

Detection of buried land mines using scattering of Rayleigh waves

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Abstract

The issue of humanitarian demining becomes increasingly important in the modern world. In the light of this, one of the most urgent problems to be solved is the development of new more effective and safer methods of land mine detection. The idea, which forms the essence of this paper, is based on using scattering of Rayleigh surface waves on buried land mines for their remote detection (at distances of 5-10 m). Rayleigh waves at frequencies 0.1 - 1 kHz seem to be a natural physical tool for this purpose. Unlike electromagnetic waves, they are equally sensitive to both metallic and non-metallic objects. Moreover, they are localised near the surface and can be effectively scattered (reflected) by any objects on the ground surface or slightly below it. In this paper, some preliminary results of theoretical calculations of the scattering of Rayleigh waves by simple models of land mines are reported. The obtained results show that scattering of Rayleigh waves can be a viable method of land mine detection.

1 Introduction

More than 100 million land mines have been laid during recent wars and conflicts in different parts of the world. Therefore, the issue of humanitarian demining becomes increasingly important. In addition to humanitarian demining, the need always exists to better protect peace-keeping troops in different part of the world on their patrol missions. In the light of the above, one of the most urgent problems to be considered is the development of new more effective and safer methods of land mine detection.

Currently, the most widely used practical device of land mine detection is a metal detector. Unfortunately, this simple device can hardly be used for detection of modern mines since most of them have very few metallic parts or do not have them at all. To tackle the problem of detecting non-metallic mines, a number of new methods have been suggested and investigated. Among them are different techniques using microwaves (e.g., ground penetrating radar), techniques based on infrared imaging, chemical sensors, etc. However, all these methods are expensive and unreliable, and no efficient device for detecting non-metallic objects is currently in operation.

The idea, which forms the essence of this paper, is based on using scattering of Rayleigh surface waves on buried land mines for their remote detection (at distances of 5-10 m). Rayleigh waves at frequencies 0.1 - 1 kHz seem to be a very natural physical tool for this purpose. Unlike electromagnetic waves, they are equally sensitive to both metallic and non-metallic objects. Moreover, they are localised near the surface and can be effectively scattered (reflected) by any object on the ground surface or slightly below it, provided their elastic parameters are different from those of the ground. In the case of land mines, the strength of Rayleigh wave scattering can be further enhanced by mines' structural resonances.

In this paper, the feasibility of this method of land mine detection is examined theoretically using a very simple model of a land mine. Calculations of the scattering carried out for typical parameters of a land mine and of the ground demonstrate that scattering of Rayleigh waves can be a viable method of land mine detection.

2 Methods of detection of buried land mines

In this section, a brief discussion of the known methods of detection of both metallic and non-metallic land mines is given.

2.1 Non-acoustic detection techniques

Infrared Imaging is based on different rates of heat release by land mines, in comparison with their surroundings, during natural temperature variations of the environment [1]. Based on this principle, it is possible to detect land mines using infrared cameras sensitive to thermal contrast between the soil over a buried mine and the soil close to it. Disadvantages of such systems are their high cost and the existence of the cross over periods (in the evening and in the morning) when the thermal contrast is negligible and, therefore, mines are undetectable. Foliage also represents a problem with this method, especially in autumn.

Gas and vapour sensors of chemical substances forming explosives are currently used in chemical technology and in airports with some success. However, they are usually too large to be employed in field applications or have too low a sensitivity [2].

Ground Penetrating Radar uses the scattering of very-high frequency electromagnetic waves emitted into the ground from the regions with different dielectric properties, including those associated with land mines (see, e.g. [3]). Although this technology is promising, its serious limitations are relatively low penetration of very high-frequency electromagnetic waves (some GHz) into the ground and high cost, compared to that of traditional metal detectors.

One can conclude that the existing non-acoustic methods and devices do not provide the required efficiency, low cost and reliability to cover the full variety of practical situations. This is hardly surprising as mines have been placed in a wide variety of terrain and it is likely that a “tool box” approach has to be adopted. Developing new efficient, safe, cost-effective and versatile methods of land mine detection would enhance the tools currently available. These include new acoustic techniques to be discussed below.

