DEVELOPMENT OF SEISMIC REFRACTION TECHNIQUE WITH FLEXIBLE SOURCES-RECEIVERS ARRANGEMENT

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DEVELOPMENT OF SEISMIC REFRACTION TECHNIQUE WITH FLEXIBLE SOURCES-RECEIVERS ARRANGEMENT

by

KIU YAP CHONG

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LIST OF SYMBOLS

$<$	Less than
$>$	More than
μ	Shear modulus
cos	Cosine
h_1	Thickness layer 1
h_2	Thickness layer 2
Hz	Hertz
lb	Pound
m	Meter
^{o}	Degree
$\sin^{-1}$	Arc Sine
t	Time
tan	Tangent
t_i	Intercept time
x	Distance from shot-point to receiver (m)
x_{cross}	Crossover distance (m)
θ_i	Incidence angle
θ_{ic}	Incidence critical angle
θ_r	Refracted angle
λ	Lame’s constant
ρ	The density of the medium

LIST OF ABBREVIATIONS

2D	Two Dimensional
D	Reflection waves
F	Normal array profile name
G	Guided waves
G10/11	In between geophone 10 and 11
IXSeg2SegY	Seismic Conversion Shareware
MASW	Multichannel Analysis of Surface Waves
PVC	Polyvinyl chloride
P-waves	Compressional waves
R	Refraction waves
R	Coefficient of Correlation
R11	New array profile name
RMSE	Root Mean Square Error
RQD	Rock Quality Designation
S	Scholte waves
S/N	Signal noise ratio
SASW	Spectral Analysis of Surface Waves
SeisOpt2D	Automatic seismic refraction processing package
S_H	Horizontal Shear Wave
SPT	Standard Penetration Test
S-waves	Shear waves
T-X	The travel time versus distance graph
USM	Universiti Sains Malaysia
V_P	Compressional waves velocity
V_S	Shear waves velocity
V_R	Rayleigh waves velocity
wMAPE	Weighted Mean Absolute Percentage Error

PEMBANGUNAN TEKNIK SEISMIK PEMBIASAN DENGAN SUSUN-ATUR FLEKSIBEL ANTARA SUMBER-PENERIMA

ABSTRAK

Kaedah pembiasan seismik adalah salah satu kaedah yang paling efektif antara kesemua kaedah geofizik yang digunakan untuk mencirikan subpermukaan tanah. Penggunaan terhad pembiasan seismik mungkin disebabkan oleh beberapa batasan yang berkaitan dengan kos survei dan kurang fleksibel. Kajian ini menggariskan penghasilan sebuah pendekatan baru dalam susunan fleksibel sumber-penerima untuk perolehan seismik pembiasan. Kaedah baru ini merupakan sebuah penyelesaian inovatif yang hanya menggunakan beberapa geofon untuk melaksanakan survei seismik pembiasan yang sepenuhnya dengan data serupa yang cukup untuk pemilihan masa ketibaan pertama untuk mengatasi batasan liputan dan ketiadaan fleksibiliti survei. Dengan menggunakan ciri-ciri asas masa ketibaan salingan, kedudukan relatif sumber dan penerima telah ditukar semasa perolehan data untuk menyerlahkan keberkesanan teknik tersebut. Data telah diperoleh menggunakan kedua-dua kaedah susun-atur seismik biasa dan fleksibel di sepanjang profil yang sama (tapak padang hijau dan tapak halangan/penyekat) untuk tujuan pengesahan sebelum menggunakan hanya susun-atur fleksibel merentasi sebuah jasad air. Keutamaan tapak padang hijau dan halangan/penyekat adalah untuk menjana masa ketibaan pertama sepadan dengan susun-atur biasa. *wMAPE* <2% dan *RSME* <10% adalah konsisten untuk tapak padang hijau dan halangan/penyekat dengan nilai korelasi yang kuat iaitu 0.99. Bagi setiap tapak, masa ketibaan pertama selanjutnya telah diproses menggunakan perisian SeisOpt2D untuk mendapatkan hasil tomografi seismik. Sebuah analisis kualitatif dan deskriptif terhadap hasil-hasil tersebut dilakukan oleh *wMAPE*, *RSME*, korelasi (*R*) dan ujian kenormalan. Hasil-hasil analisis menunjukkann peratusan *wMAPE* dan *RSME* yang rendah secara relatif, yang dikaitkan dengan korelasi yang kuat dan hasil-hasil tertabur normal. Peratusan purata *wMAPE* dan *RSME* bagi kedua-dua tapak padang hijau dan halangan/penyekat masing-masing ialah berjulat daripada 5.33% hingga 22.47% dan 8.61% hingga 26.67% dengan mengambil kira perbandingan antara susun-atur biasa dan fleksibel. Dengan nilai purata korelasi >0.85 serta nilai-nilai kepencongan dan *kurtosis* <±1.5, analisis ini selanjutnya mengukuhkan keupayaan dan keyakinan terhadap susun-atur seismik fleksibel. Tiada perbezaan ketara yang dapat ditemukan antara data yang diperolehi oleh kedua-dua kaedah. Satu garis tinjauan merentasi jasad air menggunakan susun-atur fleksibel seismik menggunakan geofon berbanding hidrofon, menunjukkan kelebihan yang jelas berbanding susun-atur biasa. Hasil tomografi seismik bagi tapak jasad air telah disahkan dengan ukuran kedalaman air *in-situ*. Hasil tomografi telah dikelaskan kepada tiga lapisan dengan halaju masing-masing. Hasil tomografi seismik yang dihasilkan oleh susun-atur seismik fleksibel boleh dianggap bersamaan dengan hasil yang dijana oleh susunatur biasa yang kini sudah diterima. Susun-atur seismik pembiasan fleksibel masih tidak sempurna akan tetapi ia adalah relevan dengan konsep, teori, dan kaedah. Berkenaan batasan susun-atur seismik fleksibel, ia boleh dibahaskan bahawa kaedah ini masih kurang matang dalam aplikasi dan memerlukan pembangunan yang wajar dari segi untuk sumber, peralatan dan perisian.

