

A Developed Shear Wave Source for Shallow Seismic Survey

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Abstract

Shear wave velocity is a fundamental parameter in determining geological structures and soil characteristics for geotechnical and earthquake engineering studies. In shallow seismic data acquisition, shear wave is generated by various seismic sources. Although the data quality is affected by the choices of the seismic source, applying highly efficient sources is sometimes limited for some users and by the budget available for a project. Therefore, this work aims to design and develop an effective shear wave seismic source as an alternative for shallow seismic surveys. The developed source consists of 4 main parts, including base plate, activated mass, lifting and shooting system, body and transportation system. It is simply operated by lifting an activated mass with a sling and puller to the armed position. Under this condition, an attached spring is under compression and the maximum potential energy is stored. When the mass is released and horizontally hit the base plate, shear wave is generated by the momentum and energy transferred from the base plate into the ground. To evaluate the source capability, a comparison of the conventional and the developed source was performed at a test site. The recorded data were compared both in qualitative and quantitative manners based on the signal-to-noise ratio, energy and frequency content, signal penetration, and repeatability. It was found that signal energy generated by one blow of the developed source is equivalent to approximately three-fold of the conventional source. There is a remarkably higher repeatability from the developed source than that from the conventional source. Moreover, it is easy to operate, portable, and minimizes required man power. Overall, the new shear source is suitable and has potential application for shallow seismic surveys.

Keywords: Shear wave, Seismic source, Geophysics, Repeatability, Data acquisition

Introduction

Near-surface seismic surveys typically utilize compressional (P) and shear (S) waves to characterize the subsurface. The basic principle in determining the seismic response and elastic properties of the subsurface in terms of seismic velocity or waveform is generating seismic energy from a seismic source and recording the reflected and refracted energy by several sensors (geophones) attaching to the ground. Typical procedures of seismic surveys consist of 3 components, including data acquisition, data processing, and interpretation. A large portion of the budget is often spent on data acquisition as it is the initial step to collect the data in the field. Conventionally, the better the data quality, the easier data processing and interpretation will be achieved. To reach the goals, the seismic source or the controlled seismic energy device has to be selected properly in different study areas.

A number of studies [1-3] have revealed that the favorable seismic source should have the following common characteristics, 1) deliver sufficient energy to the target depth; 2) generate signal with a broad-band frequency; 3) create a good repeatable wavelet; 4) have high signal-to-noise ratio (S/N) and does not create interfering noise; 5) easy to operate and having low environmental impact. It has been postulated that additional requirements such as portability, costs, safety, and minimal involved manpower should be taken into account in case of a commercial source is limited [4].

A variety of seismic sources have been used in shallow seismic research [5-7]. However, the shear wave source is the main focus of this study because, in the upper 30 - 40 m depth of investigation, shear wave velocity (V_s) plays an important role in soil characterization for geotechnical, geohazard, and earthquake engineering [8-11]. A variety of shear wave sources have been used by various researchers [12-16]. One of the common near-surface sources is the impact-type horizontally polarized (SH) waves generator. This is typically employed by the horizontal striking of a hammer on a ground-coupled vertical

(metallic or wooden) plate, generating shear waves perpendicular to the direction of the blow. The power of the hammer source depended on the weight of the hammer, the plate coupled to the ground, and the force acting from the operator [17]. In addition to the simple hammer source, an accelerated weight drop source, activated by mechanical and/or electrical detonation have been used in case of high energy requirement. The explosive type is also considered as a high energy source, but it has usage limitations due to its safety, site preparation, and permission requirements [18]. One of the most powerful sources is the shear wave vibrator. However, it is not worth using this instrument for shallow seismic survey because of its heavy weight and the need pre-signal decoder [19]. In the past decades, the V_s obtained from Multichannel Analysis of Surface Waves (MASW) is increasingly used [20-23]. This method uses surface wave energy, released from the P-wave source to calculate the V_s . However, the accuracy of V_s is highly subjected to reliable extracted dispersion curves and non-uniqueness in surface wave inversion [24]. Moreover, active MASW has a limited depth of investigation due to little low-frequency energy.

Although the state-of-the-art seismic technology is available nowadays, highly efficient commercial seismic sources are rarely used in academic institutes. This is likely due to their high costs and difficulties to use. Whereas available budget to purchase efficient commercial sources is often limited. A representative example is the Geophysics laboratory at Prince of Songkla University. Here, the currently used shear wave seismic source is a conventional sledgehammer striking horizontally on the wooden and metal plank. As mentioned earlier, although this source is cheap and easy to operate, its signal energy and repeatability is limited. To overcome these limitations, we attempt to develop a low-cost seismic source with the aims of a simple operation while providing higher signal energy and repeatability compared to the former mentioned sources.