2.2 Acoustic techniques

Seismo-acoustic scattering uses the difference in elastic properties between a mine and surrounding soil which causes a small scattering of the incident air-borne sound, in addition to a much stronger signal directly reflected from the ground surface (see e.g. [4, 5]). The main problem here is in the identification of a small object pulse from the main reflected signal and other, often dominant, scattered signals caused by the ground surface irregularities.

Nonlinear acoustic methods are based on the excitation of higher harmonics in the reflected acoustic field as a result of nonlinear vibration of a land mine under the impact of the incident airborne acoustic waves [6, 7]. The advantage of this method is in its ability to distinguish a land mine from stones and other debris.

Surface acoustic waves in combination with a ground penetrating radar - this method employs the excitation of Rayleigh surface acoustic waves in the ground by an electromagnetic shaker (which generates pulses with central frequencies of around 400 Hz). The displacement of the vibrating ground surface, including the mine area, is then scanned using ground penetrating radar [8, 9]. The main idea of this approach is to use surface acoustic waves to enhance the effectiveness of ground penetrating radar, rather than to detect the scattered surface waves at a remote distance. Under the impact of surface waves, mines can vibrate at their structural resonance frequencies. This makes them easier to detect by radar, especially in the presence of stones, tree roots, debris, etc.

Scattering of Rayleigh waves by land mines is a new proposed method of acoustic land mine detection that will be further discussed in this paper. In spite of the fact that this method seems to be quite obvious for land mine detection, it has not been properly investigated or used yet. In this author's opinion, this method may be one of the most promising methods of land mine detection. The fact that Rayleigh surface waves are effectively scattered by any surface or subsurface irregularities is well known and is widely used in industry for ultrasonic non-destructive inspection of vitally important technical constructions (at frequencies 1-10 MHz). Rayleigh wave scattering is employed also in different electronic applications, such as band-pass filters and surface acoustic wave resonators used in television and mobile phones (at frequencies 30-500 MHz). On the other hand, according to the experiments with Rayleigh waves and a ground penetrating radar [8, 9], weak signals reflected from the mine placed in wet sand (at frequencies around 400 Hz) have been detected by electromagnetic radar. These experiments confirm the possibility to detect surface acoustic wave scattering from land mines. The basic differences of the proposed method from the method used in [8, 9] are that the former derives the necessary information from the far-field acoustic scattering, whereas ground penetrating radar collects measurements of ground surface vibrations in the near scattered field of the land mine. The fact that the far field of Rayleigh wave scattering is used in the proposed method of detection allows the operator to be at some horizontal distance from a land mine (5-10 m), which increases the safety of operation.

3 General description of the method

The experimental scheme implementing the effect of scattering of Rayleigh waves for land mine detection (a view from the top) is shown in Figure 1.

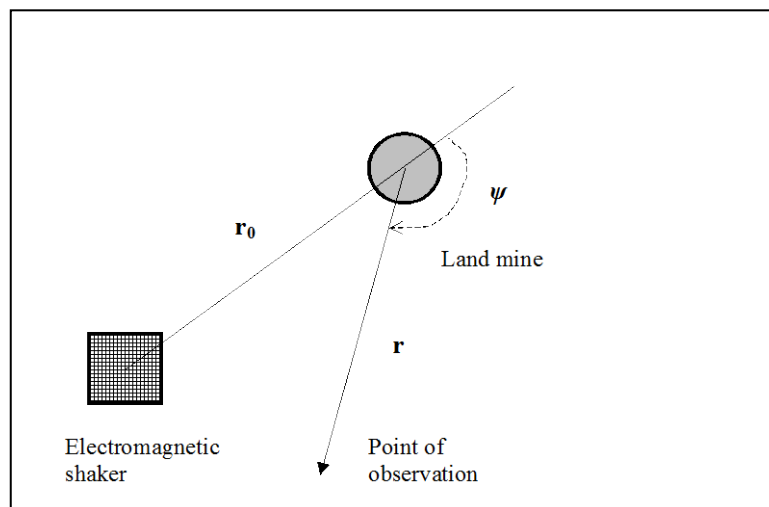


Figure 1: Geometry of the problem of scattering of Rayleigh waves on a buried land mine.

