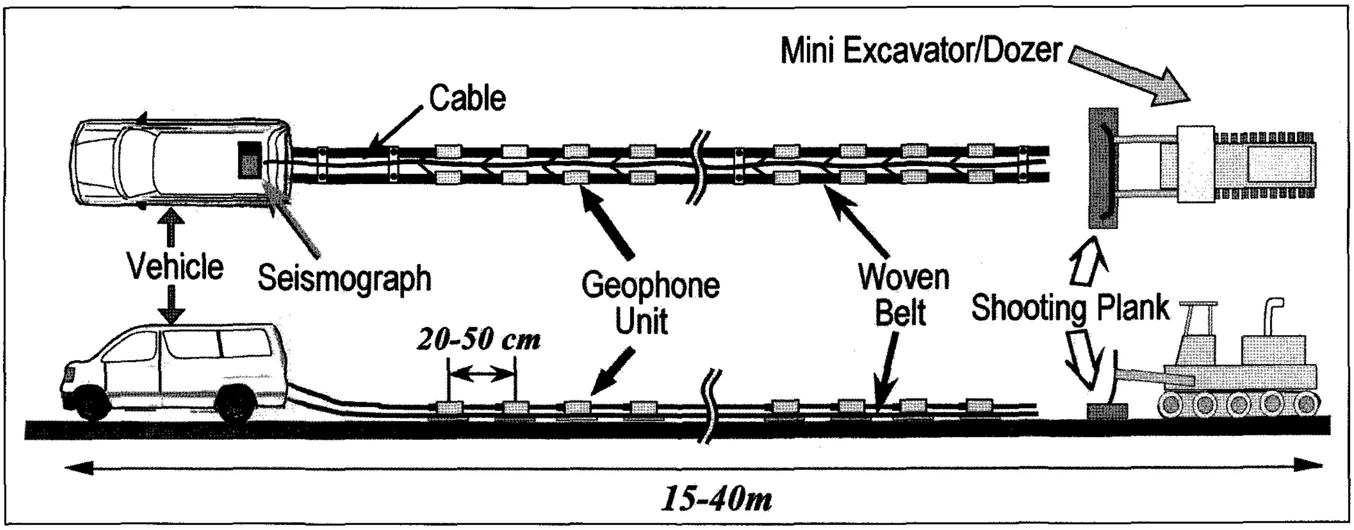

Fig. 1. Schematic illustration of the S-wave type Land Streamer.

S-WAVE TYPE LAND STREAMER

Outline of the S-wave Type Land Streamer

The S-wave type Land Streamer (Inazaki, 1992; Inazaki, 1998) is a field tool of original design for high-resolution S-wave reflection surveys on paved areas. It consists of a pair of belts, a cable, and geophone units (Figure 1), and is easy to assemble or disassemble on site within 20 minutes. The main feature of the Land Streamer tool is the non-stretch woven belts on which geophone units are mounted to form a multichannel (24 or 48) geophone array similar to a marine streamer. The tool can be towed easily by hand or by a vehicle that carries the seismic system. The woven belts, which were originally designed for cargo slings, take the full tension, and keep the spacing between geophone units on them fixed when towed. Each geophone unit houses dual horizontal component sensors, and is fastened through the belt to a metallic baseplate (Figure 2). Although each geophone unit is coupled to the paved surface by a metallic baseplate instead of being firmly planted in the ground, the Land Streamer tool provides comparatively clean data unaffected by traffic noise, even on pavement. Technical specifications for the S-wave type Land Streamers we have manufactured are listed in Table 1.