Materials and methods

Basic principle of the shear wave generator

Two fundamental types of seismic waves (body waves and surface waves) are produced when a seismic source is activated at/or near the surface of the earth [14]. Body waves, consisting of compressional waves (P-waves) and shear waves (S-waves) can propagate through an elastic media. Whereas surface waves, consisting of Rayleigh waves and Love waves can propagate along the earth's surface and interface of the media. In terms of soil particle motion, P-waves propagate by compressional and dilatational strains in the direction of wave propagation (**Figure 1(a)**). S-waves propagate by a pure strain in a direction perpendicular to the direction of wave propagation. Particle motion of surface waves involves oscillation, about a fixed point, in the direction of wave propagation. Dispersion characteristic is a specific property of surface waves.

The propagation velocities of body waves are a function of the elastic properties of the soil layer, especially V_s is a key parameter to compute the stiffness of materials [23]. Once the V_s is known, the shear modulus (μ) of soil or rock can be estimated as related by Eq. (1).

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (1)$$

where ρ is the bulk density of the soil.

In practice, P-wave energy is generated by dropping mass or striking a hammer vertically onto the ground surface, or by using explosives and vibrators [12]. On the other hand, S-wave energy is generated in the way that the soil particle motion is in a perpendicular direction to the direction of wave propagation (**Figure 1(a)**). Based on the plane of the particle motion relative to the array of sensors (geophones), S-waves are subdivided into 2 groups, including vertically polarized shear wave (SV) and horizontally polarized shear wave (SH). SH-wave is the most commonly source used for the V_s determination because it is easy to identify and does not experience mode conversion, unlike P-wave and SV-wave energy [6,12]. One of the simplest techniques is the horizontal hitting of a pendulum on a base plate or sliding mass along the slope as shown in **Figure 1(b)** [17,25]. Abe *et al.* [26] simplified the source wavelet ($w(t)$) of the impact source through the convolutional equation as follows

$$w(t) = f(t) * c(t) * i(t) \quad (2)$$

where $f(t)$ is the force function, $c(t)$ is coupling factor and $i(t)$ is instrument factor, respectively.

We can infer from a mechanical system that the maximum amplitude of seismic waves (A_{max}) is directly proportional to the momentum of the dropped weight (mv) before the impact and the impulsive force (F) acting on the ground as given by

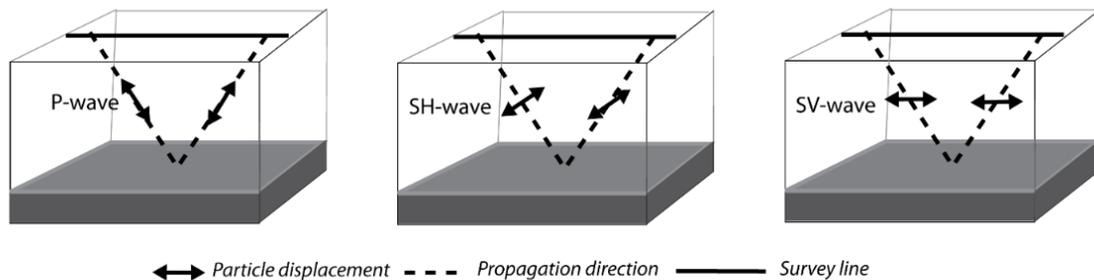
$$A_{max} \propto mv \propto F \quad (3)$$

The impulsive force is equivalent to the acquired momentum of the source area just after the impact which can be calculated from the time function for loading on collision and the duration from the moment of impact.

It is suggested by Eq. (3) that the source efficiency can be improved with the increase of weight and height of the dropped mass. In practice, however, such a source becomes an expensive and bulky source due to its heavy weight and difficulty to handle. Alternatively, it is often compensated by increasing the impulsive force on collision of weight based on accelerated weight (mass) drop principle.

In addition to the maximum amplitude delivery, the base plate design and physical condition on collision should be considered [26]. Since the base plate will be used to transfer input energy into the subsurface, a good ground and base plate coupling is required for avoiding signal attenuation. The approximately equivalent weight of the base plate and activated mass is also suggested to ensure the momentum and energy transfer to the ground by elastic collision.

a) Particle displacement and propagation of body wave



b) Simple P-wave and S-wave generator

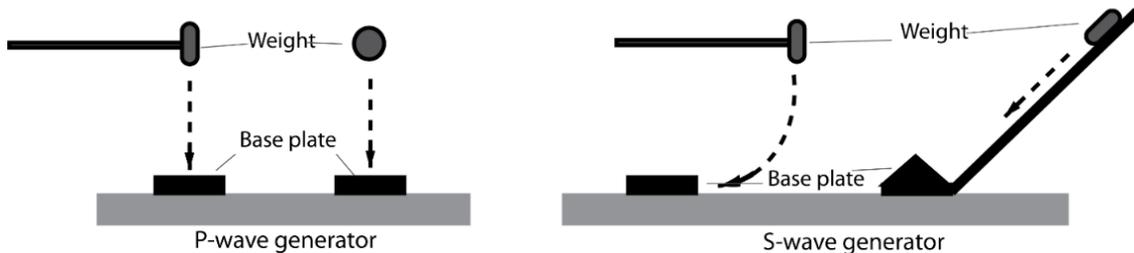


Figure 1 (a) Particle displacement and propagation of P-, SH-, and S-wave. (b) Principle of P-wave and S-wave generator.