DEVELOPMENT OF SEISMIC REFRACTION TECHNIQUE WITH FLEXIBLE SOURCES-RECEIVERS ARRANGEMENT

ABSTRACT

Seismic refraction method is one of the most effective of all geophysical methods used to characterize ground subsurface. The restricted use of seismic refraction may due to some limitations associated with survey costs and inadequate flexibility of survey. This study outlines the development of a new approach in flexible sources-receivers arrangement for seismic refraction data acquisition technique. This new design is an innovative solution which implements only a few geophones to execute a full-length seismic refraction survey, with adequately similar data to pick first arrival time in order to overcome the limitations of coverage and inflexibility of the survey. Exploiting the fundamental characteristics of reciprocal arrival time, relative positions of sources and receivers were swapped during the data acquisition to highlight the efficacy of the techniques. Data was acquired using both the common and the flexible seismic arrangement (array) techniques along the same profile (green field site and obstacle/barrier site) for validation purposes before applying only the flexible array across a body of water. The priorities of the green field and the obstacle/barrier sites are to generate corresponding first arrival time with the common array. The *wMAPE* < 2 % and *RSME* < 10 % are consistent for green field and obstacle/barrier sites, with a strong correlation of 0.99. For each site, the first arrival time was further processed using SeisOpt2D software to obtain the seismic tomography results. A qualitative, descriptive analysis of the results is done by *wMAPE*, *RSME*, correlation (*R*) and normality tests. The results of analysis demonstrate relatively low percentage of *wMAPE* and *RSME*, which is associated with strong correlation and normal distributed results. The average percentages of *wMAPE* and *RSME* for both green field and obstacle/barrier sites range from 5.33% to 22.47% and 8.61% to 26.67% respectively with regards to the comparison between the common and flexible arrays. With average correlation value of >0.85 and skewness and kurtosis values of < ±1.5 each, the analysis has further strengthened the capability and confidence in the flexible seismic array. No noteworthy differences were found between the data acquired by both methods. A survey line across the water body using the flexible seismic array utilizing geophones instead of hydrophone shows a clear advantage over common array. The seismic tomography result of the water body site was validated with the in-situ water depth measurement. The tomography results were classified into three layers with respective velocities. The seismic tomography result produced by the flexible seismic array proved to be equivalent with the result generated by the common array that is currently accepted. Flexible seismic refraction arrangement is not perfect, but it is relevant with regards to concepts, theories, and methods. Regarding the limitations of the flexible array, it could be argued that the method still lacks maturity in application and proper development in terms of sources, instruments and software.

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Seismic refraction method has been applied to solve many subsurface issues in various fields such as engineering, environmental, ground water exploration, quarry mapping, downhole applications and archeological studies (Green, 1974; Laymon and Gilkeson, 1989; Oladapo et al., 2013; Bamidele and Akintorinwa, 2014; Adewogin et al., 2016; Anda et al., 2019). Recent development in seismic method studies are more inclined towards generating a new seismic data acquisition method as seen by the innovation of implementing the land streamer to enhance time efficiency during data acquisition (Green et al., 2004; Miller et al., 2003). The invention of land streamer solves the geophone coupling issue by applying weight using a metal slab for use in survey areas with no soft ground available to plant geophones (such as asphalt road and cemented compound). Overcoming this issue is crucial in order to achieve good and firm contact for the acquirement of high-quality data.

With expanding knowledge on seismic techniques and development of seismic equipment, the usage of seismic reflection method started becoming common and frequently performed especially in oil exploration (Burger et al., 2006). However, this may also be due to the urbanization and rapid development of infrastructures and utilities which caused conventional seismic data acquisition methods to become tricky as a result of overwhelming noise and limited land for survey works. Seismic acquisition techniques such as Multichannel Analysis of Surface Wave (MASW), Spectral Analysis of Surface Wave (SASW), ray tracing, and downhole are methods frequently applied in recent years to overcome the constraints faced in urban areas (Park et al., 2007; Goh et al., 2011).

However, Palmer (2007) stated that near surface seismic refraction operations are not profitable, field procedures deployed are inefficient, result produced are outdated and software packages used are obsolete. To rejuvenate and enhance seismic refraction's environmental and geotechnical applications, some improvements or innovations should be applied to the operations as whole. Seismic refraction method continues to be the most frequently applied method in shallow subsurface survey for engineering and environmental investigations despite the limitations is due to its ability to determine the thickness of subsurface layers of the earth (Saad, 2018).

1.2 Problem statement

Seismic refraction method has received rapt attention in recent decades due to its ability to solve engineering and environmental related problems. The employment of the full-scaled seismic refraction survey requires twelve (12) to forty-eight (48) receivers or geophones, which is expensive and unaffordable for low income institutions and small-scale companies. Restrictions encountered at survey sites in urban areas include limited space needed for the current design of survey line and geophone spacing due to obstructions such as roads, buildings, pedestrian paths and water bodies. Therefore, introducing flexibility in the survey can be a merit to solve this limitation. Although the acquisition speed can be increased by using land streamer, the weight of the equipment and the survey site's accessibility need to be considered, particularly for sites with thick vegetations such as typically found in tropical countries. Development of flexible seismic technique is important as the conventional techniques are starting to become unsuitable and impractical with rapid development of infrastructures. Seismic is often referred to as the cumbersome survey among geophysical surveys despite involving more individuals during surveys. It is time to consider a better technique which can reduce the total weight of equipment needed for the survey.

This study focuses on enhancing the current seismic equipment’s efficiency by developing a new flexible seismic refraction array that is practical on site and environmentally friendly.

1.3 Research objectives

This research has the following objectives;

i. To develop a new seismic refraction array (flexible array) with flexible spacing and channels.
ii. To validate the flexible array using the first arrival time with statistical analysis by comparison to the common array.
iii. To optimize the coverage of seismic refraction survey by crossing obstacles such as asphalt roads and water bodies.

1.4 Scope of study

In this study, a flexible seismic array is introduced by applying an alternate source-receiver position. On the whole, the study focuses on seismic refraction technique by comparing the common array and flexible array regardless of any subsurface supporting data that come from other available methods. The seismic refraction data was acquired using Seismograph ABEM Mark 8 (recorder), vertical geophone (receiver), seismic cables, triggering device and hammer (seismic source).

Additional steps in data processing were also introduced to rearrange the data (traces) obtained from the flexible seismic array technique into a common processable data format (.SG2) using Microsoft Excel and IXSeg2SegY software. Since the flexible array technique is designed to be flexible in spacing and channels, there are no specific/fixed spacing or channels in this study. It is mainly decided based on the suitability of the survey with respect to the target depth and data resolution needed for the survey.

Three sites were considered in this study; green field site, obstacle/barrier site and water body site. For green field site, the flexible and common seismic arrays were applied for comparison to validate the applicability of the flexible array. The comparisons focus on the one parameter which is first time arrival only between the common and flexible arrays. A certain performance barrier needs to be achieved (low percentage in error and strong correlation) before proceeding to the production of seismic tomography results by available software (SeisOpt2D). One concern is that different seismic processing software might yield different results. Therefore, only the results produced by SeisOpt2D were considered. In order to evaluate the method’s efficiency, several important parameters were highlighted such as the comparison between the number of shot points in resolving subsurface characteristic using statistical data analysis and signal to noise ratio (S/N) comparison, which are significant performance measurements in seismic refraction data diagnosis.

