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Article

Determination of Setback Distances for On-Land Seismic Reflection Survey in Thailand

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Abstract. Explosives are commonly used to generate strong impulsive waves for on-land petroleum exploration. For each exploration area in Thailand, a concessionaire shall submit an environmental impact assessment report that commits minimum distances, or setback distances, between an explosive and various types of structures to a regulatory authority. However, the basis for determining the setback distances is not described and or based on surface mine blasting researches.

To establish a guideline for exploration contractors in Thailand, ground vibrations were measured from ten exploration sites across the country which can be grouped into three geology conditions, namely sandy ground, clayey ground and sandy ground with rock boulders. Explosives in this study were buried and packed in boreholes at depths of 9 ~ 23 m, having weights of 1 ~ 4 kg and length-to-diameter ratios of 6 ~ 25.

The measured data were used for determining the attenuation of particle velocities over distance and the frequency content of vibrations. The geometric damping was found to be the main cause of attenuation while the material damping was negligible. The attenuation in sandy ground with rock boulders was found to be stronger than sandy ground and clayey ground. Since the dominant frequencies of vibration in each ground type varied over wide range, the frequencies at the 2.5th percentile were used for the conservative sake in the vibration assessment according to DIN 4150. Based the proposed formula, the setback distances between residential buildings and a 2-kg explosive are 53, 149 and 221 m for sandy with rock boulders, sandy and clayey grounds, respectively.

Keywords: Petroleum exploration, seismic reflection survey, setback distance, Thailand.

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1. Introduction

Explosives are one of the most convenient sources for Seismic Reflection Surveys (SRS). When explosives are used, setback distances to existing structures are usually required for limiting damage caused by vibration. For each exploration area in Thailand, a concessionaire shall submit an environmental impact assessment report that commits minimum distances, or setback distances, between an explosive and various types of structures to the Department of Mineral Fuels (DMF). The current practice in Thailand is to provide setback distances of about 100-200 m for residential buildings and 500-2,000 m for historic buildings. These distances accompany typical charge weights of 1.0, 1.5, and 2.0 kg for sand, clay, and sandy with rock boulders grounds, respectively. Since the basis for determining the setback distances were not explained or based on measurements not directly related to SRS [1, 2] it is not uncommon for a local authority to request for wider separation distances than the ones submitted to the DMF. This study is an attempt to reevaluate setback distances based on field measurements from petroleum exploration fields in Thailand.

The effects of blasting vibration are commonly justified by two parameters which are the Peak Particle Velocity (PPV) and the dominant frequency of vibration on the building of concern. These parameters depend, in turn, on the characteristics of vibration source, the ground and the building.

Vibration in surface mining occurs when rock or consolidated material is broken off from a vertical face by array blasting. In an array, explosives of weight 64~643 kg are detonated in sequence with a milliseconds delay time for the interest of reducing the magnitude of vibration [3–6]. The magnitude of vibration also depends on the explosive weight, the distance from explosives to adjoined free surface, the velocity of detonation and the acoustic impedance of the ground [7–11, 18]. A general form of equations for evaluation of blasting vibrations can be written as follows:

$$v = k \cdot w^{b} \cdot r^{-n} \cdot e^{-\alpha r}, \tag{1}$$

where: v = peak particle velocity (mm/s)
k, b, n, α = non-negative fitting parameters (consistent unit, unit less, unit less, m^{-1})
w = weight of explosive per delay (kg)
r = distance between the vibration source and evaluating point (m).

The fitting parameters b, n, α in Eq. (1) were either empirically determined or theoretically assumed based on the geometry of explosive, geometric attenuation and material attenuation, respectively. The value of n depends on source geometry, vibration type and wave type as shown in Fig. 1. The material attenuation is affected by various factors such as frequency and amplitude of vibration, soil type and increases with the degree of saturation [12, 13]. The value of α falls in a range of 0 ~ 0.44 m^{-1} [14, 15].

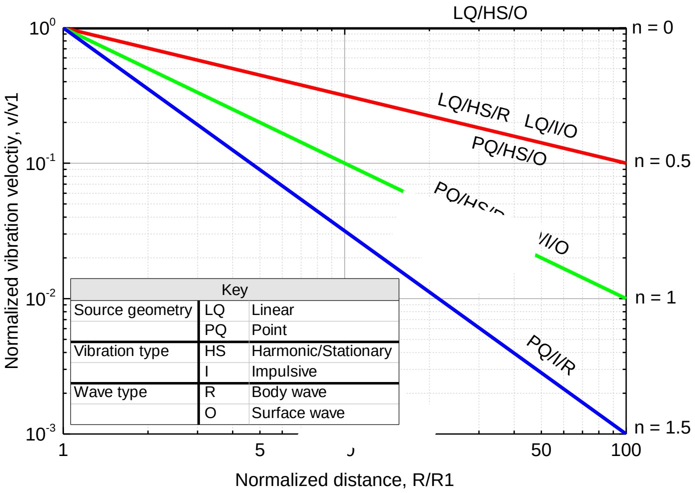


Fig. 1. Dependency of n on source geometry, vibration type and wave type (after DIN 4150).