Mechanical design and invent

The main findings from a preliminary field test of the conventional hammer striking on metal and wooden base plates allowed for the designing of the new shear wave source. Herein, we summarized the key considerations as follows:

1) In regard to material selection, the same weight of wooden and metal base plates provided comparable data quality. However, in terms of operation, the wooden plate needed loading from heavy vehicles or weight to maintain good source coupling and it is unsuitable for long-term use. Thus, harder material (iron) is recommended for making a base plate because it deforms very little after extended use.

2) The equivalent weight of the activated mass and base plate is considered to maintain the energy transfer by the elastic collision. Moreover, to increase the impulsive force and energy transfer, the activated mass is designed to move under the mechanical acceleration system. In regard to hitting angle, an optimum base plate and ground coupling was observed when the impact surface of the activated mass is oriented 20° relative to the ground surface. Although the coupling can be improved by attaching spikes to the underside

of the base plate, it comes up with time-consuming base plate installation. Thus, we consider applying weight of a person (about 50 - 70 kg) on top of the base plate to deal with this issue.

3) It was observed in the test results that the data quality at the same shot location varied and subjected to the source operator. Therefore, a mechanical shooting system was applied instead of manpower to control the repeatable signal.

4) Due to the large number of shots that will be employed in the seismic survey, a simple shooting system and transportation with minimal site preparation are considered.

The new source was designed and invented as shown in **Figures 2 and 3**. The main component of the source consists of 4 parts, base plate, activated mass, lifting and shooting system, body and transportation system. They are briefly described as follows:

1) The base plate system includes a metal plate in 3 pieces. Two metal plates with the dimensions of $25 \times 60 \times 1 \text{ cm}^3$ were attached vertically to each other to support an impact plate with dimension of $25 \times 25 \times 2 \text{ cm}^2$. The impact plate orient 70° relative to the ground, was placed firmly at one end of those 2 plates. The total weight of the base plate system is about 30 kg.

2) The activated mass is made from high-grade metal in order to withstand a long period of use and deforms considerably when subjected to plenty of hammer impacts. It has a cylindrical shape with the dimensions of 10 cm diameter and 30 cm length. The total weight of the activated mass is about 30 kg.

3) The body and transportation system consists of 2 pieces of 2.5 cm diameter with a 1 m long iron rod, forming the body and the activated mass holder. This part is locked with a base plate, lying at the right angle to the impact plate. For source transportation purposes, 2 solid wheels were installed at the bottom of the base plate as a trolley.

4) The lifting and shooting system is placed on the $10 \times 30 \times 1 \text{ cm}^3$ rectangular metal plate at the top of the body. At this position, a 50 cm long, high-stiffness spring was installed and linked at the top of activated mass for the additional storage of elastic potential energy and acceleration of the mass. A mechanical device, a wire rope winch, was used to pull and arm the activated mass.