After deciding on the optimum shot points to be applied, the flexible seismic array was tested for the obstacle/barrier site study together with the common array to demonstrate its competency and capability. The time of the first arrival for each record were evaluated once again before applying the same relevant statistical data analysis and signal to noise test to validate the flexible array.

As the flexible array had been compared to the common array twice and validated through green field and obstacle/barrier sites, the flexible seismic array was then applied on performing seismic refraction across the water body site with geophone as the detector. The validation of arrival time cannot be done in a water body site as geophones cannot be placed on the surface of water to conduct the common array. The "noise free" site condition for the water body case is preferable to obtain the most accurate first arrival time. The flexible array in this water body site will avoid the employment of hydrophones which would escalate the cost of the seismic refraction survey.

The signal to noise ratio will be compared with the previous site study as a different seismic source (tank) is used in the survey. The data analysis and signal to noise ratio have a significance in establishing the limitations and constraints of the flexible seismic array.

1.5 Research significance and novelty

This research is focused on improvising the current seismic refraction method instead of following the trend of many recent researches that focus on improving the method by developing new equipment. The key parameter in this study is time where time has been the most used product of the refraction signal, as is the case for almost all interpretive techniques that are presently available and discussed in this research, which are actually concerned with the arrival time of the signal.

On this basis, this research work seeks to develop flexible seismic refraction array by employing alternate source-receiver positioning to solve data acquisition problems encountered due to geology or landscape settings on site, such as surveys that are carried out crossing river/water bodies, on the road or along abundant buildings. It also provides flexible geophone spacing and number of channels deployed compared to the common array.

This flexible array is maturing with the wealth of well-understood seismic refraction data to introduce an important extra procedure for data rearrangement before being spun out for commercial applications. The flexible seismic array delivers significantly similar results in first time arrival picking with the additional advantage of being able to conduct seismic data acquisition across water bodies by using geophones instead of hydrophones to calculate the subsurface velocity distribution using the first-time arrival from every data.

Some other comparisons and analysis such as signal to noise and selected descriptive analysis are applied to understand the extension of the flexible array. These measures helped identify some limitations and constraints of the flexible array.

1.6 Thesis outline

This thesis consists of five chapters. The first chapter is an introduction, which provides a general summary of the research framework in developing a flexible seismic array to acquire seismic refraction data. This chapter includes problem statements, scope of study and research objectives. The structure of the thesis is also discussed here.

Literature review of this study is presented in Chapter 2, where the background and previous studies were shown. Previously used seismic refraction methods, various site studies regarding seismic investigations, recent development of new seismic data acquisition methods, the common geometry used in seismic survey are discussed in this chapter. The overview of seismic method with emphasis on its theories and principles is presented. It concludes with a chapter summary.

Chapter 3 discusses the flexible seismic refraction array data acquisition for each site studies. This chapter includes the field design and procedures for common and flexible seismic array data acquisitions along with the parameters used, survey design and any related matters to achieve the objectives of this research. General geology, survey area and research methodology flow chart are also illustrated in this chapter.

Chapter 4 is assigned to present the results of the research findings. This chapter starts with demonstrating the findings of the common and flexible seismic array data prior to comparing the two data with each other. The first arrival time picking and seismic tomography results were examined by statistical data analysis that were carried out to show the efficiency of the flexible seismic array. Consequently, to show the effectiveness and capability of this method, the results on the site study of obstacle/barrier site and across a water body are also presented and reviewed.

In Chapter 5, a summary the major findings are provided together with the contributions from this research work and the significant conclusion from the study. Recommendations and suggestions for future research are also included.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Seismic refraction P-waves or simply known as seismic refraction is often regarded as the most cost effective and non-invasive method for subsurface characterization of site investigation at a wide range (Aziman et al. 2016). Initially, Rayleigh (1885) and Love (1911) carried out fundamental and practical studies on propagation of seismic waves. The research was developed to provide an accurate arrival time to the receivers with respect to the airwaves from the cannon shot which generally helps in locating the position of the cannon during World War I. Therefore, the seismic refraction method had its initial development from 1914 to 1918 during the war, then became a prospective method in oil and gas in the 1920s and 30s due to its establishment in the Gulf area of the United States. After the 1940s, the method became more mature and successful. This is due to the enhancement of instrumentation which had been improvised to become smaller, lighter, more portable and reliable. With the steady improvement and development in the field technique to enhance the signal-to-noise (S/N) ratio and manageability of interpretation, the application of this method spread out into on-site geological subsurface and other commercial site investigations (Sjögren, 2013).

2.2 Previous works

Several reviews of the literature regarding the application of near surface seismic investigation had detailed improvements in geotechnical characterization (Anda et al., 2019; Aziman et al., 2016; Nadia et al., 2016; Nogueira, 2014; Ismail et al., 2013; Bery, 2012). In general, the growing applications of seismic refraction method had benefitted the development of both P- and S-waves refraction through data acquisition and data analysis operation. The success of seismic data acquisition on site depends on the personnel who play an important role. Whether they are equipped with skills and experiences in both fieldwork and interpretation influence the outcome of the data. Acquisition of good quality data will consequently have an impact on the results processed (Rucker, 2006).

The suitability of inexpensive P-waves sources, the availability of various vertical component geophones, the adequacy of short spread lengths attainable with small systems, and the ability to process seismic refraction data with affordable software packages have all contributed to the near-surface community’s increased activity in seismic refraction surveys over the past decade.

2.2.1 Seismic refraction general applications

This method has met with great success in delineating and solving many subsurface problems. Since then, the seismic refraction method has been widely adapted in the field applications of crustal geophysics, reconnaissance surveys in sedimentary basins, structural engineering, and mining geophysics.

According to Xia et al. (1999), the near surface S-waves refraction method effectively mapped out a series of horizontal layers for the study area in Wyoming, United States. Conversely, theoretically the deduction of horizontal layers may not fit with the complex near surface geology due to the S_H-waves with wave-type conversion along an interface in a subsurface with non-horizontal layers. Based on the real example done in the Wyoming study, the shallow S-waves refraction study yielded velocities of a converted wave rather than the desired S_H-waves. Therefore, The P-waves refraction survey is favorable for the verification of the converted waves.

In addition, this method can be used to map the subsurface structure, as demonstrated by Al-Ghani & El-Behiry (2011) about the interpretation of the seismic tomography results done by a study using seismic refraction is shown in Table 2.1. Although this study demonstrated the effectiveness of seismic survey to successfully map the subsurface structure, the existing study had a constraint in the form of inability to accurately identify the water table.