STREAMER TYPE	LS-1	LS-2	LS-3
No. of Channels	48	48	48/24
Natural Frequency	28 Hz	28 Hz	40 Hz
No. of Elements	2	2	1
No. of Belts	2	1	1
Channel Spacing	50 cm	30 cm	20 cm
Length of Active Section	23.5 m	14.1 m	9.4/4.7 m
Total Length	30.0 m	23.5 m	20.5/15.5 m
Geophone Unit	Detachable	Detachable	Fixed on Belt
Total Weight	Ca. 180 kg	Ca. 70 kg	Ca. 80kg

Table 1. Technical specifications of S-wave type Land Streamers

Similar tools were proposed by Van der Veen and Green (1998), and Van der Veen et al. (2001) developed a P-wave type land streamer. They adapted the concept of the snow streamer (Eiken et al., 1989). These streamers were developed from the towed land cable (Kruppenbach and Bedenbender, 1976) and had common characteristics: P-wave type, gimbal-mounted geophones; and branch connection of the geophones to the signal cable. In contrast, as shown in Figures 1 and 2, our Land Streamer features specially designed geophone units and baseplates, attached to a belt (Inazaki, 1998) or fastened to a pair of ropes (Inazaki, 1992). The basic design of our Land Streamer has been followed by some researchers (Pugin et al., 2002; Miller et al., 2003) since its publication (Inazaki, 1999). Recently, we have developed a new P-wave type Land Streamer (Inazaki, 2003), and a surface-wave type (Hayashi et al., 2003) with the same features mentioned above.

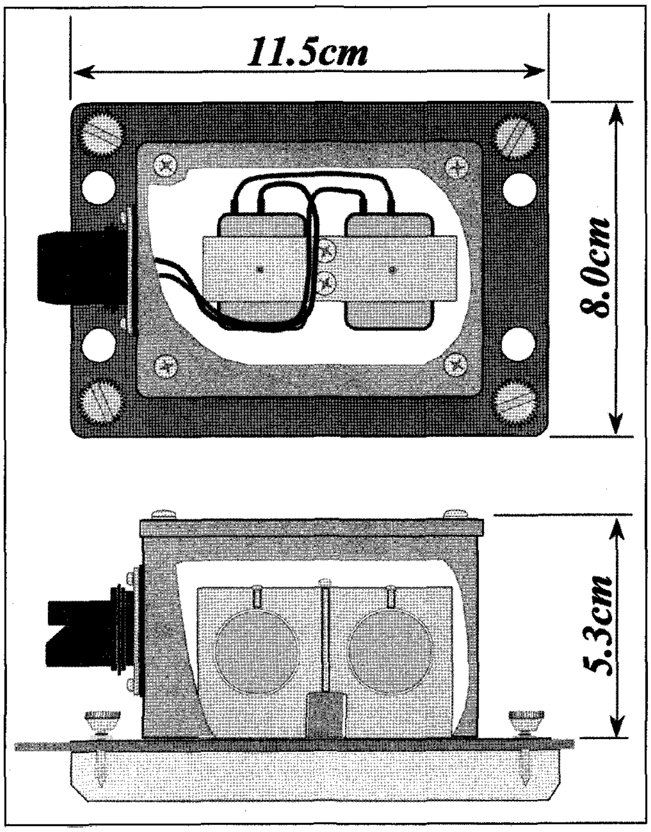

Fig. 2. A layout diagram for the S-wave type geophone unit and its mounting on a woven belt with a metallic baseplate. (revised from Inazaki, 1999).

Effect of Pavement

Figure 3 is an example of typical shot gathers recorded using the Land Streamer on the sidewalk of a three-lane highway carrying heavy traffic (over 30 000 vehicles per day). Although several traces show ringing noise due to poor coupling, clear