When the influence from explosive weight is not considered, the first two components in Eq. (1) can be lumped together for obtaining a simplified form as shown by Eq. (2). By assuming that the effect of the material attenuation is negligible, a more simplified model as shown by Eq. (3) can be obtained.

$$v = \hat{k} \cdot r^{-n} \cdot e^{-\alpha r} \tag{2}$$

$$v = \hat{k} \cdot r^{-n} \tag{3}$$

By introducing a notation of scaled distance and not (explicitly) considering the effect from material damping, Eq. (1) can be written as

$$v = k \cdot \left(\frac{r}{w^{\hat{b}}} \right)^{-n} \cdot e^{-\alpha r} \qquad ;\hat{b} = b/n,\ \alpha = 0 \tag{1'}$$

$$v = k \cdot D^{-n} \tag{4}$$

where D is the scaled distance. The parameter $\hat{b}$ seems to be related to the geometry of explosive [16]. Some values of $\hat{b}$ reported in literatures are 1/3 [17], 0.5 [19, 20], 2/3 [21, 22], and 1.5 [23].

2. Blasting and Measuring Conditions

By accompanying seismic reflection surveys at locations shown in Table 1, vibrations from their operations were recorded by calibrated geophones, consisting of four 2-Hz triaxial geophones and sixteen 4.5 Hz vertical geophones. In each study area, the geophones were installed on the ground surface at a regular interval and used to record vibrations from detonation points in nearby areas which correspond to separation ranges between 10~2,000 m. The locations of instrument geophones and explosives were recorded by surveyor-grade GPS. Based on the geometric relationship, measured signals were transformed into radial, transverse and vertical directions as well as source-to-receiver distance.

All explosives in this study were emulsion explosives (Emulex) having the detonation velocity of 5,000 – 5,500 m/s. The weight of explosive in each study area was justified by exploration contractors. On the contrary to surface mine blasting, each seismic event in this study was generated from a single borehole which was prepared under flat unconsolidated ground. This configuration can be considered as single hole-infinity burden type.

Table 1. Summaries of ground conditions and explosive properties.

Study areas			Explosive		Ground condition
Site	District	Province	Weight (kg)	Buried depth (m)	
1	U Thong	Suphan Buri	1.0	19-21	Saturate, Clayey
2	Nong Wua So	Udon Thani	1.5	5-9	Dry, Sandy with rock boulders
3	Nong Wua So		2.0	9.6	Dry Sandy
4	Tha Khantho	Kalasin	1.5	9.0	Dry, Sandy with rock boulders
5	Khemmarat	Ubon Rachatani	1.5	5-12	Dry, Sandy with rock boulders
6	Ampher Muang	Surat Thani	2.0	15-19	Saturate, Sandy
7	Yang Sisurat	Maha Sarakham	3.0	13	Dry, Sandy
8	Phayakkhaphum Phisai		3.0	13	Dry, Sandy
9	Phutthaisong	Buri Ram	3.0	13	Dry, Sandy
10	Satuek	Surin	4.0	13	Dry, Sandy

The sites were grouped from top 10~15 m layers into sandy ground, clayey ground, and sandy ground with rock boulders. Since the measurements at site 1 and 6 were carried out in a rainy season, groundwater level in these sites was close to the ground surface. Water bursts of 3~4 m high always occurred at detonation points in these areas. Photo of each ground type is shown in Fig. 2.

a) Clayey ground b) Sandy ground c) Sandy with rock boulders ground

Fig. 2. Photos taken from clayey, sandy and sandy with rock boulders ground sites.

