Analysis of a blast loading near sensitive clay slope in La Romaine village, Quebec

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Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
It is well known that blasting vibrations may be a triggering factor for soil movements and landslides. This paper describes a case history of a large slide caused by blasting in a sensitive clay deposit. The slide occurred on August 1st 2009 in La Romaine village, on the North Shore of the St-Lawrence Gulf. Two types of loading may have affected the slope stability: the blast vibrations themselves and the rapid loading impact stemming from muck-pile formation. The goal of this paper is to provide an analysis of the blast loading characteristics in order to better understand its influence on this slope failure. First, some concepts about blasting vibrations are introduced and landslide case histories involving blasting operations are reviewed. Then, data from La Romaine blast design are presented and the resulting ground motion parameters and the dynamic stresses and strains are assessed using theoretical and empirical equations.

RÉSUMÉ
Les vibrations de sautage peuvent être un élément déclencheur de glissement de terrain. Un grand glissement de terrain dans des argiles sensibles est survenu le 1er août 2009 au village de La Romaine au Québec Deux types de chargement sont survenus dans la pente et pourraient avoir affecté sa stabilité : les vibrations générées par le sautage et l'impact des débris projetés. Cet article traite du sautage et a pour objectif principal de caractériser la sollicitation dynamique survenue et de comprendre son influence sur la pente d'argile. Une brève revue de littérature sur les vibrations de construction générées par les travaux, la vitesse en pointe des particules et des cas de glissements impliquant des sautages est présentée. La conception du sautage de La Romaine est ensuite détaillée et les vitesses en pointe des particules, ainsi que les contraintes et déformations associées au sautage sont calculées à l'aide d'équations théoriques et empiriques.

1 INTRODUCTION

Blasting is widely used in both mining and civil engineering but it nevertheless remains "the most challenging and least understood source of construction vibrations" (Dowding, 2000). In geotechnical engineering, slope stability under blast vibration loading still remains an open research issue. Actually, few landslides or soil movements following blasting did occur, so its role as a landslide triggering factor remains not well understood. Also, it has been observed that when a landslide occurred in those conditions, there was also another factor involved that was known to affect the stability. However, the concern about blasting vibrations near slopes has increased in the last decade and research groups are working to increase the knowledge on the effects of blasts on slope stability (Wang et al., 2008; Ritika et al., 2011; Johansson et al., 2013; Yan et al., 2014; Zhang et al., 2014).

In 2009, a large landslide (175 m by 300 m) occurred in sensitive clay at La Romaine village in the Province of Quebec after blasting. The event and the geological setting were described by Locat et al. (2010). The influence of blast loading on La Romaine landslide was brought forward which then triggered more detailed geotechnical investigations and more advanced dynamic analysis.

The focus of this paper is on blast loading characterization. It aims at presenting a simplified evaluation of blast-related ground motion parameters and to complete it by an assessment of dynamic stresses and deformations.

Figure 1: La Romaine 2009 landslide

2 DESCRIPTION OF THE LANDSLIDE

La Romaine landslide occurred on august 1st 2009 (Figure 1). It happened during the construction of the main road, when blasting operations were needed to excavate a rock outcrop. The landslide occurred after the second blast: the blast design is presented on Figure 2 and its main characteristics are described in Table 1. Figure 3 shows the topographies before and after the landslide from aerial LiDAR. The cross-section presented in Figure 2 is identified in Figure 3.