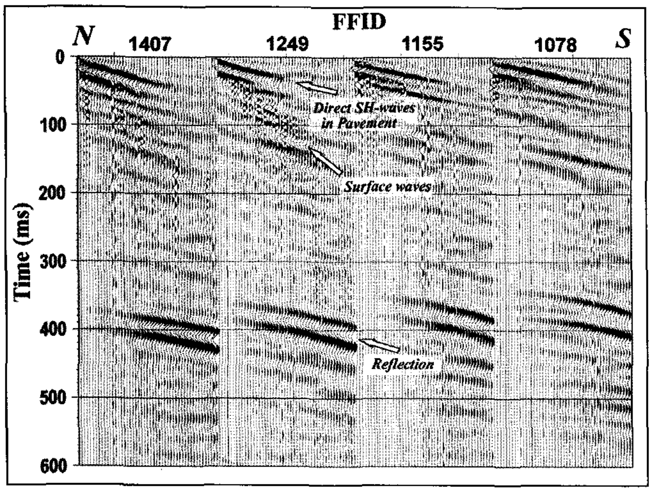

Fig. 3. Typical shot gathers recorded at four locations along a line set on the sidewalk of a busy trunk highway. The raw data were processed with only individual trace scaling. A clear reflection is obvious at 400 ms, whereas the surface waves are faint.

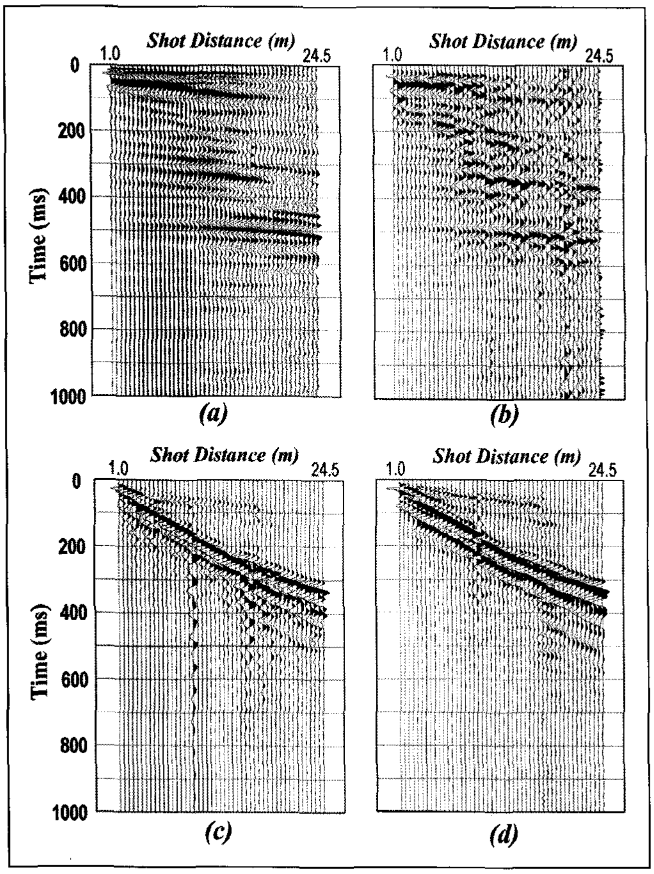

Fig. 4. Comparison of common shot gathers obtained on a paved road (upper two panels), and on the road shoulder (lower two) using the Land Streamer (left-hand two panels) or conventional spike geophones (right two). Note that the Land Streamer record on a paved road (a) is very clean whereas the shot record by means of spike geophones set on the pavement (b) shows irregular waveforms. Surface waves are dominant and no reflection events can be traced in either shot record obtained on the soft shoulder in the same site using Land Streamer (c) or spike geophones (d). The raw data were processed with individual trace scaling and band-pass filtering. (revised from Inazaki, 1999).