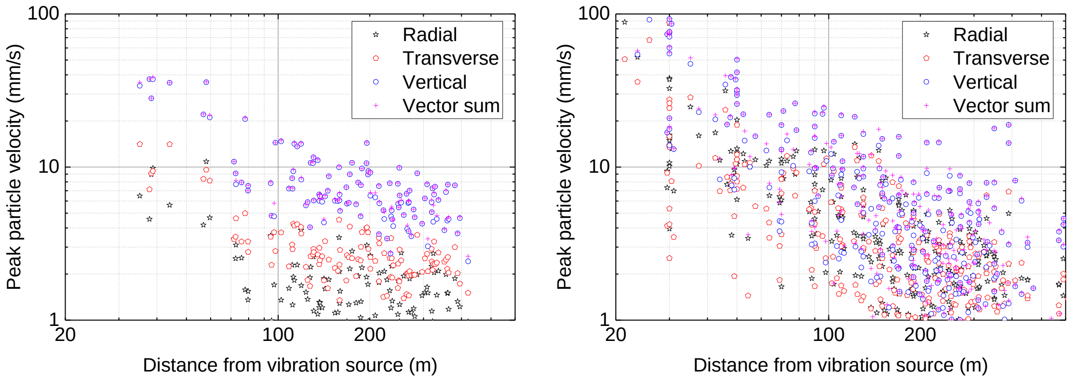
3. Results and Discussions

Vibration in Each Direction

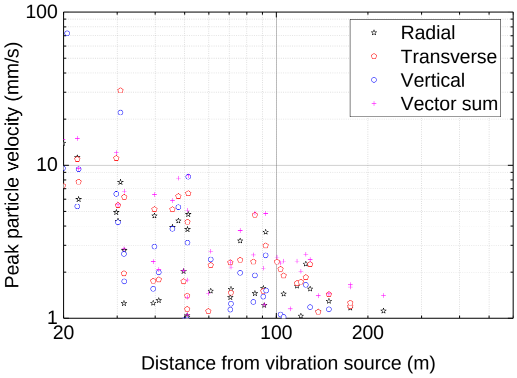
The maximum values were picked up from the recorded signals and plotted against the separation distance in Fig. 3. In this study, the maximum values of vibrations in each direction as well as the maximum value of the vibration vector were considered. The amplitude of a vibration vector at time $t (v_{s,t})$ can be calculated by

$$v_{s,t} = \sqrt{v_{r,t}^2 + v_{t,t}^2 + v_{z,t}^2} \quad (5)$$

where $v_{r,t}$, $v_{t,t}$, $v_{z,t}$ are particle velocities in radial, transverse, and vertical directions at time t, respectively.



a) Clayey ground b) Sandy ground



c) Sandy with rock boulders ground

Fig. 3. Vibration in each direction.

For clayey and sandy grounds, it can be seen that the values of vertical component were almost equal to the values from true velocity vectors and higher than the other two components. Therefore, it can be concluded that the vibrations were dominated by the vertical component. Based on this evidence, further analyses for these ground types were based on the data from 4.5Hz vertical geophones for the interest of more data points.

On the contrary, the relationship between the true velocity vectors with the vibrations in each component was scattered for sandy with rock boulders ground. The vibration seemed to come from random directions. For this reason, it is assumed that waves in this ground type propagate through a number of reflections before arriving at the instrument geophones. The maximum value from velocity vectors was used in further analyses in sandy with rock boulders ground.

Attenuation Characteristic in Each Ground Type

a) Clayey ground

Fitting analyses were carried out for determining the attenuation of PPV over distance in clayey ground. Since only 1.0 kg of explosives was used in this ground type, the Eq. (2) was used instead of Eq. (1). The data and fitting results are shown in Fig. 4 and Table 2. From the first model in Table 2, the optimum result occurred when the parameter α (which subject to a condition of non-negative value) was zero. Therefore, it was concluded that the influence of material damping is negligible.

Table 2. Results from fitting analyses for clayey ground.

Fitting models		Fitting parameters				R^2
		k	n	α	r_c	
Conventional models						
1	$v = k \cdot r^{-n} \cdot e^{-\alpha r}$	1598	1.15	0		0.819
2	$v = k \cdot r^{-0.5}$	83				0.419
3	$v = k \cdot r^{-1.0}$	879				0.793
4	$v = k \cdot r^{-1.5}$	5443				0.689
Piecewise models						
5	$v = k_1 \cdot r^{-n_1}\ ,\ r < r_c$	3089	1.35		101	0.888
	$v = k_2 \cdot r^{-n_2}\ ,\ r > r_c$	41	0.41			
6	$v = k_1 \cdot r^{-1.5}\ ,\ r < r_c$	5008			78	0.876
	$v = k_2 \cdot r^{-0.5}\ ,\ r > r_c$	64				
7	$v = k_1 \cdot r^{-1.5}\ ,\ r < r_c$	4695			35	0.841
	$v = k_2 \cdot r^{-1.0}\ ,\ r > r_c$	796				

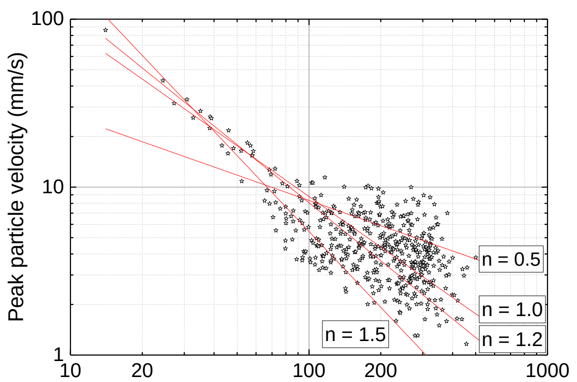


Fig. 4. Attenuation of vibration in clayey ground.