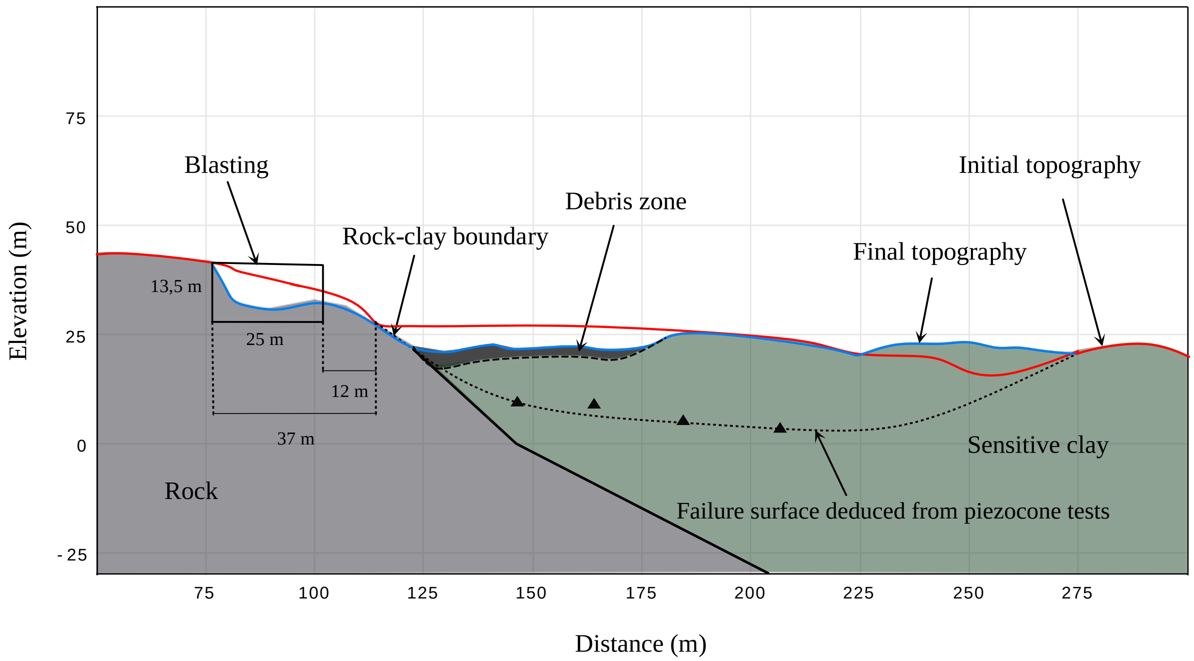

Figure 2: Topography along section AA’ before and after the blast and blasting area in the granitic gneiss rock

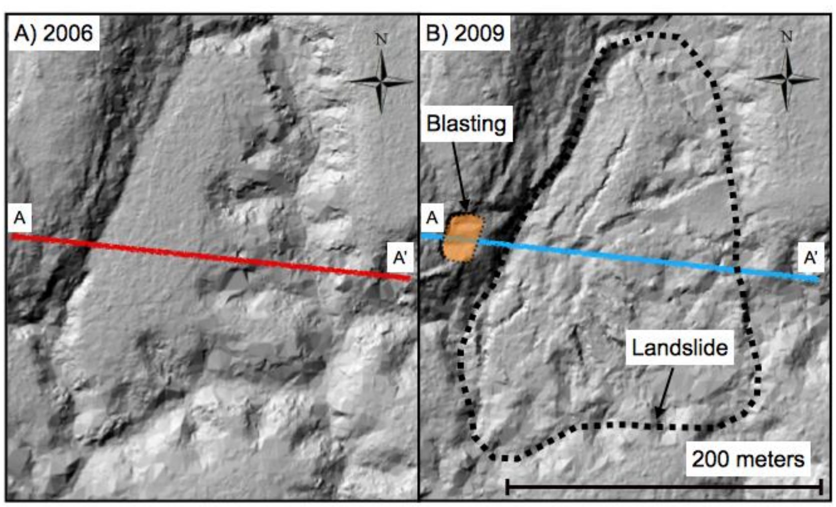

Figure 3: Topographies and localisation of the cross-section AA’ from aerial LiDAR before the landslide (2006) and after the landslide (2009)

The design of the first blast is unknown. Ground vibrations were not recorded during the blasting events. The Ministère des Transports du Québec (MTQ) carried out a first geotechnical investigation in 2009 right after the event. A more detailed evaluation involving advanced in situ and laboratory investigations, dynamic analysis and rapid loading impact is now being performed by the MTQ, in collaboration with Université Laval. A second geotechnical investigation was carried out in 2012 to get high quality samples. In summary, 15

CPTU soundings, 4 SPT soundings, 4 piezometers, aerial LiDAR, aerial photography, 1 Laval sampler sounding, 5 fundamental period tests and 5 penetrometers were done to characterise the site.