reflection events are obvious at 400 ms, and these show two-way times increasing to the north. Note that direct SH waves propagate within a pavement layer with a velocity of 450 m/s as first breaks, and that surface waves are faintly observable. The low amplitude of surface waves is one of the major advantages of S-wave reflection surveying on pavement. Figure 4 compares common shot gathers recorded at the same site under the same geometry but with different surface conditions or different tools (Inazaki, 1998). Distinct reflection events are evident at about 250 ms and 500 ms in the shot gather recorded on the pavement using the Land Streamer (Figure 4a), but the corresponding reflection events have some timing undulations in the shot gather acquired with spike geophones, which were set in clay blocks on the pavement (Figure 4b). The orderly alignment of reflection events in the Land Streamer record demonstrates the superiority of the baseplate compared with spike and clay block in coupling with the pavement. On the other hand, surface waves are dominant in both shot gathers obtained on the soft shoulder of a road (Figures 4c and 4d). We can barely identify the direct SH waves in the time-window before the surface wave arrivals, and reflection events are not evident in these records. These observations may indicate that the pavement surface acts as a strong reduction filter against surface waves. We have checked the effect by means of a specially constructed sidewalk model, and even 5 cm asphalt surfacing, without road base layers below, is sufficient to suppress surface waves (Inazaki, 2002). We therefore need not take account of the "optimum window", which had been believed to be an essential factor in acquiring high-resolution reflection seismic data (Hunter et al., 1984), when conducting S-wave high-resolution reflection surveying on paved areas.

Field Operation

High-resolution shallow seismic reflection techniques are powerful tools for delineating near-surface geological structures, but conventional fieldwork is very time consuming and costly, requiring the layout of geophones and cables, and their regular movement along a survey line. The Land Streamer tool can reduce fieldwork effort, and minimise site occupation time, for a reflection survey. Particularly in urban areas, where surfaces are mostly paved and heavily used, the tool demonstrates its appropriateness in such public spaces as streets, sidewalks, and park areas.

It takes only 10 to 20 seconds to tow or move up the Land Streamer tool to the next station, but generation of SH waves in paved areas does pose some problems. It is possible to generate SH waves mechanically and efficiently, but it is hard to suppress pre-event noise originating from mechanical sources. Hence, we have adopted the plank-hammering method to obtain a polarised SH-wave impulsive signal. In this method, one end of a wooden plank is struck horizontally using a wooden hammer. The wooden plank, placed on the paved surface at right angles to the survey line, is loaded by the blade of a mini-dozer or the shovel of a mini-excavator, as shown in Figure 1. The mini-excavator is also used to move the plank to the next shot point. To generate an impulsive signal, it is essential to couple the plank firmly with the road surface, by weighing it down with a heavy mass, so that the plank does not slip when struck. An ordinary four-wheel vehicle is inadequate for the purpose, because movement on its suspension coils affects the signal waveform. The signal is enhanced by 2- to 8-fold vertical stacking of the hammer blows. Because vertical stacking can result in poorer resolution if the triggering is imprecise, we utilize an electrical relay switch having high precision (<5 microseconds), as well as impact resistance, as the trigger sensor. The cycle time for a shot point move-up is about 50 to 75 seconds for the usual 4-fold stacking, but the cycle time depends strongly on the number of shots stacked, and so on the