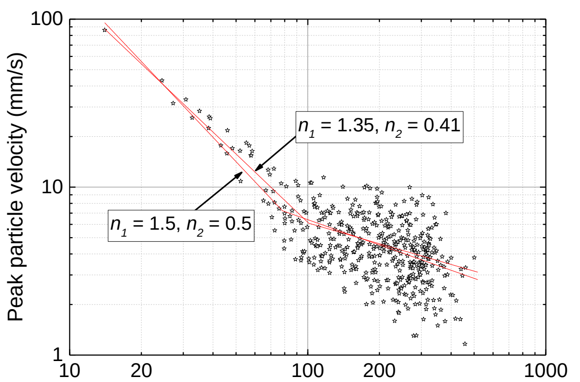


Fig. 5. Piecewise fit of vibration in clayey ground.

Further studies were carried out by comparing the first model with the 2nd to 4th models which derive the value n from theoretical basis. When the geometric attenuation parameter (n) was fixed to 1.0 and 1.5, the coefficients of determination (R^2) decreased from the optimum values but still was higher than 0.65.

It was noticed from Fig. 5 that the data was well aligned with the n = 1.5 line when the distance is less than 50 m. Although the data became more scattered when the distance was larger than 50 m, they tended to decrease over distance in the same rate as the n = 0.5 line. Therefore it was assumed, based on this observation, that the vibration in the near zone was dominated by body waves whereas the vibration in the far zone was dominated by surface waves (cf. PQ/I/R and PQ/HS/O lines in Fig. 1). To validate this assumption, the data was fitted by a piecewise function shown in Eq. (6) which is the 5th model in Table 2. Further studies were also made by setting the n_1 and n_2 to some characteristic values which are the 6th and 7th models in Table 2.

$$v = \begin{cases} k_1 r^{-n_1} & \text{, if } r < r_c \\ k_2 r^{-n_2} & \text{, if } r > r_c \end{cases} \qquad \text{subject to } k_1 r_c^{-n_1} = k_2 r_c^{-n_2} \tag{6}$$

Although the 5th model gave the best R^2, the 6th model is recommended for the interest of generalization and theoretical study.

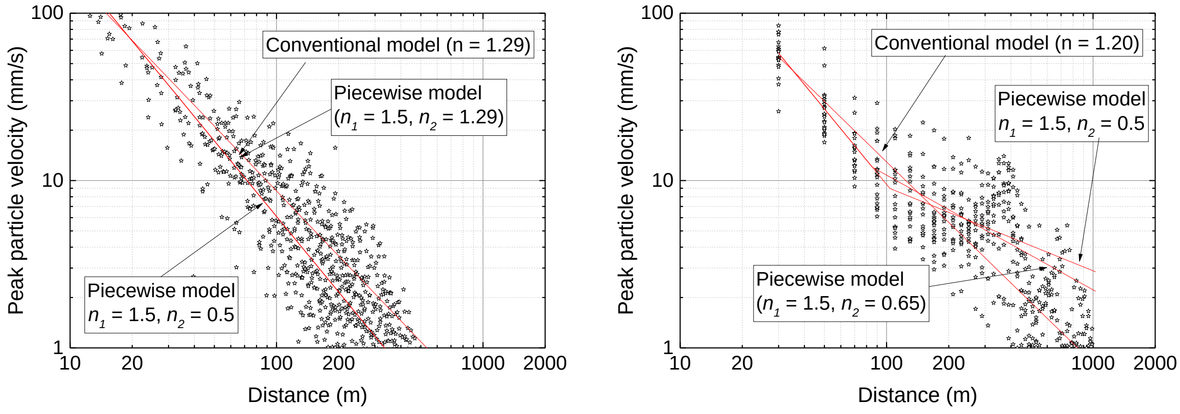
b) Sandy ground

The procedure used in the previous section was also applied in this section. It was found that the effect of material damping was also negligible in sandy ground. For the interest of brevity, only analyses by Eq. (3) will be presented. The data and fitting results are shown in Fig. 6 and Table 3. It can be seen from the first model in Table 3 that the empirical values of n ranged in between 1.20 to 1.40 with a minimum R^2 of 0.637. When the geometric attenuation parameter (n) was fixed to 1.0 and 1.5, the coefficient of determination (R^2) slightly decreased from the optimum values.

To investigate whether the attenuation rate in the near zone is different from the one in the far zone or not, the piecewise fitting analyses were carried out by assuming the value of n_1 to be 1.5 for the interest of unification with the case of clayey ground. The fit results of the 4th model in Table 3 showed that the optimum values of n_2 were close to 0.5 for the explosive weight of 3 and 4 kg but not for the case of 2 kg explosive. Since the data was not available after the distance of 500 m in the latter case, the behavior of n = 0.5 type might not be recognized by the fitting algorithm.