Table 2.1 Compiled relationship among rock types, seismic velocities and rippability (modified from Al-Gharni & El-Behiry, 2011)

Subsurface strata	**Seismic Velocity (m/s)**	**Rippability**
Soil layer (all types)	< 1100	Easily ripped
Pebbles/boulder mixed layer	1050 - 1060	Moderately difficult
Weathered rock layer	1600 – 2500	Difficult ripping/light blasting
Hard to massive rock	>2500	Blasting required

Based on the observations of the research done by Bery (2012) using seismic refraction and resistivity methods, the amount of water accumulated (during raining season) is an important key to justify the safety factor of the slope. The significance of this study is the determination of strength and physical properties of the soils from geophysical methods.

A study using seismic refraction (Aziman et al., 2016) was done at the boundary of volcanic formation and quaternary marine clay; thus, the rock head is expected to be undulating. The depth of the velocity profiles obtained is 20 m. The P- and S-waves studies were conducted using vertical and horizontal geophones respectively. Velocity profiles were classified into three layers based on the soil velocity of the P- and S-waves. Both seismic profiles yielded a good correlation with the borehole soil profiles. The borehole indicated that the soil layer consists of silt, sand and gravelly sand with shallow bedrock up to 9 m depth. Soil was categorized based on SPT N-value, where the first layer was classified as loose layer up to 6 m depth, followed by a dense layer up to 9 m and a rock core up to 15 m. Figure 2.1 shows the plot of SPT-N values with depth. The depth where the rock head began was identified using the P- and S-waves velocities, which were estimated to be above 3000 m/s and 1500 m/s respectively.

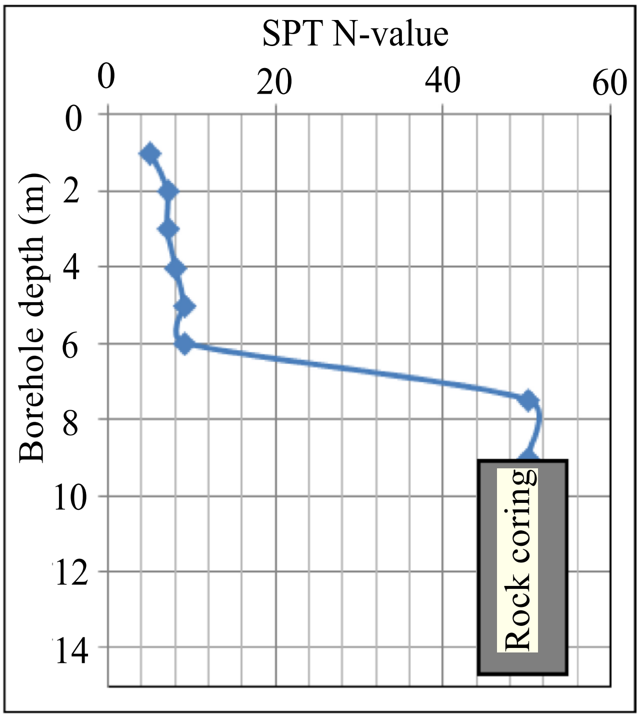

Figure 2.1 Plot of SPT N-value with depth (Aziman et al., 2016)

The latest techniques for surface wave measurement enable the acquisition of seismic refraction P- and S-waves using the same field equipment and geophone arrays settings (Rucker, 2006). This study was done by laying out a 36 m length survey line using a standard 12 channel signal enhancement seismograph and a sledgehammer energy source for seismic refraction measurements with 3 m geophone spacing and 1.5 m hammer spacing to the nearest geophone to provide adequate depth of investigation and near surface resolution for geotechnical inspection. Typical objectives for transportation work include rock or cemented soils cut excavation and swell factor characterization as well as assisting in bridge foundation and scour assessment (Rucker, 2000). Sampling rates of seismograph are typically 32-128 µsec for P-waves and 200-2000 µsec for S-waves. In this case, the P- and S-waves data interpretation was done under the standard approach. The P-waves results provided an effective constraint of velocity profile for the upper layer and indicated the absence or presence of a significant velocity reversal condition that can be identified by the S-waves which yielded greater depth of investigation for the presentation of final data sets. The results for the P- and S-waves are used to complement each other to overcome data constraints and validate the data sets. The P-waves results provided an initial model for S-waves velocity profile interpretation. The study concluded that Vs is about one-half of Vp at the shallow layer.

The study of Cha et al. (2003) illustrated the result of a shallow marine seismic refraction survey with two ships, two series of 12-channel hydrophone arrays on the seabed and a borehole sparker or percussion powder as seismic sources (Figure 2.2). Weights were attached to the ends of the cables to fix the position of the hydrophones. In general, a refraction method would produce relevant results if the ground is relatively flat, and velocities increase with depth. Correlation of both refraction investigation and drilling logs showed a remarkable consistency in seabed lithology. Therefore, to investigate the basement structure of coastal areas, rivers, and lakes, refraction method is an efficient and cost-effective way.

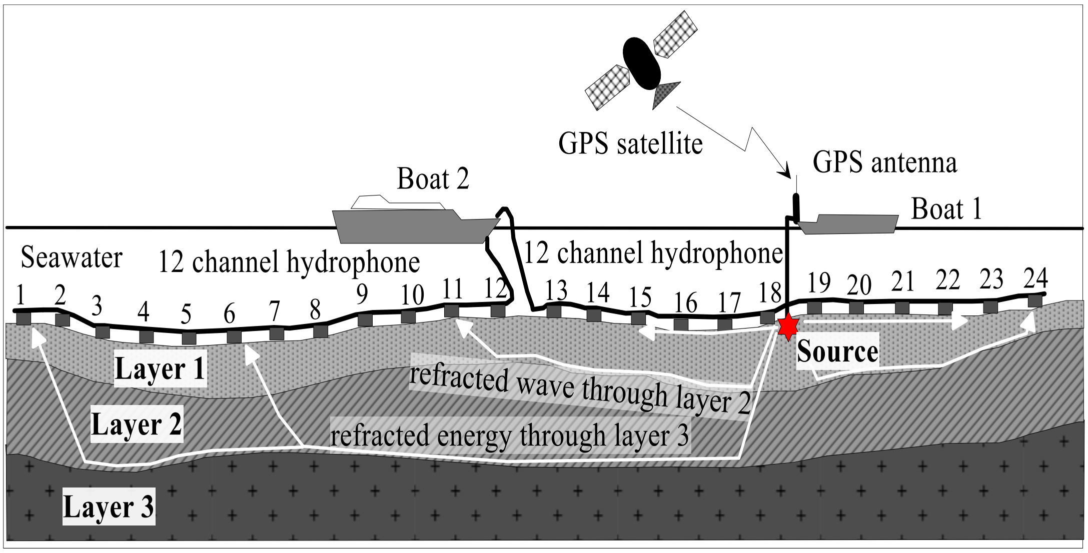

Figure 2.2 A schematic diagram of the water bottom refraction survey (Cha et al., 2003)