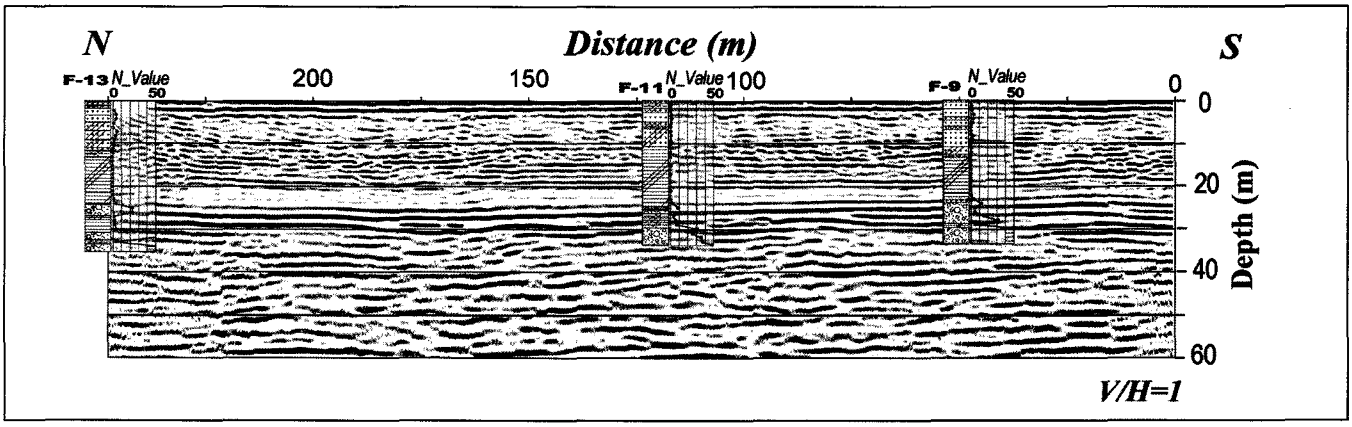

Fig. 5. A migrated depth section of Line_A, at the Tenpaku site, with geotechnical drilling data superimposed. A series of strong reflections, which is correlated with a gravel layer, is traced throughout the section.

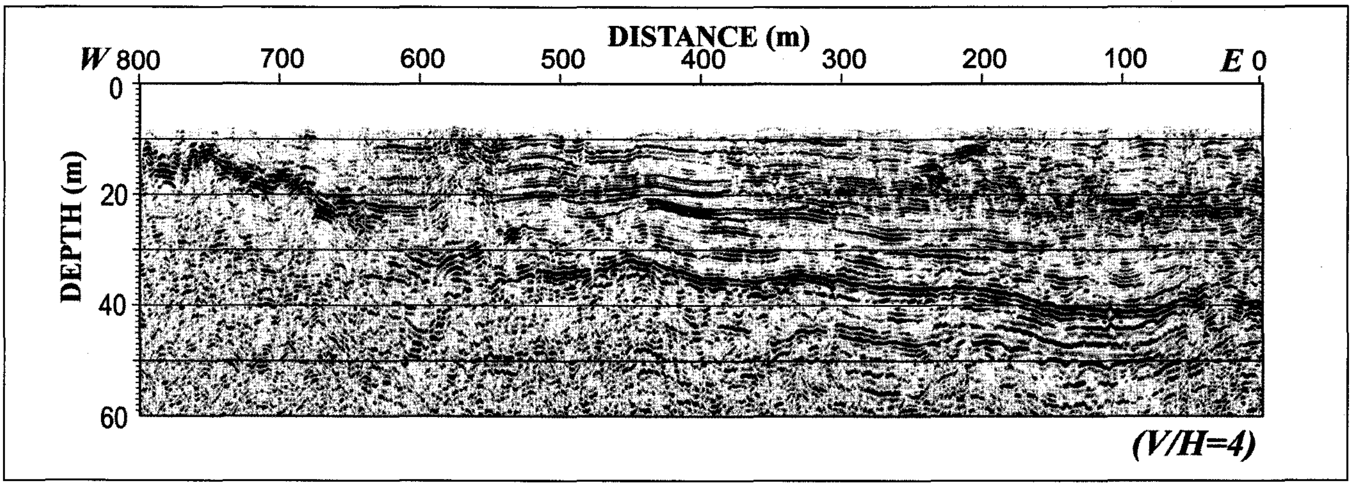

Fig. 6. A migrated depth section along line KH1_S, at Kehinomiya site. A number of reflections gently dip eastward and show wavy undulation, which may be attributed to the recent deformation of an active fault. Vertical exaggeration is set to 4. (revised from Inazaki, 1999).

noise level. The average acquisition time was about 50 shots per hour and 300 shots per day, and maximum performance reached 100 shots per hour and 500 shots per day.

HIGH-RESOLUTION S-WAVE REFLECTION SURVEYS

We have conducted nine S-wave Land Streamer tool experiments at three sites in Japan since 1997, and production surveys at 13 sites including 24 lines in that time. Overseas demonstrations were also carried out in Spring 2001, in cooperation with Bay Geophysical, Inc., and Blackhawk Geoservices, Inc. Representative results of the production and test surveys at three sites are presented below.