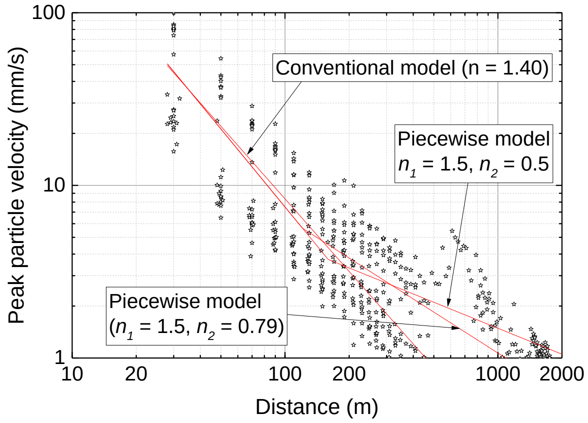
Table 3. Results from fitting analyses for sandy ground.

Fitting models		Explosive weight (kg)	Fitting parameters					R^2
			k_1	n_1	k_2	n_2	r_c	
Conventional models								
1	$v = k \cdot r^{-n}$	2	3257	1.29	▨	▨	▨	0.827
		3	3268	1.20	▨	▨	▨	0.830
		4	5172	1.40	▨	▨	▨	0.637
2	$v = k \cdot r^{-1.0}$	2	1276	▨	▨	▨	▨	0.783
		3	1500	▨	▨	▨	▨	0.813
		4	1137	▨	▨	▨	▨	0.599
3	$v = k \cdot r^{-1.5}$	2	6100	▨	▨	▨	▨	0.811
		3	9734	▨	▨	▨	▨	0.808
		4	7552	▨	▨	▨	▨	0.635
Piecewise models								
4	$v = k_1 \cdot r^{-1.5}\ ,\ r < r_c$ $v = k_2 \cdot r^{-n_2}\ ,\ r > r_c$	2	6100	▨	2884	1.39	1244	0.811
		3	9458	▨	253	0.69	85	0.852
		4	7486	▨	246	0.79	121	0.640
5	$v = k_1 \cdot r^{-1.5}\ ,\ r < r_c$ $v = k_2 \cdot r^{-0.5}\ ,\ r > r_c$	2	6100	▨	8	▨	748	0.811
		3	9485	▨	91	▨	104	0.851
		4	7501	▨	47	▨	159	0.639



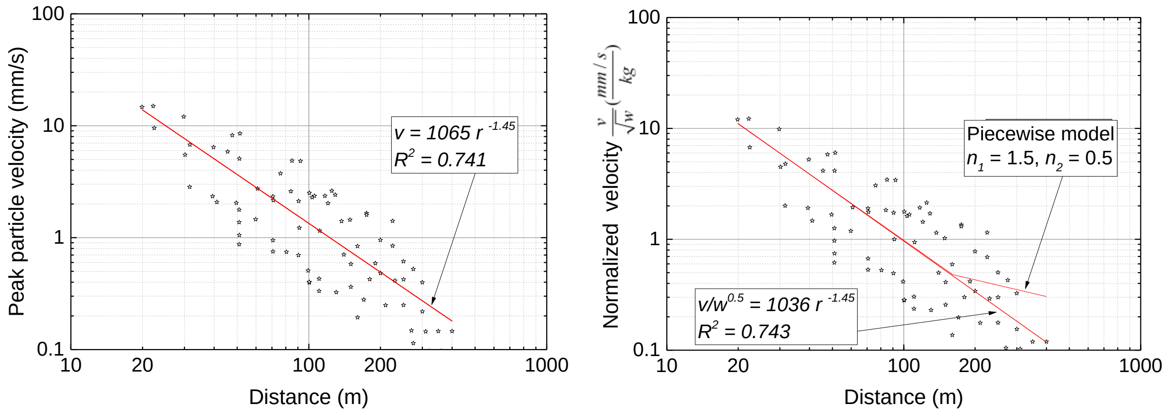
a) 2kg explosive

b) 3kg explosive



c) 4kg explosive

Fig. 6. Attenuation of vibration in sandy ground.



a) Original scale

b) Normalized by explosive weight

Fig. 7. Attenuation of vibration in sandy with rock boulders ground.