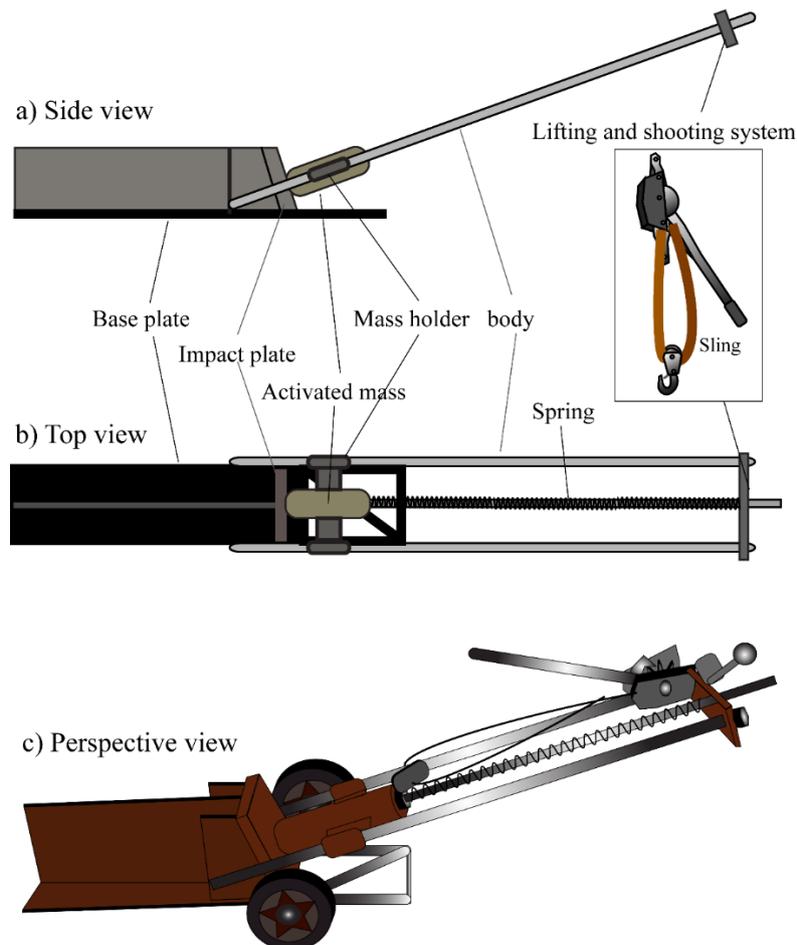


Figure 2 Shear wave source design.

The developed source is operated using a simple mechanical system. By swinging a handle of the winch, the mass is lifted by a puller to the armed position. At this position, the maximum gravitational and elastic potential energy is stored. After releasing the mass, the kinetic energy increases and the mass hit the base plate nearly in the horizontal direction (20°) with great impact velocity. Then, shear wave energy is generated by the momentum and energy transfer from the base plate to the ground. When the activated mass m hits the base plate mass M , we can estimate the input energy (E) acting on the soil interface and transmitted into the ground by applying the law of mechanical energy conservation.

$$E = mgh + \frac{1}{2}kx^2 = \frac{1}{2}mv^2 \quad (4)$$

where h is the height of mass, k is the stiffness of spring, x is the length of spring contraction and v is the impact velocity of mass when crashing the plate. By ignoring the effects of radiation pattern and inelastic attenuation, we expected the high input energy and impulsive force acting on the ground.



Figure 3 A developed shear wave source.

Seismic source performance testing

A comparison test of the former and the developed source was conducted at a test site in order to assess the source performance in terms of operation and data quality. Shear wave refraction surveys were acquired with the concurrent profiles. Field geometry and procedures for both sources were similar as displayed in **Figure 4**. Data were collected by a Geometric SmartSeis seismograph using the same recording parameters with a record length of 1,024 ms. In this experiment, 12 14-Hz horizontal geophones were applied as sensors with 3 m spacing. A series of them were firmly placed on the ground surface transverse to the direction of the line with the source energy vector similarly orientated for SH-wave recording. The 2 sources were shot in similar manner at both end and middle of the test profile. The hammer and activated mass were struck 5 times (stacked) at each shot location sought to enhance signal-to-noise ratio. The data from 1 blow were also recorded for signal repeatability comparison purposes.

To investigate factors that influence the characteristics of the source, the comparison test was performed both qualitative and quantitative manners. In qualitative comparison, the source operation, visual inspection of signal-to-noise ratio, and data inversion results were examined. In quantitative comparison, signal energy, frequency content, signal penetration, and repeatability were analyzed.



Figure 4 Shear wave source comparison test. (a) Survey geometry, and (b) Data acquisition in the field.

Results and discussion

The shear wave source characteristics are summarized in **Table 1**, and compared and described in the following section.

Table 1 Summary of the source characteristics.

Characteristic	Conventional source	Developed source
Net weight	40 kg	110 kg
Activated mass	10 kg (hammer)	30 kg
Base plate	30 kg	30 kg
Shooting system (Accelerated weight drop)	by manpower	by mechanical system
Operation time	1 - 2 min	2 - 3 min
Frequency content	5 - 250 Hz	5 - 250 Hz
Input energy	~200 J ¹	~300 J ¹
Repeatability	Variable ²	Repeatable ²
Cost	100 - 150 USD	500 - 700 USD

¹Calculated based on Eq. (4)

²See section repeatability for details

Source characteristic and operation

Although the net weight of the developed source (110 kg) is about 3 times higher than those of the conventional source (40 kg), they are comparable in terms of operation. Site preparation requirements for both sources are minimal and a fairly undisturbed surface is needed. In this test, we observed that the base plate coupling is influenced by ground surface conditions where on a hard ground surface, the base plate undergoes movement along the surface after impact. This is solved by excavating and removing soft materials from the ground surface under the base plate. It is interesting to note that the role of spring in the developed source is not only to accelerate the mass but also to prevent the activated mass rebound. The 2 sources are operated conveniently by 1 - 2 source crews. However, the conventional source requires manpower for hitting and moving the source along the survey line, making it difficult to perform a large number of shots. The rate of shooting is about 2 min/shot point for the conventional source and about 3 min/shot point for the developed source, respectively. Although, the overall budget of the developed source is about 4 - 5 times higher than those of the conventional source, it is considered as a low-cost source when compared to the commercial one. Moreover, even though the developed source has the possibility of working under harsh climatic conditions, we should avoid working under this type of environment because there will be noise in the seismic data.