Delineation of the Bearing Layer at Tenpaku Site

A high-resolution S-wave reflection survey using the Land Streamer was carried out at the Tenpaku site facing Nagoya Port in central Japan, to delineate the bearing-layer topography for the foundation design for a planned viaduct. The sediments at the site are composed of Holocene soft silt and clay, unconformably overlying Neogene sediments that were regarded as the good bearing layer based on geotechnical boring. However, the depth to the bearing layer (the top of the Neogene sediments) was expected to vary because of a buried fault inferred to be at the site.

The survey line was set on the sidewalk of a trunk highway that had heavy traffic of over 30 000 vehicles a day, to traverse the inferred faulted zone. Although acquisition conditions were poor, we obtained comparatively clean data after 16-fold vertical stacking, as shown in Figure 3. Recording parameters of the survey are listed in Table 2. Both shot and receiver spacing were set to 0.5 m. The S-wave seismic source consists of an 8 kg wooden hammer used manually to strike one end of a plank placed on the sidewalk, weighed down by a mini-excavator. Average recording speed was only 24 shot move-ups per hour because of the large number of shots in the vertical stack. The net recording time was 19.5 hours over four survey days in March 1997, and 6 crew members were involved.

The data were processed on a workstation using the FOCUS processing package (Paradigm Geophysical Inc.). The initial processing steps included data conversion, geometry definition, band-pass filtering, and editing. Next, the data were sorted into CMP space. Subsequently, NMO, mute, and residual statics were applied. After CMP stacking, the data sets were subjected to velocity filtering and time-variant band-pass filtering. Finally, the depth section was obtained after AGC, time migration, and depth conversion.

A migrated depth section is shown in Figure 5. The horizontal trace interval is 25 cm, and the wavelengths in the vertical direction are estimated to be about 2 m, so it is expected that the profiles have enough resolution to assure detailed interpretation at shallow depths. A series of strong reflection events can be traced in the section at about 24–30 m in depth. These events are continuous along the line, and gently dip toward the north. A number of other reflections can be recognized above and below this series; however,