Finally, when the n_1 and n_2 were fixed to 1.5 and 0.5 respectively, the coefficients of determination (R^2) decreased slightly from the 4th model but still better than the 1st model except for the case of the 2 kg explosive. Again, the fit algorithms decided to use the n_1 which was close to the optimum value (1.29) than the n_2.

c) Sandy with rock boulders ground

Only 1.5 kg of explosives was used in this ground type. Due to the reason mentioned earlier, the maximum values from velocity vectors were used instead of the data from vertical geophones. The fit result is shown in Fig. 7. When the data was normalized by the square root of the explosive weight, which will be explained in the next section, the slope of the best fit line became close to 1.5 with slightly improved R^2. It can be concluded that the attenuation of the $n = 1.5$ type can be adopted for this ground type. It was also observed that the vibration level in sandy with rock boulders ground was significantly smaller than the other ground types.

The Influence of Explosive Weight and Ground Type

Based on Eq. (2), the magnitude of vibration near to its source (i.e. $r = 1$ m) is controlled by two parameters which are explosive weight and the parameter k.

The influence of explosive weight on vibration level was studied from the measurements in sandy ground where the explosive weight varied between 2 – 4 kg. Based on the first model in Table 3, the values of k seemed to be proportional with the explosive weight. However, when the parameter n was fixed to either of 1.0 or 1.5, the values of k did not properly vary with the explosive weight. For this reason, an alternative strategy based on the fundamentals of wave propagation theory was adopted.

From a theoretical point of view, the energy of vibration is proportional to the square of the amplitude of a wave. Since the energy of explosive is proportional to its weight, the amplitude of a wave could be normalized by the square root of explosive weight. The normalized equations as well as their qualities of fit for all ground types are shown in Table 4. The R^2 of all cases were higher than 0.7 and seemed to be sufficient for practical purposes.

The parameter k reflects the influences from remaining unconsidered factors, such as the energy loss at the detonation point, the stiffness of the ground, and so on. This parameter was empirically linked with ground type in this study. From Table 4, the k_1 of sandy ground and sandy with rock boulders ground compared to clayey ground were 87% and 20%, respectively. The corresponding ratios for the k_2 were 48% and 9% for sandy ground and sandy with rock boulders ground, respectively.

It was also noticed that the value of r_c, or the boundary where the attenuation characteristic changed from $n = 1.5$ to $n = 0.5$, varied in opposite direction with k_1 and k_2. The r_c increased to 1.79 and 2.06 times when the ground type changed from clayey to sandy and sandy with rock boulders, respectively.

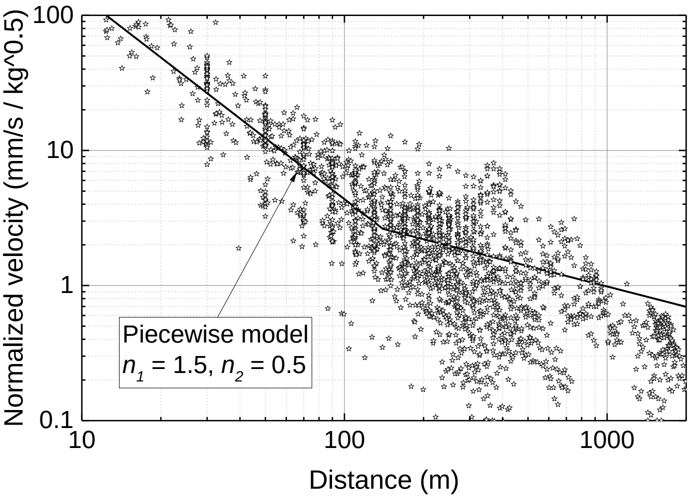


Fig. 8. Prediction model (Normalized velocity for sandy ground).

Table 4. Results from fitting analyses with a consideration on explosive weight.

Fitting models	Ground type	Fitting parameters			R^2
		k_1	k_2	r_c	
$\bar{v} = k_1 \cdot r^{-1.5}\ ,\ r < r_c$ $\bar{v} = k_2 \cdot r^{-0.5}\ ,\ r > r_c$ where $\bar{v} = v / \sqrt{w}$	Clayey	5008	64	78	0.876
	Sandy	4356	31	140	0.793
	Sandy with rock boulders	981	6	161	0.743

Frequency Content and Comparison with DIN 4150's Guideline

DIN-4150 suggests that the effects of a vibration event on structures can be evaluated from its maximum velocity accompanied with the main vibration frequency (usually referred to as the dominant frequency). The guideline in DIN-4150 can be explained by three lines in Fig. 9. For instance, significant damage will not occur on buildings under preservation order when a point, representing dominant frequency-maximum velocity pair, is lower than the L3 line.

To adopt the aforementioned guideline, it was interesting to know the variation of dominant frequency over distance such as the ones shown in Fig. 10. Based on the same figure, the dominant frequency was not correlated with the distance, but rather depends on the ground condition. Statistics in Table 5 showed that the dominant frequency of saturated sandy ground were higher than the ones of dry ground. For sandy with rock boulders ground, the dominant frequency was high and scattered over a wider range. The dominant frequency of clayey ground was also higher and less scattered than other cases.