Signal-to-noise ratio (S/N)

By visual inspection of the signal and background noises in the raw shot gathers, qualitative analysis of the signal-to-noise ratio (S/N) was compared (**Figure 5**). Generally, noise can result from a combination of cultural and environmental effects, such as traffic, and vibrations from machinery, rain, wind, ocean wave, etc. It is seen in the far-offset shots that the signal has undergone attenuation and background noises become the dominant components, which results in a reduction in the S/N. Although it has been reported that heavier sources do not necessarily correlate to a higher S/N [27], we observed a relatively higher S/N of the developed source in this study. Provided that the 2 sources have tested in the same environments, this is probably due to the lower source-generated noises and the better ground coupling of the developed source relative to the conventional source. As expected from the results, a higher S/N is also observed when increasing the number of stacks.

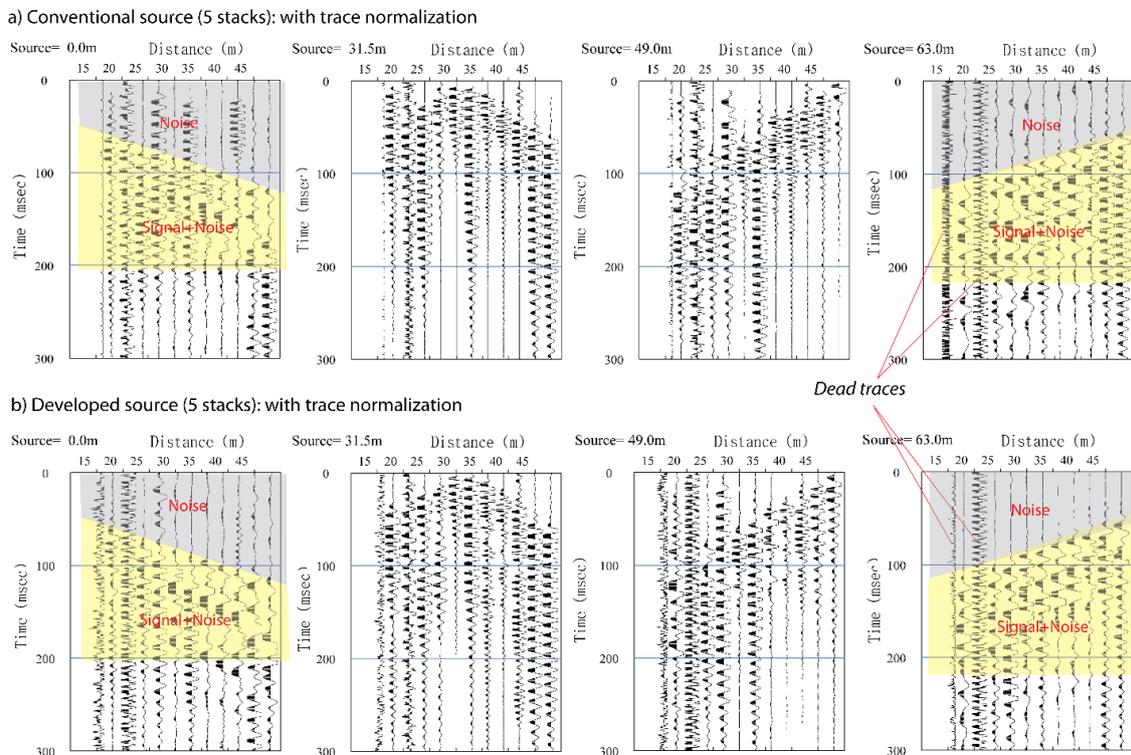


Figure 5 Comparison of raw data. (a) conventional source. (b) developed source. Shaded areas highlight the differences in signal-to-noise data.

Energy and frequency content

Power spectra of the data as shown in **Figure 6** were obtained by taking the Fourier transform of data from the time domain to the frequency domain. A comparison of power spectra reveals that both sources provided a useful frequency range of about 5 - 250 Hz. In the range of 20 - 100 Hz, the developed source generated a higher signal energy than the conventional source. On the other hand, the lower signal energy components of the developed source were observed at a frequency higher than 150 Hz. We can infer that the greater the input energy, the greater loss of high frequency in the subsurface.