The investigations showed the presence of a thick layer of sensitive clay under 2-3 m of peat. The rock is a granitic gneiss. The clay is very homogeneous and its properties are summarized in Table 2. The failure surface is well known and was identified by comparing CPTU soundings in the landslide with CPTU in intact clay.

Table 1: Blast design and related parameters from blasting report

Number of holes	150
Spacing and burden	2.5 m X 2.5 m
Volume of rock excavated	8 300 m^3
Delay	17 ms or 25 ms
Duration	779 ms
Mean charge per delay	83 kg
Collar	Unknown

Table 2: La Romaine soil properties

Soil	Clay and silt
Shear strength (S_u)	25 to 50 kPa
Water content (w)	60%
Plasticity index (I_p)	4 to15
Liquidity index (I_L)	2 to 7
OCR	1.2-1.3
Shear wave velocity (V_s)	100 to 200 m/s
Density (ρ)	1 670 kg/m^3

3 LITERATURE REVIEW

3.1 Blast vibrations characteristics

In earthquake engineering and dynamics of structures, the characterization of the loading is an important step for dynamic analysis. The duration, the intensity and the frequency range are the most important parameters to characterise a motion. Those factors have a direct effect on the response. Blasting is a time varying force considered as a non-periodic load and produces a combination of many wave types. The principal are compressive (P), shear (S) and surface (R). Explosions produce body waves at shorter distances. Shear and surface waves become predominant at larger distances, when other layers or boundaries are intercepted (Dowding, 2000). The motion travels spherically from the blast and attenuates with the increase of volume material (Kong, 2012). Blast vibrations can be recorded with geophones in three directions: longitudinal, vertical and radial.

Examples of blast vibrations are presented in figures 4 and 5: the Figure 4 shows a single blast and the Figure 5 presents a multihole blast recorded in the three directions.

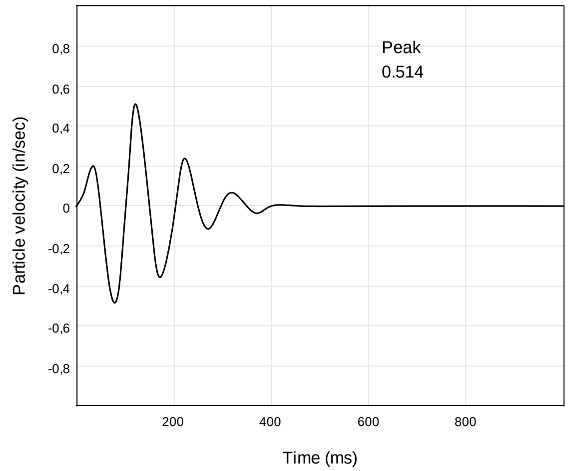

Figure 4: Signal example of a single blast modified from Anderson (1989)

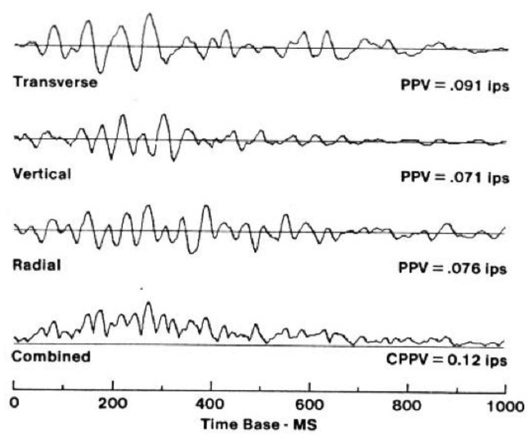

Figure 5: Signal example for a multihole blast (Siskind et al., 1989)

The ground particles move back and forth, in the same way as an earthquake ground motion. Most of construction blasts are multiple explosions delayed by milliseconds. This kind of solicitation is cyclic, but non-periodic, because it generally does not repeat itself for a given period of time. Also, a short time delay may have the effect to overlap the vibrations. In theory, if 2 holes detonate with less than 8 ms of interval delay, it may have the same effect on vibrations intensity that if they had detonated at the same time (Worsey, 1986; Dowding, 2000). In addition of increasing the particle velocity, the overlap of vibrations makes it difficult to discern the type of wave in the recorded motion and the knowledge about this is limited (Dowding, 2000).

