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Local amplification of deep mining induced vibrations part.2: Simulation of ground motion in a coal basin

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ABSTRACT

This work investigates the impact of deep coal mining induced vibrations on surface constructions using numerical tools. An experimental study of the geological site amplification and of its influence on mining induced vibrations has already been published in the previous paper (Part 1: Experimental evidence for site effects in a coal basin). Measurements have shown the existence of an amplification area in the southern part of the basin where drilling data have shown the presence of particularly fractured and soft stratigraphic units. The present study, using the boundary element method (BEM) in the frequency domain, first investigates canonical geological structures in order to get general results for various sites. The amplification level at the surface is given as a function of the shape of the basin and of the velocity contrast with the bedrock. Next, the particular coal basin previously studied experimentally (Driad-Lebeau et al. [1]) is modeled numerically by BEM. The amplification phenomena characterized numerically for the induced vibrations are found to be compatible with the experimental findings such as: amplification level, frequency range and location. Finally, the whole work was necessary to fully assess the propagation and amplification of mine induced vibrations. The numerical results quantifying amplification can also be used to study other coal basins or various types of alluvial sites.

1. Mine induced vibrations

As shown in Driad-Lebeau et al. [1], mining operations may induce a redistribution of the stress field based on the mechanical behavior of the rockmass. This can lead to a substantial microseismic activity [2–7]. The rupture process generates elastic waves, which are propagated through the geological structure up to the free surface. Seismic monitoring was thus performed in numerous mines [1]. In recent years, the impact of mine induced vibrations on surface constructions (i.e. houses or buildings located close to a mine) has been studied. This type of dynamic loading is different from seismic excitations coming from natural earthquakes (return period, amplitude, frequency range, etc.).

Detailed studies were carried out for a coal basin in the framework of a French research program called "SisMine" initiated by INERIS and sponsored by the French collieries [1]. LCPC and University Paris-Est-Marne la Vallée were associated with this research program in order to develop a numerical methodology aimed at simulating the impact on surface constructions of weak amplitude vibrations. The SisMine research program is subdivided into three parts, each one devoted to specific goal as following: Part 1: experimental estimation of site effects in the coal basin [1]; Part 2: numerical estimation of site effects in the coal basin and comparison with experimental results (present paper) and Part 3: impact of deep mining vibration on surface constructions—numerical approach.

This paper numerically investigates the propagation and amplification of mine induced vibrations in coal basins. It consists in a general study of various basin geometries (canonical basins) and detailed analyses of the Gardanne coal basin (Provence, France). Comparisons with experimental results from the field are also proposed.

2. Experimental analysis in the field

2.1. Site description

The Gardanne basin is located between Aix-en-Provence and Marseille (South of France) several kilometers westward from the city of Gardanne (latitude: 43° 27′ 16″ North and longitude: 5° 28′ 34″ East). It overlays a coalfield which forms the eastern part of the arc basin and constitutes an E–W oriented geological unit (Gaviglio et al., 1996) [37]. The general tectonic features and

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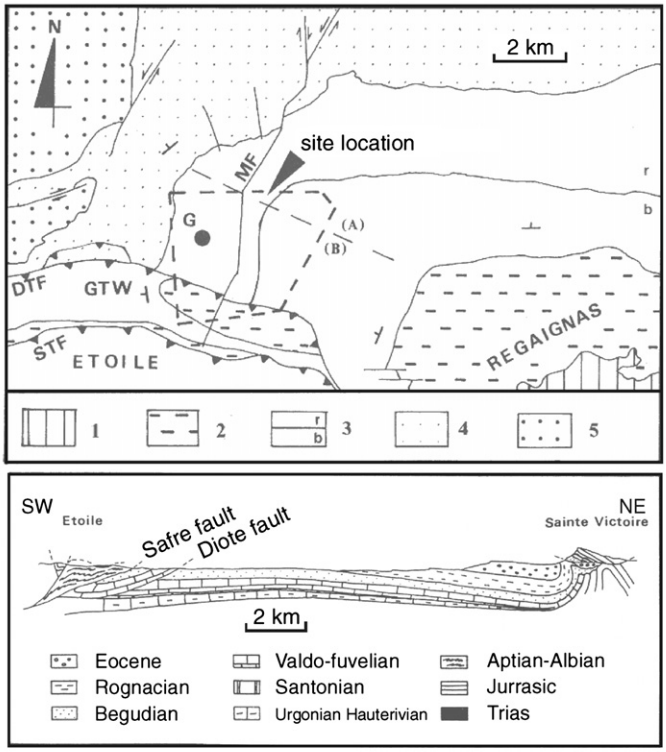