In the recent decade or so, the work by Grelle and Guadagno (2009) led to the growth of awareness in using seismic refraction method for exploration and development of hydrological reservoirs. The study included the procedure to identify groundwater levels by means of seismic refraction profiles by assuming that the shear waves velocity, V_{SH} increases at a much lower rate than the compressional waves velocity, V_P in a saturated soil. The objective of this survey is to identify the water table. Seismic refraction surveys of the P- and S_H-waves were performed on the same line with the same geometry in order to obtain a perfect overlay result. Based on the propagation of the P- and S-waves in the unsaturated and saturated media, a water seismic index (WSI) was defined which correlated to groundwater level. One of the major aims of this study is to create awareness and increase the use of seismic refraction data to explore and develop hydrological reservoirs. The P- and S_H-waves data acquisition array are shown in Figure 2.3 with 5 equally spaced distance shots. No offset shots were reported in this study for both refraction studies.

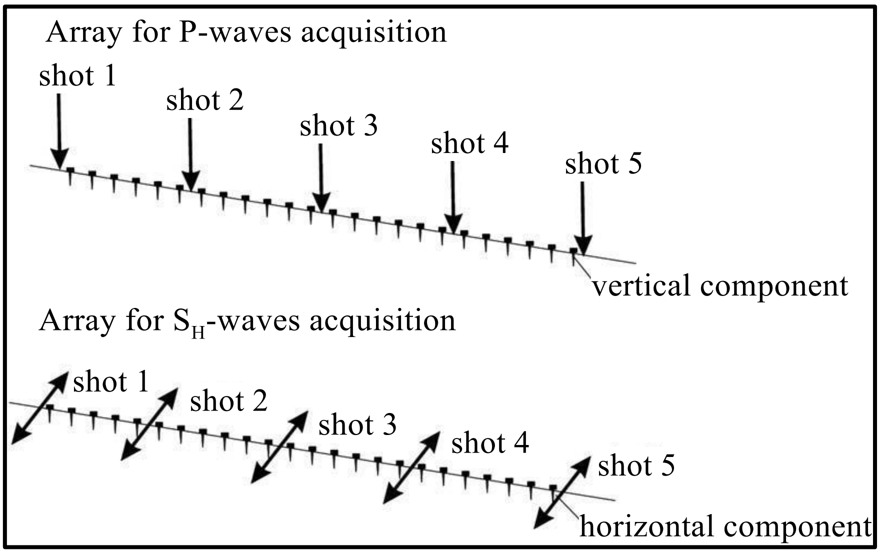

Figure 2.3 Array and typology sources of the P- and S_H-waves (Grelle and Guadagno, 2009)

Seismic refraction method was applied by Adewoyin et al. (2016) to obtain information on the depth of specific layers in the subsurface and to determine the strength of each subsurface layer. The main purpose of the study is to deduce the most competent layer for the construction of pile foundation. Seismic refraction method delineated the third layer as the most competent layer which is between the depth of 7.5 m and 18 m into the subsurface. This also correlated well with geotechnical investigation by percussion drilling test and cone penetration test.

According to Green (1974), the seismic refraction survey has been the most successful method in delineating problems located <100 m in depth. This method obtained reliable results, including bedrock depression in coastal dune area, location of ancient buried river channels, measurement of overburden thickness for proposed roads, depth of underground pipelines and quarry site investigations. This method can determine the composition of rock and hence the possibility of removing the rock by bulldozer, ripper or explosive and can also determine the interface depths and rock types for foundations or structures such as buildings, bridges, tunnels and dams.

Several cases of seismic appplications have been mentioned, some focusing on engineering and environment, others on geology. One of the tough challenges for all researchers in this domain is to develop and improve this method by revising and reinforcing some new ideas. The seismic refraction started to become a more common practice by an enormous number of scientists since the 1920s when reports on this method first started to emerge. The rapid evolution of this method happened when this method is fostered by near surface study. Seismic refraction carries a great prospect for research due to the infrequent practice compared to other geophysical methods.

2.2.2 Highlight of the data acquisition

According to Saad (2018), the seismic refraction shot points must be located in-line with the layout survey line. It is recommended to have five shot points in-line and two far end offsets (one on each side) to obtain optimal information with respect to the overburden depth. There is no fixed equation to determine the distance of an offset as the offset shot is used to locate the last layer with only single velocity gradient detected if possible. It is also advisable to take the shot at the start of the line to estimate the offset distance so that it can cover the last layer (Saad, 2018). Several authors such as Anda et al. (2019), Nadia et al. (2016) and Ismail et al. (2013) had applied similar arrangement of shot points' locations for seismic refraction surveys in archaeology, environmental and engineering applications.

An investigation of seismic refraction application by Al-Gharni & El-Behiry (2011) was done on the shallow subsurface at Wadi Thuwal, North of Jeddah with a total of 5 shot-points (Figure 2.4). As mentioned before, 5 shot points were performed on each spread of the seismic survey; two offset shots, one forward, reverse and shot in the middle of the spread. As this method have been successful over the years to delineate and map out the subsurface structure, this study also attempted to utilize the survey results to determine the water table depth and evaluate the hydrogeologic conditions with the geological structure (faults and fractures) identified.

