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Classification of near-surface anomalies in the seismic refraction method according to the shape of the time–distance graph: A theoretical approach

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ABSTRACT

In this paper, we analyse the influence of near-surface anomalies on the first arrivals of seismic waves. The traveltimes of first arrivals are calculated using the eikonal equation and are depicted in the form of the time–distance (t–x) graphs. We classify five simple geological models according to the shape of the t–x graphs and relate these results to more complex models one can find in the natural settings.

All simple models are based on the two-layer model that is modified by a near-surface anomaly. We investigate the following cases: (i) a circular cavity impenetrable to seismic waves positioned in the upper layer, (ii) a circular object positioned in the upper layer, (iii) a part of the border between the layers is deformed into concave shape, (iv) a part of the border between the layers is deformed into convex shape, and (v) a vertical fractured zone positioned in the lower layer. The resulting t–x graphs are classified according to their shapes into three groups. The graphs in the first group are characterised by a peak point and the geological models (i) and (iii) belong to this group. The graphs in the second group are characterised by a depression in their shape and the geological models (ii) and (iv) belong to this group. The graph that corresponds to the model (v) differs from all other graphs and belongs to the third group. The seismic refraction method clearly distinguishes the models that belong to different groups, but the method cannot distinguish the models that belong to the same group because the shapes of their t–x graph are almost identical.

1. Introduction

Geophysical research of near-surface anomalies is usually conducted as part of preparatory works in civil engineering projects. In order to prevent possible future damage, special attention is devoted to the detection of underground cavities and objects during the construction of buildings, roads, dams and other infrastructural objects. For these purposes, numerous techniques based primarily on seismic, gravimetric, electrical and magnetic methods have been developed. Seismic methods that are often used in the near-surface imaging include the seismic reflection method, methods based on analysis of surface waves and the seismic refraction method.

The seismic reflection method deals with seismic waves reflected back from the interfaces between contrasting geological layers. The energy is reflected at the interface of layers due to difference in their acoustic impedance. Since a cavity causes strong contrasts in the acoustic impedance, the seismic reflection method is widely used in the detection of underground cavities: abandoned coal mines (Guy et al., 2003; Miller and Steeples, 1991), gypsum mines (Grandjean et al., 2002; Piwakowski et al., 1997), caverns and collapsed caves (Baker et al., 1997).

The use of surface waves in the near surface investigations is based on the fact that in non-homogenous systems, phase velocity of a surface wave depends on the frequency of the wave — the system is dispersive. A technique named Spectral Analysis of Surface Waves (SASW) uses experimentally obtained dispersion curves to reconstruct the shear wave velocity model, i.e. to map the underground (Nazarian et al., 1983). Since near surface anomalies affect surface wave dispersion, fluctuations in the dispersion curve are used to detect anomalies (Ganji et al., 1997). To reduce the effect of noise, Park et al. (1999) improved SASW method through the application of Multichannel Analysis of Surface Waves (MASW). Campman et al. (2004) experimentally confirmed that the MASW method can be used to obtain spatial images of subsurface heterogeneity, whilst Gelis et al. (2005) and Nasseri-Moghaddam et al. (2007) researched the influence of cavities of various shapes, positioned at varying depths, on surface waves. Because of limitations on the resolution of shear wave velocity profiles obtained with MASW, Xia et al. (2007) studied the feasibility of directly detecting near-surface cavities and vertical faults with surface-wave diffractions. Grandjean and Leparoux (2004) used numerical modelling in combination with a specially built test site to study the influence of the cavity on surface and

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P-waves. They analysed several experimentally obtained signals: Rayleigh-wave phase shifts, Rayleigh-wave diffraction and attenuation, direct P-wave attenuation and P-wave diffraction.

The seismic refraction method, based on the analysis of first arrivals, is simple and inexpensive, and thus often used in near-surface exploration. To determine the distribution of underground seismic velocities, it is necessary to interpret the first arrivals. There are numerous interpretation methods available. One of the first widely used methods, the plus–minus method (Hagedoorn, 1959), can be applied even without the use of computers. This method is typically used to map underground refractors in simple geological models. The analysis of complex geological models requires more powerful methods such as the generalised reciprocal method (GRM) (Palmer, 1981) and the refraction convolution section (RCS) (Palmer, 2001a, 2001b). Recently, Engelsfeld et al. (2008) investigated the influence of underground cavity on the first arrivals of seismic waves through the numerical modelling of eikonal equation. They derived mathematical formulae for the position and size of a circular cavity, whilst the precision of their calculations was experimentally confirmed.

One of the problems in geophysical investigations is possibility of multiple interpretations of experimental data. In the seismic refraction method this means that different geological models may result in the same or very similar first arrivals. This may result in the bad choice of an initial tomography model and as a final result in an incorrect image of the underground structure under observation. Hence, different geophysical methods are combined to characterise given geological structure. For example, Cardarelli et al. (2010) detected a region of low-velocity zone using seismic refraction tomography, which they interpreted as a cavity only by combining these data with data obtained by electrical resistivity tomography. Park et al. (2010) combined 2-D electrical resistivity and 3-D gravity methods to detect cavities in a karst area. The problem of non-uniqueness in the seismic refraction tomography could be also resolved by means of other refraction attributes derived from the traveltime, amplitude data and the complete seismic traces using the generalised reciprocal method (Palmer, 2010a, 2010b).