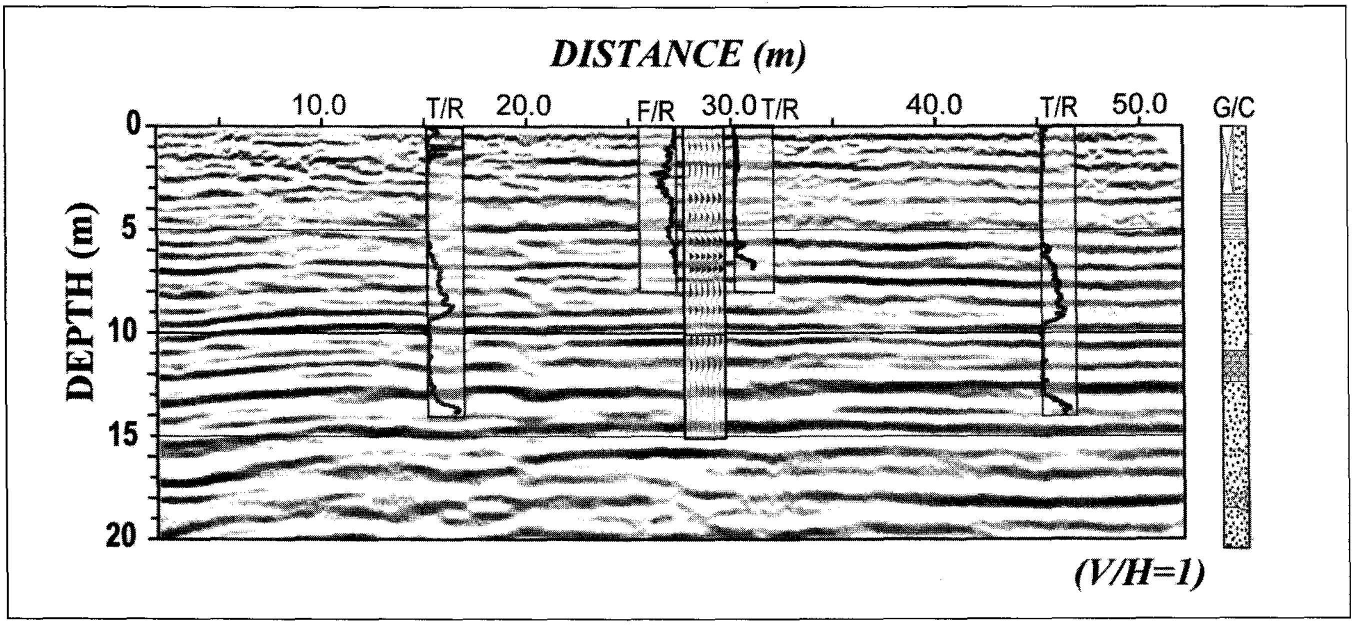

Fig. 7. A depth section of line LS_20P along a sidewalk model built in a test field. CPT profiles (T/R: tip resistance, F/R: friction ratio) at 15, 30, and 45 m, and a VSP section at 30 m, are overlaid on the section along with borehole data (G/C: geological column) from a hole adjacent to the line. (revised from Inazaki, 2002).

Site	Tenpaku	Kehinomiya	PWRI
Line	Line_A	KH_1S	LS_20P
Tool Used	LS-1	LS-1	LS-3
Survey Length	235 m	822 m	60 m
Geophone Spacing	50 cm	50 cm	20 cm
No. of Channels	48	48	48
Source Type	Plank Hammering	Plank Hammering	Plank Hammering
Vertical Stack	16	4–8	2
Shot Interval	50 cm	50 cm	20 cm
Min. Offset	1 m	10 m	40 cm
Total Record	472	1599	262
Recording System	ABEM Mk6	ABEM Mk6	ABEM Mk6
Crew Person	6	6	4
Recording Time	19.5 h	37.0 h	2.0 h
Average Speed (shot move-ups/hour)	24	43	130
Acquisition Date	Mar/1997	Nov/1997	Aug/2001

Table 2. Parameters for the S-wave Land Streamer reflection surveys

neither discontinuity nor deformation is apparent. The depth section is significantly consistent with the geotechnical drilling data that is superposed on the section. The seismic events correlate with the Holocene basal gravel (HBG) bed and the underlying Neogene gravel layer. Moreover, the depths of these events are in accord with the depths where N-values increase abruptly, at each drilling point. It is well known that the N-values obtained by the Standard Penetration Test (SPT) are closely related to S-wave velocities in unconsolidated sediments. Note that the seismic events split into two in the southern portion of the section, where the Holocene basal gravel bed thickens as shown in the column labelled F-9.

Detailed Imaging of Flexure of a Buried Active Fault

Detailed S-wave seismic reflection surveys were conducted in the fall of 1997 at Kehinomiya, situated at the western edge of the Niigata Plain in central Japan. A major active fault, the Yahiko Fault, extends along the plain for over 70 km. The surveys were aimed to image detailed structure in the shallow part of the fault. The Yahiko Fault is described as a reverse fault with upthrow of the western side. The cumulative displacement of faulting during the Pleistocene is estimated to be 3000 m. However, few fault traces are recognized in the surface topography at the target site because of the thick overlying alluvial sediments. A 200 to 500 m wide flexure zone was estimated at the site from drilling data.

We placed 3 lines across the inferred flexure zone, along the paved roads at the site. The S-wave type Land Streamer was used to acquire data with a 21-bit, 48-channel digital seismograph. Recording parameters for the KH1_S line are shown in Table 3. Shot and receiver spacing were both set to 0.5 m, and the offset between the shot point and the tail of the Land Streamer was 10 m. A total of 1599 records were obtained during 6 days by 6 crew personnel. The average recording speed was 43 shots per hour. The maximum speed reached 80 shots per hour and 360 shots per day. We used the VISTA package (Seismic Image Software Ltd.) for data processing. The data processing was similar to that applied to the Tenpaku site data.