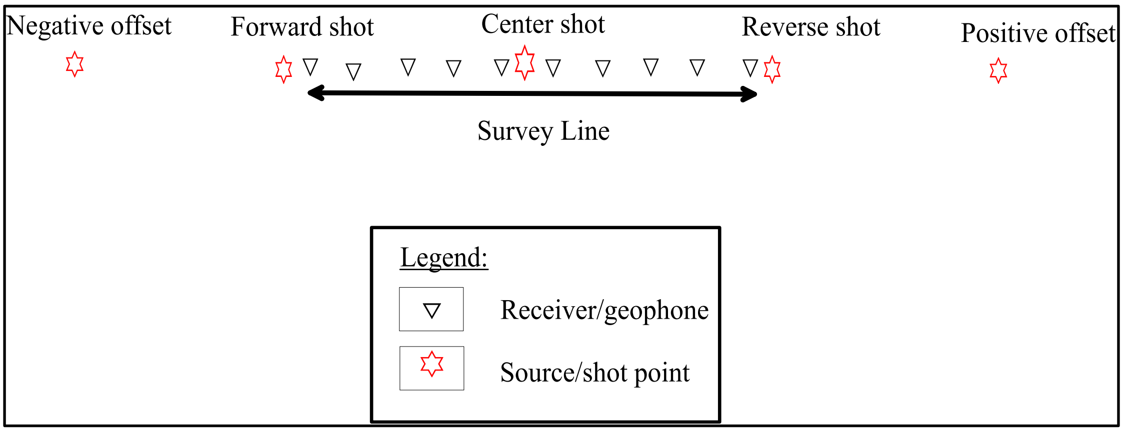

Figure 2.4 Schematic plan of field seismic refraction survey layout (modified from Al-Gharni & El-Behiry, 2011)

A study of P- and S-waves using seismic refraction method was conducted at Sejagung Sri Medan (Aziman et al., 2016). This study also employed 5 in-line shot points; as well as 2 far offset shots (Figure 2.5).

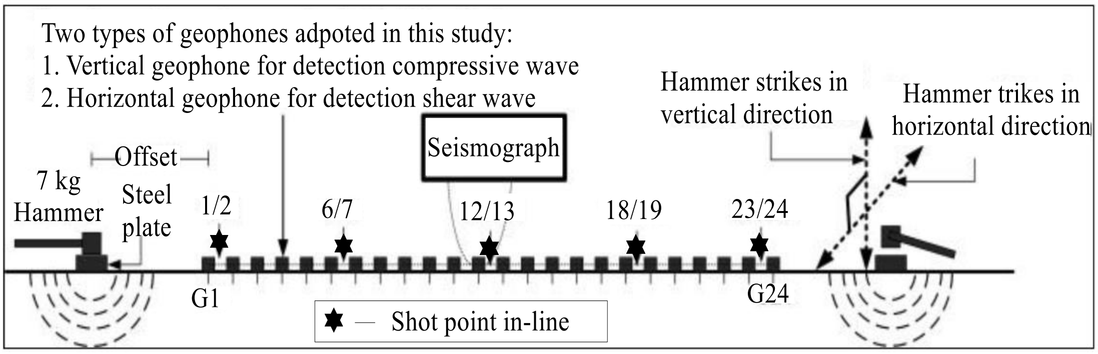

Figure 2.5 Shot point locations for seismic refraction method (Aziman et al., 2016)

Seismic refraction is one of the methods employed by Bery (2012) to monitor the stability of slope for the residual soil site in main campus of Universiti Sains Malaysia (USM). A fixed spacing of 1 m for a 24 channel seismic survey was conducted using 14 Hz geophones and ABEM Terraloc Mark 8. This survey utilized a sledgehammer as the source for 15 shot points (6 offset and 9 in-line shots) along the survey line in order to get detailed tomography results to correlate with the resistivity method.

Brixova et al. (2018) presented a review of several case studies using seismic refraction tomography method in Western Carpathians, Slovakia. There are 4 types of study cases (Table 2.2) conducted in four different locations with the aim of mapping the shallow subsurface. The first site covered the archaeological study at Katarinka and the second site estimated cold ash thickness at the thermal power station. The third and the fourth cases were done to locate the groundwater level at the western part of Slovakia and delineate the fault border between the Turiec Basin and the Mala Fatra Mts. Generally, all these cases had simply represented the application of seismic refraction for archaeological, environmental, engineering and geological investigations. All the results from these studies are significant where the basement of subsurface was mapped out, the coal storage ran at about 20m depth and the groundwater depth was 3.35m. Lastly, the seismic results were used to map out the fault and fracture in the subsurface in each of the four cases respectively.

Uyanik (2010) did a study on unconsolidated topsoil using P- and S-waves with a target depth of 1 m to obtain velocities that would reduce the effect of disturbance from air waves. In this study, vertical and horizontal components’ geophones (100 Hz) were connected to a 12-channel digital recorder to record seismic P- and S-waves respectively. The 12 geophones were grounded in a line with 0.2 m spacing (Figure 2.6). A total of 6 offset shot points were applied in this study located at 0.3, 0.6 and 0.9 m from both ends of the line. The P-waves source was generated by hitting a 1 kg plastic hammer on a wooden cone at each shot points. The S-waves energy source was impulse in nature, generated by hitting to the left or right end of the flat-lying square timber with a human as the load on top. The purpose of the loaded weight is to increase the friction between contact area of the timber and ground surface. The result produced V_P value of very near surface soil lower than V_P value in air (330 m/s) and a ratio between V_S over V_P of about 0.67 in dry unconsolidated top-soils. The advantage of this study is applicable in near surface construction work to determine the amount of organic layer of topsoil to be removed until the V_S/V_P ratio is less than 0.67.

Table 2.2 Setup of seismic data acquisition for the different case studies (Brixova et al., 2018)

Seismic data acquisition setup	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Geophone spacing	2 m	5 m	3 m	5 m
Total channels	24	36	36	36
Geophone frequency	10 Hz	4.5 Hz	4.5 Hz	4.5 Hz
Negative offset location	-2 m	-20 m	-24 m	-2.5 m
Positive offset location	2 m	20 m	24 m	2.5 m
Source spacing	2 m	20 m	12 m	10
Total shot points	26	11	12	20

Oladapo et al. (2013) carried out a seismic refraction study at Gurara Dam Phase II proposed site for dam construction. The surface investigation involved off-end/reverse and split spread shootings on five profiles at 120 m length each. A total of 7 shot points were recorded for each spread consisting of 2 far end offsets with lengths of 30 m from each spread end and 5 equally split distance shots. Stacking the shots several times was done to increase low signal to noise ratio for good data recording. Noticeable seepage characteristics were present in the seismic refraction results conducted on the Gurara Phase II dam axis from spread 1 and 2 out of five spreads. The weak zone delineated on spreads 1 and 2 of the river indicate buried stream channel characteristics that need attention.