In this paper, we provide the physical explanation for non-uniqueness of the seismic refraction method by relating the shape of the *t*–*x* graphs (first arrivals) to the propagation of seismic waves. We have researched and compared five simple two-layer models modified by near-surface anomalies: an underground cavity model, a buried object model, a model with a concave boundary layer, a model with a convex boundary layer and a model with a vertical fractured zone. These simple models are often found in the karst regions and are usually investigated in near-surface exploration (Šumanovac and Weisser, 2001). First arrivals obtained using numerical calculations are presented in the time–distance graphs. The time–distance graphs are classified into three groups according to their shapes, which are the consequence of the propagation of seismic waves through the studied anomaly. We use this classification to show which models can be clearly distinguished, and in which cases misinterpretation is possible. Additionally, we have shown how the results obtained for five simple models could be used as a guideline in the analysis of more complex models. The following complex models have been analysed: The cavity of irregular shape in the three layer model with dipping interfaces, the buried object of irregular shape in the three layer model with dipping interfaces, a combination of a circular cavity and a buried object in a two layer model, and combination of a cavity and a convex bulge in a two layer model.

2. Numerical modelling

The first arrivals are obtained as a solution of the eikonal equation using numerical modelling. The eikonal equation in two dimensions has the following form:

$$\left(\frac{\partial t}{\partial x}\right)^2 + \left(\frac{\partial t}{\partial z}\right)^2 = \frac{1}{v^2(x,z)} \quad (1)$$

where t is the traveltime at the point (x, z) and v represents the seismic velocity at the point (x, z). For a known geological model, i.e. known velocity field, the traveltimes are calculated for each point in 2-D space. As the eikonal equation is a nonlinear partial differential equation, it is not possible to obtain a general analytical solution. Therefore, various numerical methods have been developed (Cao and Greenhalgh, 1994; Podvin and Lecomte, 1991; Sethian, 1996; Sethian and Popovici, 1999; Vanelle and Gajewski, 2002; Vidale, 1988, 1990).

In this paper, traveltimes are calculated on the 2D grid, which consists of 1000×1000 nodes. The distance between neighbouring nodes is $d/1000$, where d denotes the length of the profile. The source of the waves is positioned on the surface either at the left edge or at the right edge of the profile. The velocity at each node is predefined. The numerical algorithm used to solve the eikonal equation is based on the method of finite differences. The algorithm is in accordance with the procedure first proposed by Qin et al. (1992), and a detailed description of the algorithm is given by Engelsfeld et al. (2008). First arrivals, which are calculated for each node, are used to plot the graph of the wavefronts. The *t*–*x* graph is plotted using first arrivals of the 1000 nodes on the "surface".

3. Description of simple geological models

Simple geological models analysed in this paper are two-layer models modified by a near-surface anomaly (Fig. 1). The layer with the lower seismic velocity ($v_1 = 800$ m/s) is above the layer with the higher seismic velocity ($v_2 = 3200$ m/s). The boundary between the layers is parallel to the surface and is at a depth of $h = 7$ m. The length of the seismic profile is $d = 50$ m. A model with the circular cavity with the radius $r = 2.5$ m is depicted in Fig. 1a. The centre of the cavity is positioned at a depth of $z = 3.5$ m and its distance from the left edge of the profile is $x = 25$ m. Fig. 1b depicts the model with a buried object. The shape, dimension and position of the object are the same as in the case of the underground cavity, whilst the seismic velocity within the object is $v_2 = 3200$ m/s. Fig. 1c shows the model where part of the boundary between layers is concave, whilst Fig. 1d shows the model where part of the boundary between layers is convex. The concave and convex boundaries between layers have a semicircular shape with the radius of curvature $r = 2.5$ m, and are positioned at the distance $x = 25$ m from the left edge of the profile. Fig. 1e depicts a model with a vertical fractured zone. The width of the fractured zone is $s = 6$ m, it is centred in the profile and its seismic velocity is $v_3 = 1500$ m/s.

4. First arrivals and the propagation of seismic waves in simple geological models

The first arrivals have been calculated for all models. The source of the waves is positioned on the surface at the left edge of the profile. The *t*–*x* graph and the graph of the corresponding wavefronts are presented. The wavefronts are depicted up to a depth of 25 m with the time interval between two adjacent wavefronts $\Delta t = 0.0008$ s.

4.1. Underground cavity model

Since the underground cavity model has been analysed in details by Engelsfeld et al. (2008), in this paper we present only the numerically obtained *t*–*x* graph (Fig. 2). In the case of a two-layer model with a horizontal boundary, *t*–*x* graph is a piecewise linear function (Mussett and Khan, 2000). Underground cavity, which is impenetrable for seismic waves, modifies this graph as shown in Fig. 2. The distance from the source of the waves at which the influence of the cavity starts (ends) is denoted by x_1 (x_2). At distances less than x_1 and greater than x_2, the *t*–*x* graph has a shape typical of a two-layer model with a horizontal boundary. A discontinuous change of the slope of the graph occurs at the distance x_p. The crossover distance x_c is also denoted.