The frequency content is another important parameter to characterize a dynamic load. Review of published data in the literature has shown that blasting vibrations frequency content can be very different from one blast to another. It is influenced by the design and can range from 10 Hz to 200 Hz (Kramer, 1996). The mean duration of a blast motion is in the order of 1 sec, comparatively to 20 sec or more for a major earthquake ground motion.

3.2 Particle Velocity

Peak particle velocity and particle velocity time histories are the most often used ground motion parameters to study blast vibrations in civil engineering as it is well known that it better relates to cosmetic cracking and other structural damages (Dowding, 2000). When a wave is traveling in a body at a certain propagation velocity, the particles of the body are moving in a given direction. The particle velocity is the speed of particles motion when the wave crosses them; it is not the velocity of the wave itself. For example, if a compressive wave propagates from a point to another, the particles move in the same direction as the wave propagation as shown in Figure 6a. For a shear wave, the motion direction of particles is perpendicular to the wave propagation (Figure 6b).

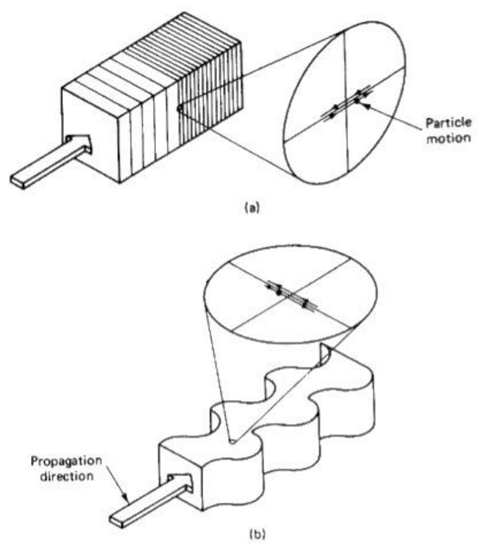

Figure 6: Particle motion for compressive wave propagation (a) and for shear wave propagation (b) (Dowding, 2000)

The peak particle velocity (PPV) corresponds to the maximum value of the velocity time history. There is a strong correlation between scaled distance, charge per delay and peak particle velocity. A multitude of empirical equations exist to estimate the peak particle velocity from soil types (Charlie, 1985; Charlie, 1988; Persson et al., 1994; Dowding, 2000; Veyera et al., 2002). The general equation is:

$$PPV = K(R / W^{1/2 or 1/3})^{a} \quad [1]$$

Where K and α are constants related to the site and geology, R is the distance between the blast and the measuring point and W is the charge per delay. The exponent 1/2 or 1/3 depends on the type of scaling. The square-root scaling is used when the charge is considered cylindrical and the cubic-root scaling is used when the charge is considered spherical (Dowding, 2000; Dowding, 2006; Kumar et al., 2013). Both are commonly used. The best way to estimate PPV for a particular site is by performing small charge field tests and recording vibrations at different location from blasting explosion. A graph of PPV measured in function of the scaled distance ($R/W^{1/2}$ or $R/W^{1/3}$) then shows how the site attenuates the signal with distance. The constants K and α can be found graphically. Once the scaling law is found, the charge per delay can be adjusted considering the allowable PPV.

3.3 Blasting effects in soils

The passage of each wave type through soils involves deformation. Extensive field and laboratory studies were carried out by Charlie (1988); Veyera et al. (2002) and Charlie et al. (2001) but were focused on non cohesive soils. They observed liquefaction in field experiments and in the laboratory. They also observed an increase in pore pressure that is directly related to the dynamic stresses generated by the vibrations. They concluded that blasting vibrations have a direct effect on soils and these can affect the stability. Cohesive soils like clay or sensitive clay were not considered in these studies.