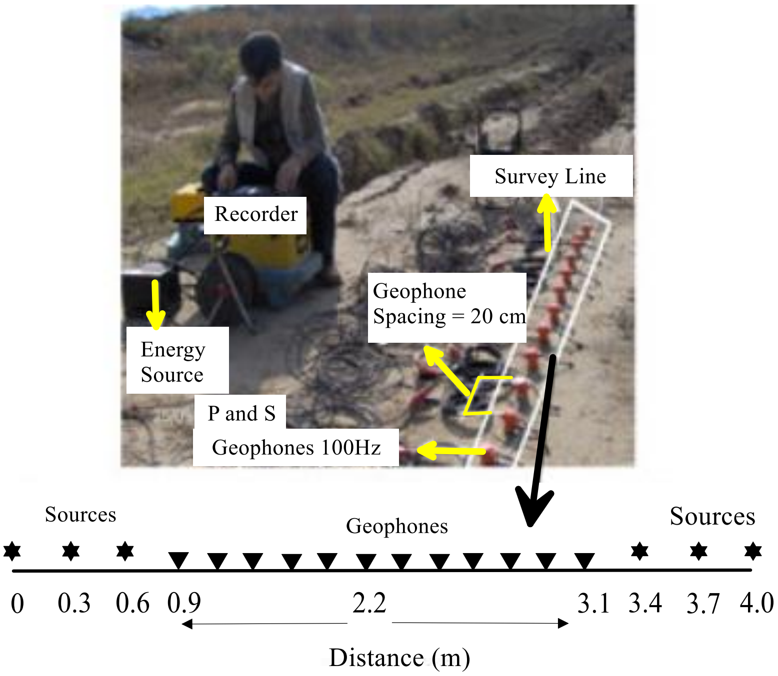

Figure 2.6 Very shallow /high resolution seismic refraction survey (Uyanik, 2010)

Laymon and Gilkeson (1989) successfully carried out a seismic refraction survey for groundwater exploration with 4 shot points on each spread using 12 channels seismograph. The shot locations were located at both ends of geophones 1 and 12 and the offset shots were done one geophone spacing away from both ends. The reason behind having the geophones 1 and 12 shots was to check for the travel times of both shots. They should be the same since the wave travelled along the same path (Figure 2.7). The process was done for all 3 spreads (Figure 2.8). The application of stacking enhanced the signals and functioned as a multistage high-cut filter, a multistage low-cut filter, and a notch filter which can be used to remove disturbance from the power line (50 Hz or 60-Hz). These pre-data acquisitions can be utilized to help diminish noise and provide clearer signals.

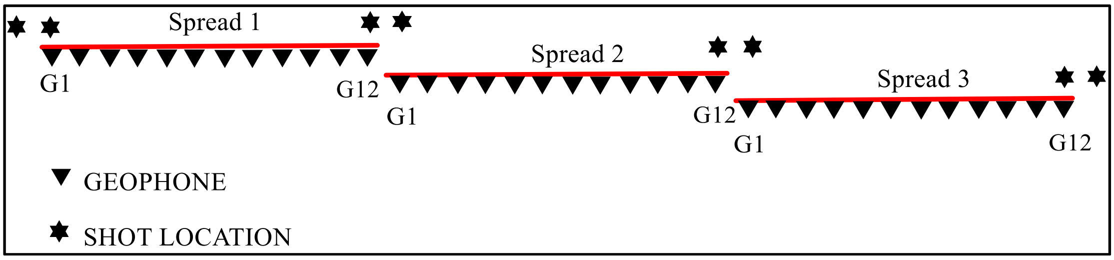

Figure 2.7 SIPT method for seismic data acquisition (Laymon and Gilkeson, 1989)

Two case studies by Cha et al. (2003); Case I and Case II were considered (Table 2.3) with different locations, source types, tidal range and bathymetry settings. The number of source points for this study was suggested to be 7 to 10 points per spread.

Table 2.3 The site summary of the field examples (Cha et al., 2003)

	Case I	**Case II**
Location	Mokpo (the Yellow Sea)	Busan(the East Sea)
Bathymetry	Less than 3 m	3 ~ 15 m
Tidal range	3 ~ 4 m	Less than 1 m
Source Type	Electrical sparker	Percussion powder
Num. of receiver	24 channels	24 channels
Num. of source per a spread	7-10 points	7-10 points

To characterize reclaimed land for geotechnical parameters, Adewoyin et al. (2016) had conducted shallow ground seismic refraction for the site investigation. The survey used a 24-channel seismograph system with constant geophone spacing. The shot points were termed the offset (-2 m), quarter spread (between 6th and 7th geophones), mid-spread (between 12th and 13th geophones), three quarter spread (between 18th and 19th geophones), and off-end shots (+2 m) respectively. Multiple shots along the profile was done to obtain adequate coverage of the refractor surface and to provide adequate lateral resolution. Time-distance graph was plotted with seismic refraction processing software after the first arrival picking of the P-waves were done.

Patskan and Quesada (2006) carried out the MASW method on a flat obstacle/barrier covered area for shallow seismic investigation. The seismograph used was Geometrics Geode Seismograph with Geostuff land-streamer which consisted of 24 units of 4.5 Hz Mark vertical geophones. The constant spacing between geophones was set at 0.65 m with an offset of 4 m from the end of the line. The spread and shot points were moved forward in 1.50 m increments. An unexpected seismic refraction event occurred according to the data acquired; where soil velocities were much slower than those of the obstacle/barrier surface. The seismic refraction analysis showed that the P-waves velocities for a first layer were 213 m/s, and refracted waves were between 457 to 762 m/s. Both models were used to examine up to approximately 9.2 m depth. The refraction results were unexpected but provided a beneficial addition to the exploration of the site and can be applied in similar environments.

Redpath (1973) discussed the idea of carrying out seismic refraction survey across a river or water body where the line of detectors was laid either across the bottom of the river or floated on the water surface. However, these procedures are considered impractical since the survey requires special cables and detectors. Fortunately, theoretically refraction shot and detector are interchangeable. A consideration was made in that the arrangement of having detectors along a line crossing a river with shots on the banks can be reversed; so that the detectors are now on the banks and the shots are in the river (Figure 2.8). The detector/geophone on the far bank were connected to the recording instrument by a cable running across the water body. Since the shot can be instantly transmitted to the seismograph, the distance of the shot from the detectors can be determined and recorded in the seismograph. In some cases, the distance from shot to detector was determined by recording the direct arrival of the explosive impulse through the water. If the detectors are placed very close to the water's edge, the shock arrival through the water can often be seen on the record as a high-frequency signal. With the water velocity of ±1500m/s, the distance to the shot can be determined easily. The arrival times and distances were plotted and interpreted using normal processing software. However, in some cases of overwater surveys, it may not be possible to place detectors on the ground simply because the body of water is too large, or the disturbance of the current may affect the work process.