The pulses of Rayleigh waves with the central frequency f are generated by an electromagnetic shaker that applies a vertical concentrated force F_0 to the ground. A buried land mine is assumed to be located at the horizontal distance r_0 from the centre of the shaker, the centre of the land mine being located at the depth h below the ground surface. The point of observation is assumed to be located at horizontal distance r from the land mine, and its angular position is described by the angle ψ counted in respect of the radius-vector \mathbf{r}_0 (see Figure 1).

3 Theoretical estimates of the scattered amplitudes

The theory of scattering of Rayleigh surface waves is generally well developed (see e.g. the monograph [10]). However, most of the published papers in this area deal with the scattering on surface inhomogeneities, such as surface cracks, grooves, metal electrodes, etc. Land mines can be located on the ground surface as well. But in the majority of cases, they are buried below the ground surface. Therefore, the theory of Rayleigh wave scattering should be modified to consider subsurface inhomogeneities.

There are relatively few publications that consider Rayleigh wave scattering on subsurface inhomogeneities. In what follows we will use the recently published paper [11] that considers the scattering of Rayleigh on a small subsurface irregularity in the Born approximation of the perturbation theory. For simplicity, the size of irregularity in [11] is assumed to be much less than the Rayleigh wavelength at a given frequency. Also, for simplicity, it is assumed that the area of irregularity differs from the surrounding ground only in average mass density. Elastic properties of the irregularity are considered to be the same as the elastic properties of the ground. Of course, this is a very strong restriction that generally does not allow a potential user to obtain precise numerical results. However, for the purpose of preliminary estimates of the amplitudes of scattered Rayleigh waves and their dependence on the geometrical and other parameters of the problem this simplified model is acceptable. Note that, when incident Rayleigh waves interact with an irregularity, be it surface or subsurface one, the scattering takes place into longitudinal and shear bulk waves propagating in all directions into the bulk of the medium and into other Rayleigh waves. In what follows we will consider only scattering into other Rayleigh waves, keeping in mind its specific applications for land mine detection.

In light of the above, we will make our estimates using the approximate expression for the vertical component of the displacement amplitude in the scattered Rayleigh wave obtained in the paper [11]:

$$u_z^{sc} = f_0 \Delta m \frac{k_R q_l [q_l v_x^2(h) \cos \psi + q_l v_z^2(h)]}{2\pi \rho_0^2 c_l^2 q^2(\xi)} v_z(z) \frac{\exp(ik_R r_0 - k_R \gamma_0)}{\sqrt{r_0}} \frac{\exp(ik_R r - k_R \gamma + i\pi/2)}{\sqrt{r}}. \quad (1)$$

Here ρ_0 is the mass density of the ground, $k_R = \omega/c_R$ is the wavenumber of the Rayleigh wave and c_R is its velocity, r_0 is the horizontal distance from the excitation force (a shaker) to the position of the land mine (see Figure 1), r is the horizontal distance from the mine to the point of observation (detection of the scattered Rayleigh wave), f_0 is the amplitude of the excitation force, and Δm is the mass excess due to the presence of the land mine instead of the extracted ground of the same volume, angle ψ is the horizontal angle of observation in respect of the radius-vector \mathbf{r}_0 . In comparison with the original expression derived in [11], we have added the effect of ground attenuation on the propagation of both incident and scattered Rayleigh waves by including the relevant terms proportional to the ground energy loss factor $\gamma \ll 1$ into the exponential functions in (1). The time factor $\exp(-i\omega t)$ is assumed.