In practice, the effect of blasting on slope stability remains not well understood. Few soil movements or landslides triggered by blasting have been reported in the literature and studied. Furthermore, when sensitive clays are cyclically loaded, it is well known that their undrained shear strength increases with frequency (Âhnberg and Larsson, 2012), which may partially explain the relatively few case histories involving clay slopes. It is also well known that their undrained resistance decreases with the increase of the cycle numbers. Nevertheless, there are some cases in which slope failures were observed after a blast in different types of soils, even in sensitive clays. It is important to notice that in most cases, the role of blasting in the failure was not clearly confirmed, since there was often another factor known to decrease the stability (Johansson et al., 2013). Table 3 summarizes landslides in sensitive clay cases with blasting. Table 4 presents landslides cases in other types of soils implying blasting activities near the slope.

Table 3: Landslides in sensitive clay with blasting activity near the slope

Case	Year	Reference	Type
La Baie (Canada)	1910	Locat et al. (2010)	Flow
Hawkesbury (Canada)	1955	Eden (1956)	Spread
Toulnustouc (Canada)	1962	Conlon (1966)	Spread
Namsos (Norway)	2009	NTNU (2009)	Flow
Lödöse (Sweden)	2011	Johansson et al. (2013)	-

Table 4: Landslides or other movements in other types of soils implying blasting activity

Case	Year	Reference	Soils
Russia	1935	Charlie et al. (1987)	Earthfill
Sweden	1973	Johansson et al. (2013)	Stratified
Finneidfjord (Norway)	1978	L'Heureux et al. (2010)	Clay with thin sand layers
Trondheim (Norway)	1990	Woldeselassie (2012)	Sand and silt
Finneidfjord (Norway)	1996	Woldeselassie (2012)	Clay with thin sand layers
Finneidfjord (Norway)	2006	L'Heureux et al. (2007)	Clay with thin sand layers
Lac Melville (Canada)	-	Locat and Lee (2002)	Deltaic sandy sediments
Mitkof Island (Alaska)	1976	Vandre and Swanston (1977)	Sand and silt

4 METHODOLOGY

4.1 Estimation of peak particle velocity (PPV)

The PPV depends on the distance to blasting location, the charge per delay and the site characteristics. Since there were no blasting vibrations recorded on the La Romaine site, it was not possible to develop the site attenuation law. The PPV of La Romaine blast was thus estimated from published scaling laws. Several scaling laws are available and examples of cubic-root scaling and square-root scaling are shown in Figure 7 and Figure 8 respectively for sands, rock, soils in general and for clay. All of those relations were already in equation form except for the Norwegian data (Figure 7) where the equation was defined herein from the vibrations presented in Johansson et al. (2013). The corresponding scaling law is:

$$PPV = 1000(R/W^{1/3})^{-1.33} \qquad [2]$$

The site parameters can be found graphically: α is the slope and K is the origin (when $R/W^{1/3}$=1) (Dowding, 2000). This seems to represent the only available data in literature for sensitive clays.

In view of this, the problem now is how to choose an appropriate scaling law to estimate PPV at La Romaine. First, it is important to understand the type of scaling. For La Romaine case, the authors believed that the square-root scaling is more justified to estimate PPV, because it has been shown that this type of scaling is more appropriate for surface blasting. The cubic-root scaling is more appropriate for buried explosives cases where propagation is done in 3D (Hao et al., 2001). Second, it is relevant to choose a scaling law with the soils that represent best the site. The distance from blasting to estimate the PPV is also important. For this project, the rock-clay interface is the location point. So, the scaling law chosen is Dupont (1980) square-root scaling law because the wave propagation to the interface is done also rock.

The estimation of PPV is very important in blasting vibrations characterisation because the PPV will be used to calculate stresses and strains.