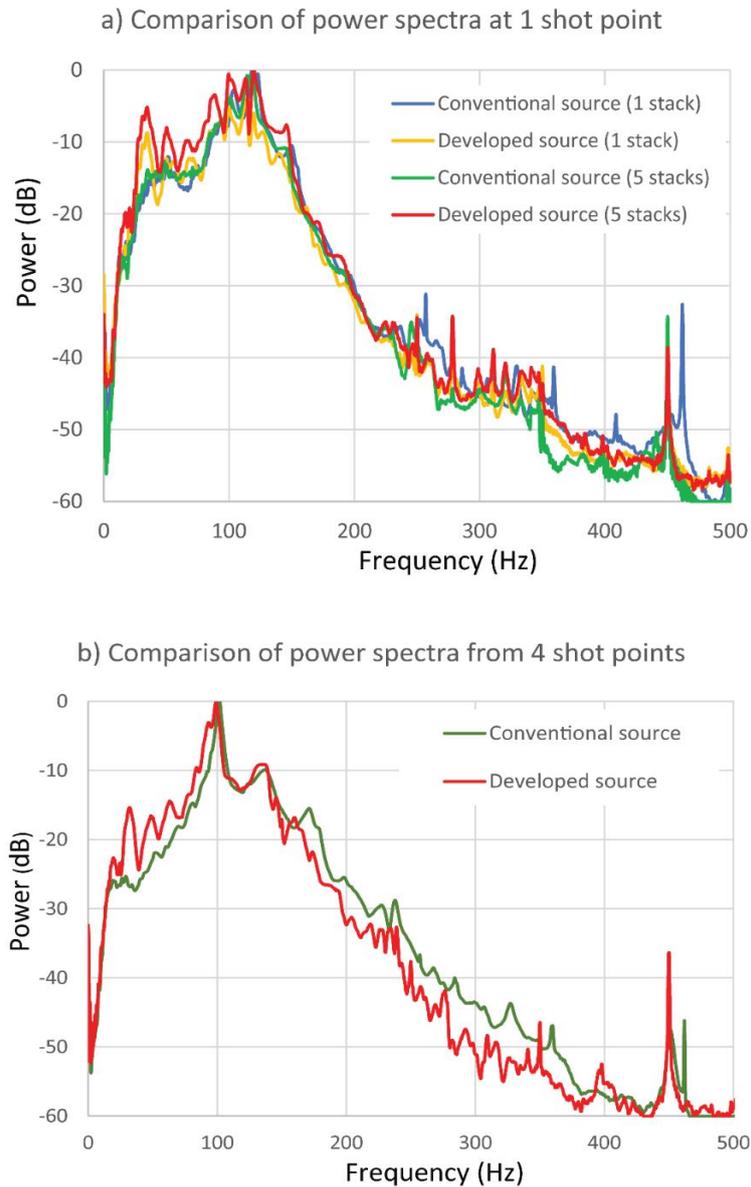


Figure 6 Comparison of power spectra: (a) Signal from 1 shot point and (b) Signal from 4 shot points.

Signal penetration

In addition to the power spectrum, **Figure 7** depicted the normalized amplitude decay of the raw waveform obtained from the 2 sources. This comparison provided insight into the signal energy and signal penetration in the subsurface. It is observed that one hit of the developed source delivers about 3 times higher amplitude than that of the conventional source. Note that the wave energy is proportional to the square of the amplitude, thus, the quantity of signal energy of the developed source is about 9 times higher than the conventional source. The result suggests that reducing 2 - 3 stacks of the developed source could yield equivalent signal energy as the conventional source. As a result, we believe that costs and time

associated with the rate of production can be minimized. The results also showed that by increasing the number of stacks, the signal energy is enhanced. In fact, the depth of investigation in seismic refraction surveys is limited by the seismic source and the geophone spread length. In this test, there is a noticeable greater penetration depth above 150 ms of the developed source. This supports the findings that the heavier sources are capable of generating low-frequency energy and a greater depth of investigation is observed [4].

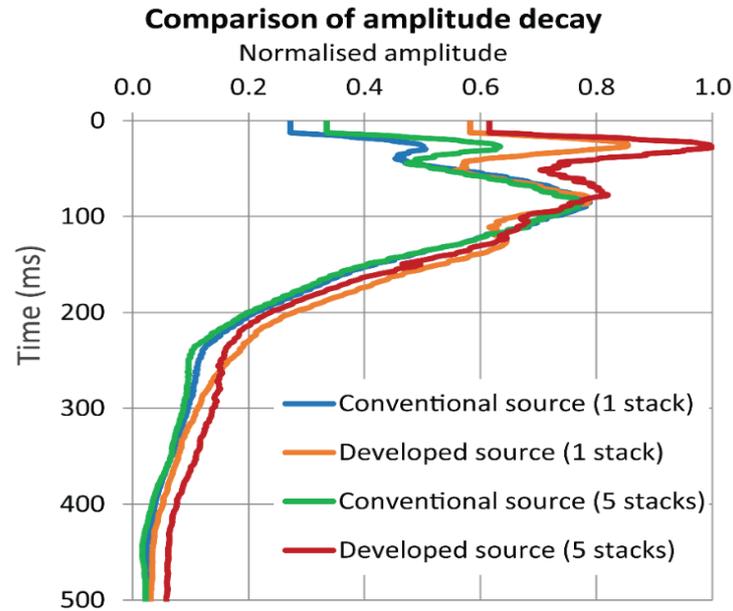


Figure 7 Comparison of amplitude decay.