It can be seen from Fig. 9 that less vibration velocity is permitted when the dominant frequency decreases. Therefore the dominant frequency at $\mu{-}2\sigma$, which is approximately lower than 98% of the population, will be assumed in further analyses for the conservative sake. Since the limit values of L1, L2, L3 lines stop decreasing when the dominant frequency is lower than 10 Hz, the frequency of 10 Hz will be assumed when a $\mu{-}2\sigma$ is less than 10 Hz.

Using the proposed formula in Table 4, the dominant frequencies in Table 5 and DIN 4150's guideline, the setback distances between residential buildings and a 2-kg explosive at 80% one-side upper prediction level were found to be 53, 149 and 221 m for rocky, sandy and clayey grounds, respectively.

Table 5. Statistics of dominant frequency in each ground type.

Ground type	Sample size	Mean, μ (Hz)	S.D., σ (Hz)	$\mu - 2\sigma$ (Hz)
Clayey ground (Saturate)	871	49	14	21
Sandy ground (Dry)	1116	17	18	<10
Sandy ground (Saturate)	978	42	21	<10
Sandy ground (all data)	2094	29	23	<10
Sandy with rock boulders ground (Radial direction)	111	45	52	<10
Sandy with rock boulders ground (Transverse direction)	111	36	38	<10
Sandy with rock boulders ground (Vertical direction)	524	31	44	<10

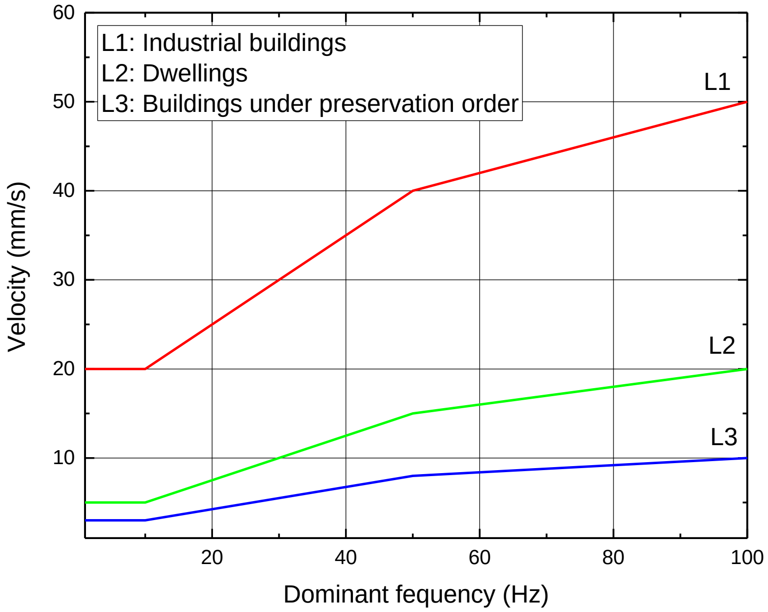
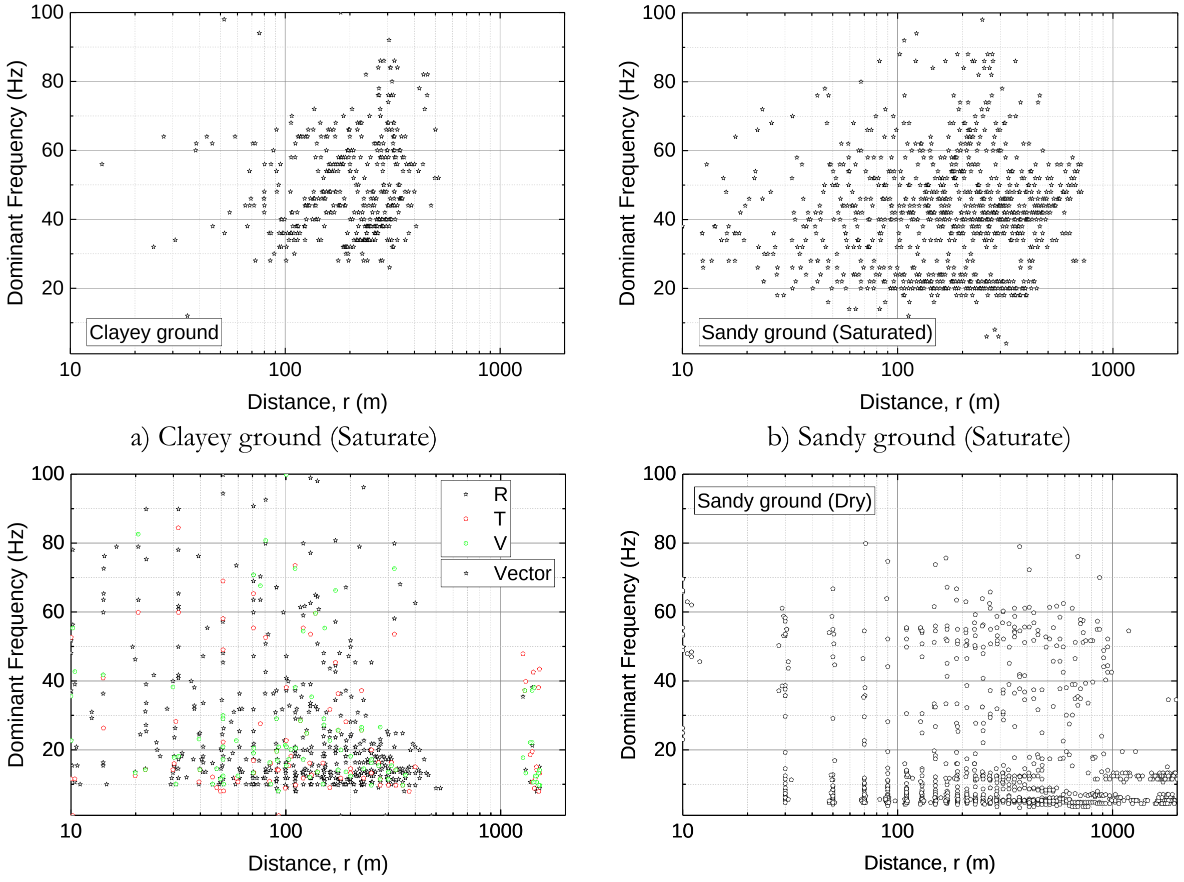