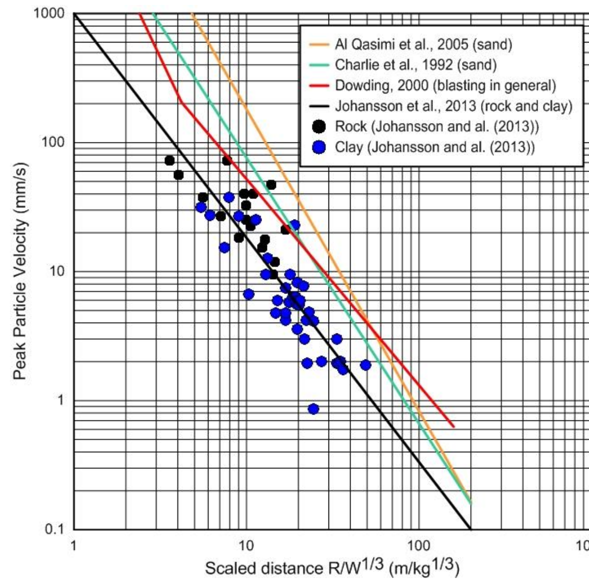

Figure 7: Peak particle velocity as a function of cubic scaling for different types of materials

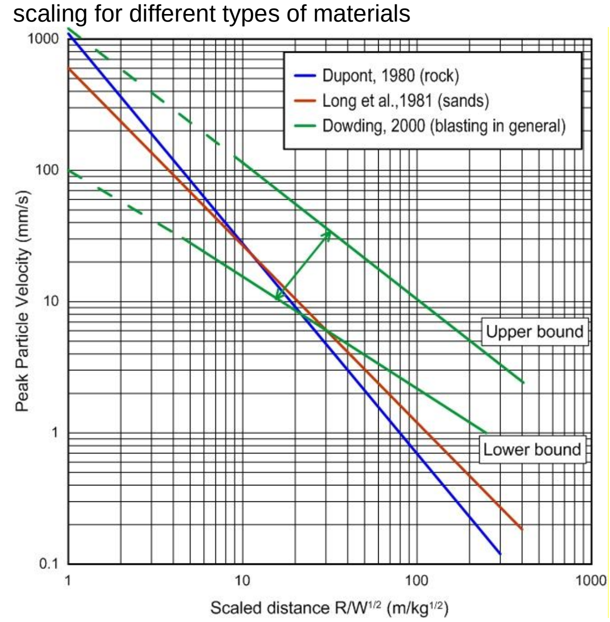

Figure 8: Peak particle velocity as a function of square-root scaled distance for different types of materials

4.2 Ground strains from plane-waves approximations

The two demonstrations presented in this section come from Dowding (2000). The normal stress can be estimated with the peak particle velocity in theoretical equation of plane-wave propagation. The derivation starts with the second Newton's law:

$$F = m\ddot{u} \qquad [3]$$

In the present case, the force F can be expressed as the increment of stress Δx induced by the wave multiplied by the contact area A. The mass corresponds to the material density multiplied with the area A and the distance traveled by the wave Δx. The acceleration $\ddot{u}$ can be expressed as the rate of change of the particle velocity $\Delta\dot{u}$ per unit of time.

$$\Delta\sigma A = \rho\Delta x A\frac{\Delta\dot{u}}{\Delta t} \qquad [4]$$

By considering that the maximum stress σ occurs at the same time as the peak particle velocity $\dot{u}_{\max}$, Equation 4 can be expressed:

$$\sigma = \rho V_c\dot{u}_{\max} = \rho V_c PPV \qquad [5]$$

The same development is used to calculate the shear stress τ associated to the shear wave velocity, V_s.