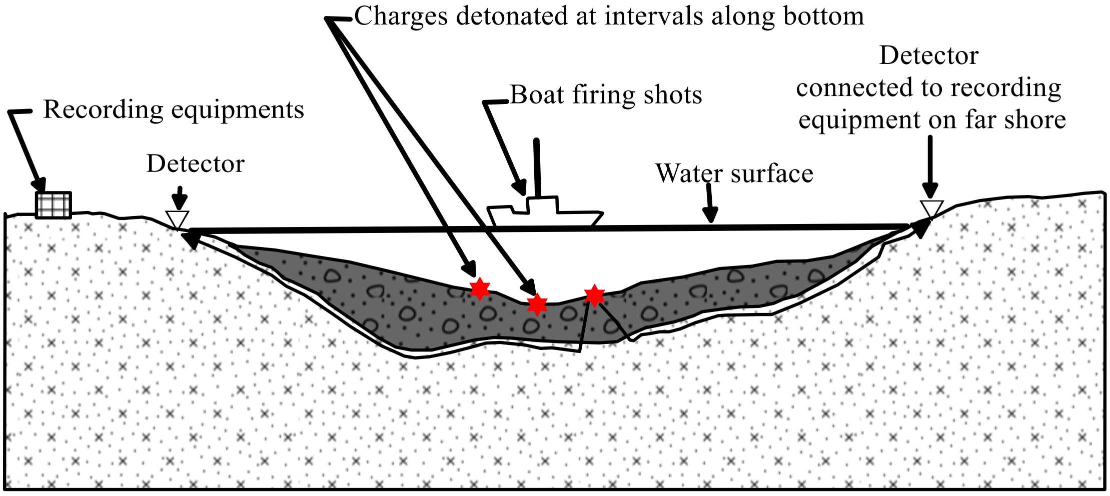

Figure 2.8 Schematic of refraction survey across body of water (Redpath, 1973)

All seismic refraction research so far had focused on horizontal array more than any other types of possible arrays. Hunter & Pullan (1990) had gone out of the box to execute a vertical array seismic investigation at Ottawa river (Figure 2.9) to study subseabottom unconsolidated sediments with the aim to encounter the engineering problem. The primary target of array was for application on the ice-covered waters of continental shelves especially in northern part of the globe with the added capability for application on deep ice-covered rivers or lakes and can also be performed in open waters with a two-ship operation. The vertical array had proven to be more effective in determining the velocities of subseabottom unconsolidated sediments while horizontal array is more accurate when delineating the subbottom bedrock. This study had conducted a few validation investigations which include the vertical and horizontal array sensitivity comparisons, the tolerance of the minimum and maximum misalignment angle of the vertical array and the effect of the water depth layer on the results. The vertical array had raised some attention and has since been applied by other researchers such as Riedesel et al. (1999), Wang et al. (1999) and Wang & Li (2002).

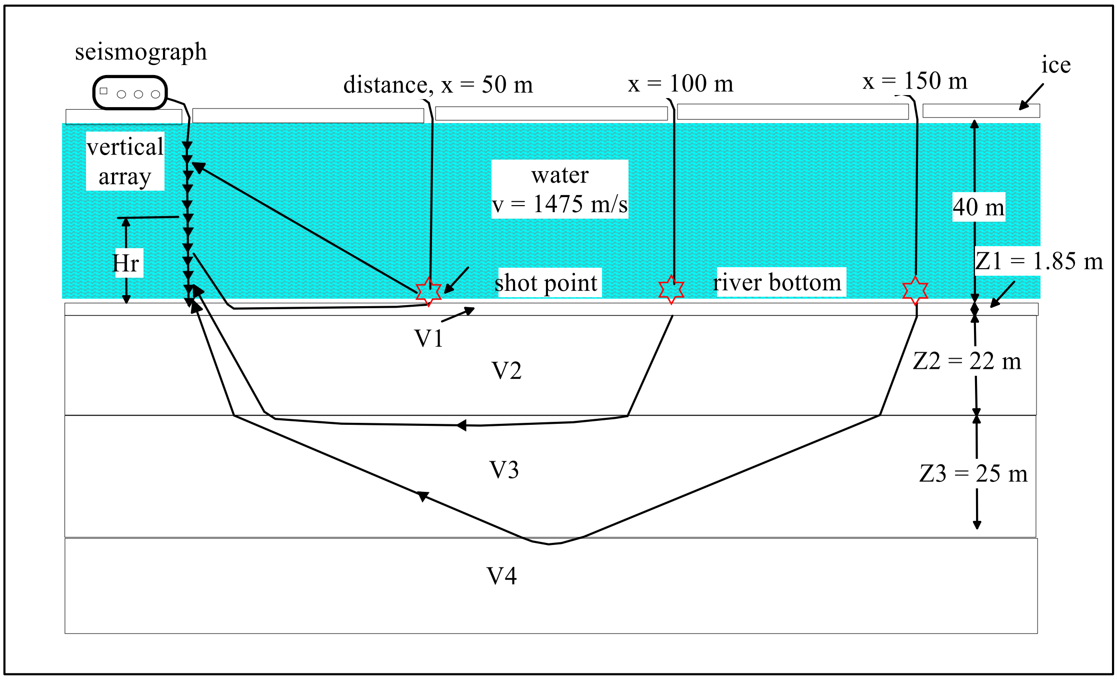

Figure 2.9 Field set-up for the Ottawa River vertical array experiment (modified from Hunter & Pullan, 1990)

An important question that has not been addressed by the highlights of the review is the importance of inline shots and whether or not the addition of more near offset shots can help resolve the near surface layer. There are no fixed shot points in each of the surveys conducted and sometimes it can change to suit the design of the surveys. To illuminate an uncharted area, the last two literatures in this section have become the study motivation.

2.2.3 Limitations of current method

Sloan et al. (2013) conducted a study to determine the feasibility and limitations of near surface seismic refraction and surface waves to detect and localize a shallow tunnel in unconsolidated sediments. Air filled cavities could be detected by using multichannel analysis of surface waves (MASW) method, but the seismic refraction tomography showed only a small variation in the tunnel's location. This study concluded that under such geological settings, these methods are not the best choice to locate clandestine tunnels, and that integration of geophysical methods would be most favorable for this purpose.

Paine (1999) conducted a study on geological information and seismic refraction data which were analyzed together with measurements of the Falling Weight Deflectometer (FWD) that correspond to the rock types. It is difficult to identify the relationship between the physical properties by rock type and the pavement deflections according to depth. A refraction system optimized for on-pavement use was designed and fabricated based on the success of the refraction experiments in acquiring significant data for pavement analysis. New instrumentation for the system includes a portable seismic source, a recording array with reduced distance and weight, and used less detectors compared to previous system with fixed locations for source points and detectors. A foldable series of sections makes up the recording array, and the seismograph was capable of recording and filtering refraction data, selecting first arrivals, and analyzing refraction data. This instrument was used to acquire refraction data on pavement, select first arrivals, and calculate compressional wave velocities and layer depths.