Repeatability

The concept of the repeatable seismic source is that if 2 data sets have similar waveforms or the phase difference is at minimum, and on the contrary, if the data sets have different waveforms or the phase difference is at maximum [5]. In this study, the assessment of repeatability is performed by instantaneous phase differences of 2 data sets at the same shot point. The instantaneous phase derived from the complex trace signal $F(t)$ [28] can be expressed as

$$F(t) = f(f) + jf^*(t) \quad (5)$$

where $f(t) = A(t) \cos \theta(t)$ is a real component, called the conventional seismic trace, and $f^*(t) = A(t) \sin \theta(t)$ is an imaginary component, called the quadrature trace. Then, the instantaneous phase $\theta(t)$ can be written as

$$\theta(t) = \tan^{-1} \left[\frac{f^*(t)}{f(t)} \right] \quad (6)$$

As outlined by the dashed area in **Figure 8**, the most of low phase different zones (about $\pm 50^\circ$) lie before 500 ms in the shot gathers. The higher phase difference at the greater time may be due to the signal energy attenuation with dominated random noise energy. We can see that the zone of small phase different in the developed source data is broader than those of the conventional source data. This implies that the developed source generated a signal with higher repeatability. We believe that the discrepancy in repeatability is more or less influenced by the shooting mechanism of the source. In other words, the developed source provided a better signal-controlled source, whereas the conventional source is dependent on the physics of the person performing the impact. Even impacts from the same person can vary in consistency.

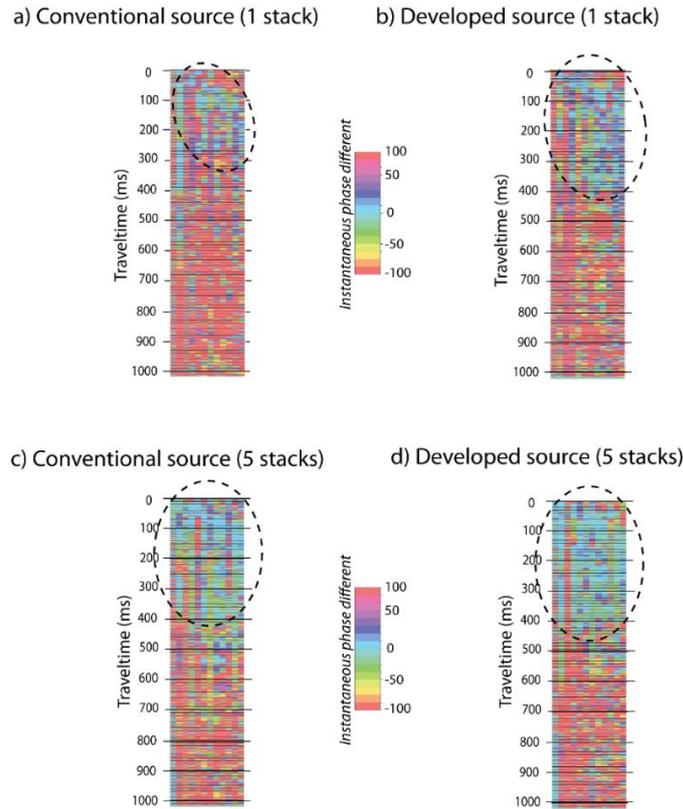


Figure 8 Comparison of instantaneous phase differences. Dashed areas highlight the low phase differing zones.

Comparison of the inversion results

It is interesting to compare the velocity distribution obtained from the 2 sources in order to evaluate the reliable results corresponding to the subsurface geology. In the principle of seismic refraction, velocity-depth model and/or tomographic images can be produced through traveltime inversion of the seismic wave propagating between the seismic source and the receivers [29]. In this study, the data were processed based on seismic tomography analysis to construct a 2D shear wave velocity distribution of near-surface structures with varying velocity gradients and changing layer thicknesses. The main procedures for determining subsurface velocities consist of the following steps [30,31].

- 1) Picking the 1st-arrival traveltimes in the recorded data to serve as input observed data (t_{obs}).
- 2) Setting up an initial model in terms of a set of unknown model parameters, called model parameterization.
- 3) Forward calculating the 1st-arrival traveltime based on the given initial model (t_{cal}). The traveltime of a ray is the discretized integral of the slowness along the ray as given by:

$$t_i = \sum_{j=1}^N l_{ij} s_j \quad (7)$$

where t_i is the traveltime of the i th ray, l_{ij} is the segment length of the i th ray that intersects the j th cell, and s_j is the slowness (reciprocal velocity) in the j th cell.