Fig. 1. *Top*: geological setting and location of Gardanne colliery (1: Upper Jurassic; 2: Campanian; 3: Begudian and Rognacian (3b,3r); 4: Eocene; 5: Oligocene). The coalfield is located in the Campagnian limestones. *Bottom*: geological cross-section of the Gardanne basin *[after Driad-Lebeau et al., 2009]*.

geological setting of the basin are quite simple (Fig. 1). The Gardanne basin is composed of a fluvio-lacustrine of the upper Cretaceous and the Eocene overlaying a substratum of the Jurassic (or lower cretaceous). The stratigraphy sequence consists mainly in marls, limestones and sandstones of the Valdonnian together with limestones of the Fuvelian (hard and brittle) with intermediate lignites (Fig. 1). The shallower sequences are represented by clay–sandy limestones of the Rognacian and Begudian. The presence on the surface of marine abrasion and molasses deposits has marked the influence of a sedimentary episode of the Miocene.

Among the 8 coal levels having been exploited since the Middle Ages, the last seam mined until the closing of the mine (2003) was the so-called “Grande Mine”. That is the most significant layer (2.5 m thick) located at depths ranging from 1000 to 1400 m. The coal layers were worked with a long wall caving method that uses two roadways and extracts coal along a straight front having a large longitudinal extension. The stoping area close to the face is kept open to provide a security zone for the staff and the mining equipment.

2.2. Experimental results on induced vibrations

The seismic events induced by mining exploitation were recorded by using the mobile network described in [1]. These data have been processed in the frequency domain and all events of magnitude greater than 2.5 have been considered (mine depth is approximately 1 km). Such events constitute the vibrations of interest in terms of impact on surface constructions. In Fig. 2, *H/V* spectral ratios from mine induced vibrations recordings were computed for 10-instrumented sites (8 residences and 2 free-surface sites). They are plotted as average *H/V* spectral ratios plus/minus one standard deviation.

As shown in Fig. 2, the *H/V* spectral ratios highlight significant variations in resonances and amplitude peaks (evidencing amplification) at the investigated sites. Spectral ratios above 8 are found in the frequency band 3–8 Hz at sites FOU, LER, LAG and MON and NAY (see [1] for these various locations). The sites HEN and NAY, where outcrops are mainly marl-limestone, present a weak resonance (amplitude of nearly 3–4) at 3–6 Hz. This observation is coherent with the geological setting where the limestone dominates. In this particular case, the amplification effect is not very significant. It is interesting to note the response of the site MON, which presents a broad resonance at 4.5 Hz with an amplitude of 7. Indeed, according to the geology (limestone-marls), the *H/V* ratio would be expected close to that of the site HEN. It suggests that the observed amplitude could be related to a topographic effect. Indeed, the corresponding house is located on the slope of a hill, which culminates at 210 m.

3. Modeling wave propagation in soils

3.1. Numerical methods for wave propagation

To analyze wave propagation (seismic waves, vibrations, etc.) in 2D or 3D geological structures, various numerical methods are available:

- the finite difference method is accurate in elastodynamics but free surface or interface conditions has to be carefully considered [8,9],
- the finite element method is efficient to deal with complex geometries and numerous heterogeneities (even for inelastic constitutive models [10]) but has several drawbacks such as numerical dispersion (error in terms of phase velocity) and numerical damping [11–14]) and (consequently) numerical cost in 3D elastodynamics,
- the spectral element method has been increasingly considered to analyze 2D/3D wave propagation in linear media with a good accuracy due to its spectral convergence properties [15–17],
- the boundary element method allows a very good description of the radiation conditions but is preferably dedicated to weak heterogeneities and linear constitutive models [18–21]. Recent developments have been proposed to reduce the computational cost of the method especially in the high frequency range [22–24],
- the Aki-Larner method which takes advantage of the frequency–wavenumber decomposition [25,26],
- the scaled boundary finite element method which is a kind of solution-less boundary element method [27],
- other methods for simple geometries such as series expansions of wave functions [28].

Furthermore, when dealing with wave propagation in unbounded domains, many of these numerical methods require absorbing boundary conditions to avoid spurious reflections [14,15]. For instance, it is possible to couple FEM and BEM [19,29] allowing an accurate description of the near field (FEM model including complex geometries, numerous heterogeneities and nonlinear constitutive laws) and a reliable estimation of the far-field (BEM involving accurate radiation conditions).