The unspecified parameters q_l and q_t are defined by the expressions $q_l = (k_R^2 - k_l^2)^{1/2}$ and $q_t = (k_R^2 - k_t^2)^{1/2}$, where $k_l = \omega/c_l$ and $k_t = \omega/c_t$ are the wavenumbers of longitudinal and shear waves respectively, c_l and c_t are their velocities, h is the burial depth of the centre of the land mine, $q(\xi) = F'(k_R)/k_t^3$,

where $F'(k_R)$ is the derivative of the Rayleigh determinant (the left-hand side of the Rayleigh equation) taken at $k = k_R$, where $\xi = c/c_R$ and $n = c_t/c_l$. The explicit expression for $q(\xi)$ takes the form [11]:

$$q(\xi) = \frac{2}{\xi(2\xi^2 - 1)^2} \left[4\xi^2 - 1 - 8\xi^6(1 - n^2) \right]. \quad (2)$$

Functions $v_x(z)$ and $v_z(z)$ in the expression (1) are the known functions describing the change in horizontal and vertical components of Rayleigh waves with depth z [11]:

$$v_x(z) = 2\xi^2 \exp(-k_t z \sqrt{\xi^2 - n^2}) + (1 - 2\xi^2) \exp(-k_t z \sqrt{\xi^2 - 1}), \quad (3)$$

$$v_z(z) = (1 - 2\xi^2) \exp(-k_t z \sqrt{\xi^2 - n^2}) + (2\xi^2) \exp(-k_t z \sqrt{\xi^2 - 1}). \quad (4)$$

Note that the expression (1) has a very clear interpretation. The presence of the distances r_0 and r in the exponential functions and in the denominators describes the effects of propagation of the incident cylindrical Rayleigh wave from the shaker to the land mine, and of the scattered Rayleigh wave from the land mine to the point of observation. It is sufficient to analyse the expression (1) only, i.e. the vertical component alone, because the horizontal component in Rayleigh waves is related to the vertical one.

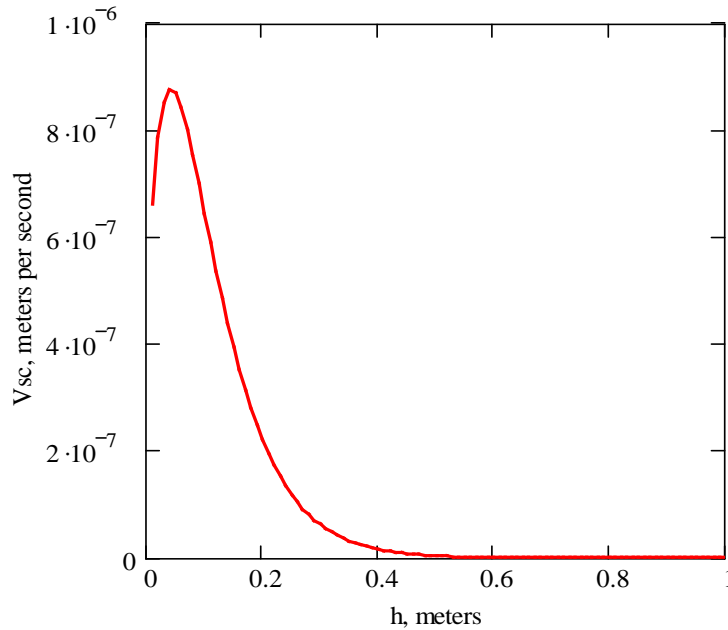


Figure 2: Amplitude of vertical vibration velocity of the scattered Rayleigh waves as a function of the burial depth h of the land mine; the angle of observation $\psi = 180$ degrees - the case of back scattering.

The numerical estimates of the amplitudes of the Scattered Rayleigh waves have been carried out for the following values of the parameters: $f_0 = 10$ N, $f = \omega/2\pi = 250$ Hz, the detection depth $z = 0$ (i.e. it is assumed that a receiving transducer (e.g. accelerometer) is placed on the ground surface), distances: $r_0 =$

5 m, $r = 5$ m, the mass excess $\Delta m = 0.2$ kg (note that the mass excess can be both positive and negative, if the average mass density of the land mine is larger or smaller than the mass density of the ground respectively); ground parameters: $c_R = 90$ m/s, $c_t = 98$ m/s, $c_l = 140$ m/s, $\gamma = 0.01$, $\rho_0 = 1800$ kg/m³. Calculations have been carried out according to the formulas (1)-(4). Note that final results were calculated not for the amplitude of vertical displacement $|u_z^{sc}|$ given by (1), but for the amplitude of vertical vibration velocity $|v_z^{sc}| = |\omega u_z^{sc}|$, measured in meters per second.