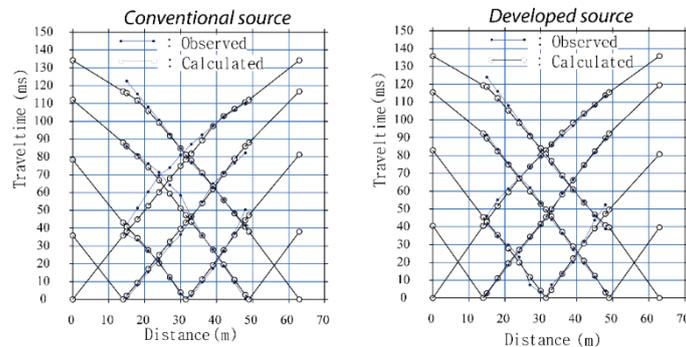
- 4) Performing an inversion by adjusting the model parameter values (the velocity structure) with the object of minimizing the residual ($r = t_{\text{cal}} - t_{\text{obs}}$) between the calculated and picked traveltimes in the least squares manner. The objective function to be minimized is set as follows:

$$\varepsilon = \frac{1}{2} \sum_{i=1}^M r_i^2 = \frac{1}{2} \sum_{i=1}^M \sum_{j=1}^N (l_{ij} s_j - t_i)^2 \quad (8)$$

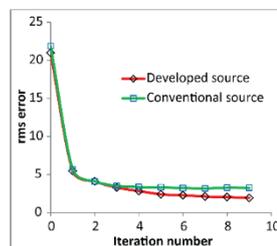
The velocity model is updated iteratively until the root-mean-square (RMS) error of the traveltime residual is less than a predefined tolerance.

In this work, the processing steps were set similarly for the 2 data sets, except the 1st breaks were picked differently depending on the quality of data (**Figure 9(a)**). As reported from the least-squares inversion scheme (**Figure 9(b)**), the final RMS error of the inversion process for the developed source and the conventional source is 0.19 and 0.32 ms, respectively. This suggests that the developed source traveltimes provided a more accurate velocity model than the conventional source traveltimes when the inversion parameters were kept similar. A potential explanation for the discrepancy in RMS error and convergence rate is that the more accurate traveltimes in the developed source data is affected by the higher repeatability of the waveform. Regarding the tomographic images, the final models obtained from the 2 data sets exhibited consistent patterns of velocity distributions in the upper 25 m depth at the test site (**Figure 9(c)**). The tomographic images reveal overall 2 distinct subsurface layers with velocity increased with the depth. The 1st layer is 9 - 13 m thick with a range of low Vs about 300 - 500 m/s. The lack of ray coverage below 20 m depth suggests that the depth of investigation is limited in the 2nd layer with the Vs of higher than 500 m/s. However, based on the scope of the current study, the judgment on the reliable model relevance to the structural interpretation could not be drawn. Additional data regarding geology information, as well as the initial model and other inversion parameters should be explored further in future studies to gain confidence in this aspect.

a) Comparison of traveltime curve



b) Comparison of rms error



c) Comparison of tomographic section

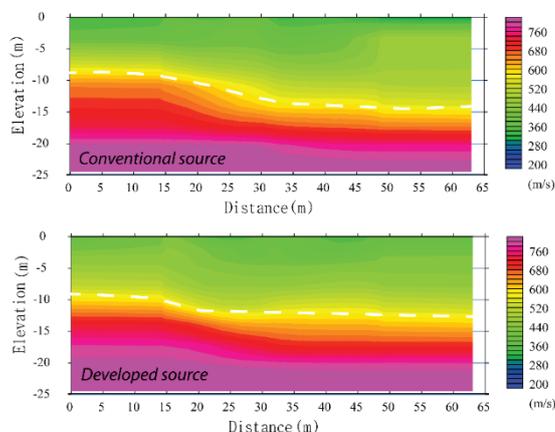


Figure 9 Comparison of tomography results: (a) Traveltime data, (b) RMS error, and (c) Tomographic section.

Conclusions

The new shear wave seismic source has been developed and tested as an alternative source for shallow seismic surveys. The key advantages of the developed source are that it is simple to operate and reduces required manpower. Comparisons between the signal obtained from the developed and conventional sources highlight some key points. There is a noticeably higher input signal energy transfer offered by the source leading to the deeper target depth of investigation. Moreover, the better repeatable waveform led to greater accuracy of the 1st break picking in the data processing. As a practical tool, the source is fairly cost-effective, transportable, safe, and has a minimal environmental impact. Consequently, the new shear source is suitable and has potential application for shallow subsurface investigation.

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