Fig. 9. Guideline values at building foundations for short-term vibration (after DIN 4150).



a) Clayey ground (Saturate)

b) Sandy ground (Saturate)

c) Sandy with rock boulders ground

d) Sandy ground (Dry)

Fig. 10. Variation of dominant frequency with distance in each ground type.

4. Conclusion

Ground vibrations were measured from ten on-land seismic reflection surveys in Thailand. Explosives in this study were buried and packed in boreholes at depths of 9 ~ 23 m, having weights of 1 ~ 4 kg and length-to-diameter ratios of 6 ~ 25. The studied areas were grouped into three geology conditions, namely sandy ground, clayey ground and sandy with rock boulders grounds. Based on the results in this study, the conclusions can be made as follows;

1) Vibrations in clayey and sandy grounds were dominated by the vertical component. Therefore, the vibration assessment may be cost-effectively done by merely vertical geophones, or, by vertical geophones and cross-checked by a few of triaxial geophones. On the contrary, the peak particle velocity occurred in random directions in sandy with rock boulders ground. Therefore, it is recommended to assess the vibration damage by the velocity vector instead of one-directional velocity for this ground type.

2) The attenuation of vibration can be described by setting the geometric damping parameter to 1.5 for the near zone and to 0.5 for the far zone. This characteristic conformed to the condition of body waves generated by an impulsive point source and Rayleigh waves generated by harmonic point source, respectively. The latter could have occurred if the ground vibrated under its natural mode of vibration.

3) Vibration velocity at a distance can be determined from equations shown in the table that follows. The units for v, r, rc, and w are mm/s, m, m, kg, respectively. It is noted that equations on the left most column will only give the best estimate of the mean value. Therefore, it is recommended to add the predicted normalized velocity ($\bar{v}$) by a constant of 1. By doing this, the modified value will be approximately at 80% one-side upper prediction level provided that $r > r_c$.

Fitting models	Ground type	Fitting parameters			R^2
		k_1	k_2	r_c	
$\bar{v} = k_1 \cdot r^{-1.5}$, $r < r_c$	Clayey	5008	64	78	0.876
$\bar{v} = k_2 \cdot r^{-0.5}$, $r > r_c$	Sandy	4356	31	140	0.793
where $\bar{v} = v / \sqrt{w}$	Sandy with rock boulders ground	981	6	161	0.743

4) Observed data shows no significant correlation between the dominant frequency and distance. Although the observed data were rather scattered, the dominant frequency seemed to be related with ground condition. The dominant frequencies of vibration were around 17 Hz in dry sandy ground, 42 Hz in saturated sandy ground, 49 Hz in saturated clayey ground and 31~ 45 Hz in sandy with rock boulders ground. The presence of ground water could increase the dominant frequency significantly.

5) Due to the uncertainty in determining the dominant frequencies of vibration in each ground type, the dominant frequencies were assumed to be the values at the 2.5th percentile for the conservative sake in the vibration assessment in this study. Based the proposed formula and the assumed frequencies, the setback distances (approximately at 80% prediction level) between residential buildings and a 2-kg explosive were found to be 53, 149 and 221 m for sandy with rock boulders, sandy and clayey grounds, respectively.

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