Figure 2 shows the results of the calculation of the vertical vibration velocity of the Rayleigh wave scattered by a land mine as a function of burial depth of the land mine, h . It can be seen that the scattering is efficient only for shallow depth, $h < 0.2-0.3$ m, i.e. when h is substantially smaller than the Rayleigh wavelength at the given frequency. This is quite an obvious property of Rayleigh wave scattering, which was also mentioned in [11], because Rayleigh waves simply do not 'notice' a buried obstacle if its depth is larger than the effective Rayleigh wave penetration into the ground, which is of the order of one Rayleigh wavelength at a given frequency.

The dependence of the amplitude of vertical vibration velocity of the scattered Rayleigh waves on the observation angle ψ is illustrated in Figure 3 for the value of burial depth of the centre of the land mine $h = 0.05$ m. It can be seen that the scattered field shows some directivity, with larger scattering amplitudes being in the forward direction ($\psi = 0$).

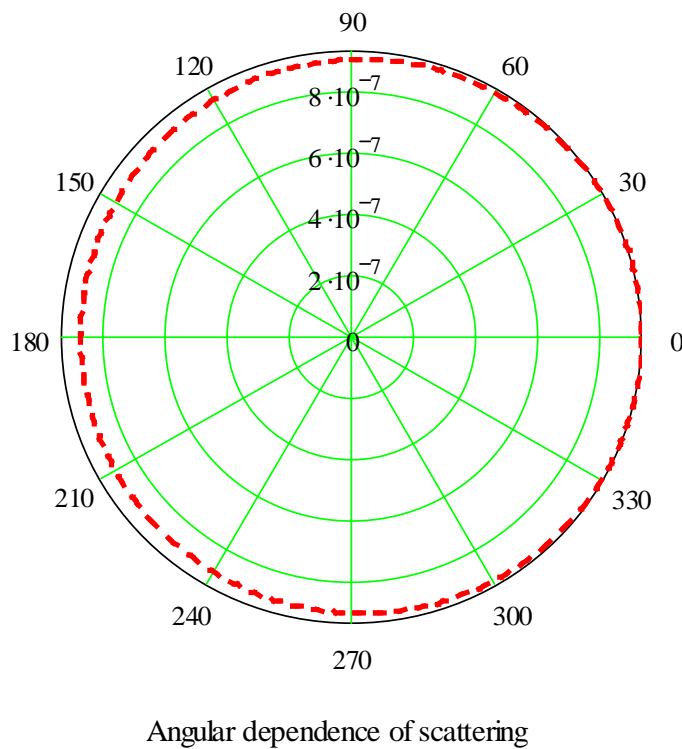


Figure 3: Amplitude of vertical vibration velocity of the scattered Rayleigh waves as a function of the angle of observation ψ ; the value of burial depth of a land mine $h = 0.05$ m.

It should be emphasised again that the above calculations based on the very simple model of a land mine have been carried out with the purpose of initial rough estimates of the expected amplitudes of scattered Rayleigh waves. For more precise calculations, one would need to take into account the difference between the elastic parameters of the land mine and the ground. In addition to this, structural vibration

properties of land mines should be taken into account as well. Interaction of the incident Rayleigh waves with structural resonances of a land mine may cause a resonant scattering of Rayleigh waves accompanied by a substantial increase in the scattered amplitudes. This effect could be used for a better recognition of buried land mines if their structural vibration properties are known. A detailed discussion of these issues is beyond the scope of this paper.

4 Conclusions

It has been demonstrated in this paper that scattering of Rayleigh waves on buried land mines can be used for remote detection of land mines (at distances of several meters). It has been shown how the amplitudes of scattered Rayleigh waves depend on the land mine's burial depth, on Rayleigh wave central frequency, and on the elastic parameters of the ground.

For further investigations, internal structural resonances in buried land mines may prove important since a variation of the frequency of incident Rayleigh waves may then help to distinguish these objects from other clutter and debris.

Important also are the differences in soil compacting above the land mine and in the surrounding area. To clarify the effect of this issue and of many other issues, a detailed experimental investigation of Rayleigh wave scattering on buried objects simulating land mines should be carried out.

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