Figure 6 shows the migrated depth section of the KH1_S line. The portion above 10 m in depth is not imaged because of the large offset and resultant NMO stretch. A number of reflections gently dip eastward, showing wavy undulations. A strong reflection can be traced along the line from about 10 m in depth at the western end, descending to 40 m at the eastern end of the section. This event is correlated to the top horizon of the HBG. Furthermore, a 20-m-deep reflection onlaps onto the HBG reflection at location 650 m. The undulation pattern in the near surface layers, consistent with the shape of the HBG, and the onlap structure, strongly suggests that these can be attributed to deformation caused by recent faulting.

Ultra-shallow S-wave Reflection Experiment using Short-spacing Type Land Streamer

A short-spacing version of the Land Streamer was manufactured for ultra-shallow reflection surveying in paved areas (Inazaki, 2002). Shortening geophone spacing is one of the effective ways to obtain high-resolution images of the near surface. We focussed on depths shallower than 20 m, where various kinds of engineering works have been intensively conducted, particularly in urban areas. This zone has also been remained as a blind spot for both Ground Penetrating Radar (GPR) and the conventional shallow seismic reflection method. Taking account of line coverage speed and resolution, we set the spacing at 20 cm. We tested the Land Streamer from the viewpoints of the performance of data acquisition and resolution capability. To do the evaluation test, we first built a 60 m long asphalt sidewalk in our test field.

The CMP-stacked depth section of line LS_20P, set on the test sidewalk, is shown in Figure 7. A VSP section at 30 m and CPT (Cone Penetration Test) profiles obtained at 15, 30, and 45 m are superposed on the profile, together with a geological log from a borehole adjacent to the line. The uppermost 2 m below the surface is composed of reclaimed fill. The reconstructed profile is quite consistent with these superposed geological data. For example, an event correlating with a thin sand bed, which occurs about 5.5 m in depth and is identified in the CPT "tip resistance" (T/R) profile at 30 m, is clearly traced along the profile. An event with strong amplitude appears at 6.5 m. This correlates with the top of the main sand bed. The reflector at 9.5 m corresponds to the boundary between the sand bed and the organic soil. The reflection event representing the bottom of the surface fill can be traced at about 2.2 m. A reflection event at 3.5 m is also traced, which can be seen in the VSP and the bore log, but not in the T/R profile. This horizon is correlated with the top boundary of weathered ash fall deposits, clearly detected in the "friction ratio" (F/R) profile at 30 m.

As is well shown in the profile, ultra-shallow reflection using the short-spacing type Land Streamer can clearly image detailed structure of the subsurface shallower than 20 m. Because of the reduction in CMP fold, resolution is less in the uppermost layer. It is estimated the practical minimum detection depth is about 1 m, five times the geophone spacing for this profile.

CONCLUSIONS

The S-wave type Land Streamer is a powerful tool for high-resolution shallow reflection. The Land Streamer tool provides comparatively clean data, particularly on pavement, unaffected by traffic noise. Hence, the tool will expand the opportunity of applying high-resolution seismic reflection surveys in highly developed areas or urban areas, where the surface is mostly paved and traffic noise is considerable. Because the tool is very compact and easy to assemble, we can set it up and start up measurement within 20 minutes after arriving at a site, and minimise the time needed onsite.

We have evaluated the influence of pavement structure on data acquisition on pavement using the Land Streamer. Results showed that the pavement structure acts as an effective reduction filter for surface waves, because much of the energy of surface waves generated coherently with S-wave signals leaks downward, because of the high S-wave velocity in the pavement compared to the velocities in the underlying soft sediments. Another advantage of pavement is that it supplies a homogeneous surface condition. Therefore, static corrections are a minor issue for the Land Streamer survey on paved areas.

The results of our high-resolution S-wave reflection surveys using the Land Streamer contributed to the detection of concealed faults, the mapping of detailed structure in a flexure zone, and the delineation of a bearing layer covered with soft sediments.

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