Ground strains can also be calculated from plane-wave approximation. Assuming the generalized sinusoidal function of a plane-wave propagation:

$$u = u_{\max}\sin\mathrm{K}(x - V_c t) \qquad [7]$$

where u is the displacement of particles, $u_{\max}$ is the maximum displacement or amplitude, K is the wave number $2\pi/\lambda$ where λ is the wavelength, x is the location, V_c is the compressive wave velocity, t is time. The first time derivative of Equation 7 gives the peak particle velocity (assuming K =1 rad/m):

$$\dot{u} = \frac{du}{dt} = -V_c u_{\max}\cos(x - V_c t) \qquad [8]$$

In engineering, the strain ε is the change in length divided by the initial length. In that case, ε is equal to the difference of displacement, u divided by the distance traveled, x. It can be expressed as the distance derivative of Equation 8.

$$\varepsilon = \frac{du}{dx} = u_{\max}\cos(x - V_c t) \qquad [9]$$

Substituting 9 in equation 8, the strain can be expressed in terms of peak particle velocity and wave propagation velocity (Equation 10).

$$\varepsilon = \frac{PPV}{-V_c} \qquad [10]$$

Equation 10 can be modified to calculate the shear strain γ by using the shear wave velocity V_s instead of V_c. Numerical simulations are carried out in the study of Johansson et al. (2013) to obtain the soil deformation associated to blasting. Their results show that the strain is estimated with good accuracy with Equation 10.

4.3 I-Blast simulation

A simulation was carried out with the software I-Blast (I-Blast, 2009) to analyze the blasting sequence and obtain a preliminary evaluation of blast ground motion parameters. Necessarily, some parameters have to be estimated. The given 12.6 m hole's depth with 83 kg explosive charge is considered here as a mean value. The collar was estimated at 0.9 m. The explosives used for the blasting were ANFO and Emgel 200. The holes depths have been adjusted to fit the topography because the rock is plunging towards east (see Figure 2). This has been done with aerial LiDAR and by considering that the base of the blasting area is at the same elevation as the future road. The charge per hole was modified to fit the height of each holes. In summary, the first row of holes has a depth of 8.3 m with a charge of 46 kg and the last row of holes a 14.6 m depth and 88.8 kg charge. The general analysis of the blast was done in the software by modeling all holes and their corresponding time delay (Figure 9).

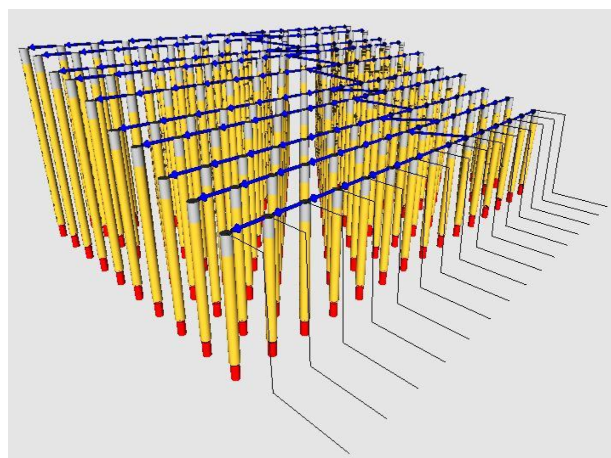

Figure 9: Blasting sequence modeled with I-Blast

5 RESULTS

5.1 Peak particle velocity

The peak particle velocity was estimated with the attenuation relationship of Dupont (1980) (K = 1 100 and α = -1.6). PPV was also calculated with the software I-Blast using the site parameter of Dupont's law. The I-Blast simulation showed, according to the blast design that two or three holes could have detonated simultaneously in a regular manner. The PPV was calculated with Dupont's law for two cases: one for the closest charge corresponding to 2 holes (46 kg charge each) at 14.5 m and the other for the biggest charge to detonate which corresponds to 4 holes for a total charge of 208.1 kg at 19.52 m. 14.5 m represents the closest distance from the blast to the rock-clay interface (12 m + 2.5 m for burden). The PPV calculated with Dupont's law for both charges are presented in Table 5. PPV were also calculated with Dupont's parameter in the I-Blast simulation and is presented in Table 5.

5.2 Stresses and strains from plane-wave equations

The compressive stress, shear stress, compressive strain and shear strain were calculated for the blast design of La Romaine with theoretical equations presented in methodology (equations 6 and 10). The density ρ is 1 670 kg/m^3, V_c and V_s used are 1 500 m/s and 100 m/s respectively (values at the top of the clay layer). The results are compiled in Table 5 and 6. The I-Blast simulation also provided the distribution of fragmented rock size. The mean diameter is 15 cm, which is comparable with the observations made in the field.

Table 5: Summary of results from PPV obtained with Dupont's law

Parameter	2 holes (14.5m)	4 holes (19.52m)	I-Blast
PPV	569 mm/s	678 mm/s	433 mm/s
Compressive stress	1 425 kPa	1 698 kPa	1 085 kPa
Shear stress	95 kPa	113 kPa	72 kPa
Compressive strain	0.04%	0.045%	0.03%
Shear strain	0.57%	0.68%	0.43%

6 DISCUSSION

The peak particle velocity obtained with the simplified analysis is 678 mm/s obtained with the denotation of 4 holes while the I-Blast simulation gives a maximum value of 433 mm/s with the attenuation law. Table 6 shows several conservative limits used in practice. It can be noted that the particle velocities estimated herein are much higher than the recommended values, even if those values are considered conservative. They have been related mainly to cosmetic cracking and not to soil behaviour. Studies from Charlie (1988) indicate that liquefaction is observed in non-cohesive soils for a peak particle velocity of 75 mm/s. The high values obtained in the study of the blast of La Romaine can be explained by the large explosive charge used in each hole and also by the short distance between the blast and the rock-clay boundary (12 m).

Table 6: Vibration limit criteria applied in practice

Vibration limit	Reference	Soils
25 mm/s	Johansson et al. (2013)	Clay
25 mm/s	Charlie (1985)	Saturated loose sands or silts
50 mm/s	Charlie (1985)	Other soils
50.8 mm/s	USBM	General

Also, the calculated stresses and strains are relatively high. The simplified analysis showed that the vibrations generated by the blasting are higher that generally considered in practice.

Stability analyses were carried with in the software Slope/W in drained conditions and it was found that the slope at La Romaine was stable before blasting. For a first slide in the slope, the safety factor is 2.8 and for the actual failure surface it is 4.8. Another stability analysis was carried out in undrained conditions and showed that the static weight of the fragmented rocks was not enough to trigger the slide (SF = 1.9). The failure thus can't be explained with conventional stability analyses and static conditions. For the authors, there are four hypotheses to explain La Romaine landslide:

i. the landslide was caused by the dynamic impact of the blasted rocks;
ii. the landslide was caused by the blast vibrations;
iii. the landslide was caused by the combination of the dynamic impact of blasted rocks and the blast vibrations;
iv. the vibrations generated important deformations at the rock-clay boundary, creating a local failure that progressed on the failure surface till the slope attained global failure

7 CONCLUSION

The effect of blast vibrations on slopes is a complex subject and depends on many factors like the blast type, slope geometry and soils involved. From literature, some landslides or soil movements have occurred after blasting, but the implication of blast was not specified. Laboratory studies and field experiments show that blasts can increase pore pressure and lead to liquefaction in non-cohesive soils.

This paper focuses on a large landslide that occurred in sensitive clay, a soil that can be sensitive to vibration by cyclic softening. For now, the event is well documented: the failure surface is well detailed, the volumes of the landslide, the blast and the debris zone are known. Many field tests were carried out on the site and that makes that particular case relevant.

The characterization of the dynamic solicitation is a required step in dynamic analyses. In this study, the blast was analyzed with an analytical method. This paper shows that the ground motions from the blast vibrations were very large, with a maximal estimated PPV value of 678 mm/s calculated with empirical equations. In fact, this value is higher that the common limit for blasting near soils or structures sensitive to vibrations showed in table 6. Theoretical equations were used to estimate the stress and strains associated with the blast. The estimated maximal compressive stress is 1 698 kPa and shear stress 113 kPa. The strains associated to the stresses are 0.045% and 0.68% for compressive and shear stress respectively. In summary, the stresses, strains and PPV calculated for that blast are much higher that those generally allowed.

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