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Stress wave propagation test and numerical modelling of an underground complex

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ABSTRACT

Ground vibration is the most important environmental effect of blasting, and tools for its understanding and control are a prime necessity for the excavation of tunnels and caverns in hard ground. This paper contributes to an improved understanding of the way waves travel in the ground, particularly when there are excavations in the path of propagation, while also enhancing existing numerical models to better simulate that behaviour and thus provide better means to address underground vibration impacts. To this purpose, twenty low intensity blast between neighbour tunnels of an underground complex were performed, followed by a numerical study of the test. The test and simulation showed that, contrary to what is implied in semi-empirical attenuation laws, factors like the propagation path or local amplification can be more important than instant explosive weight and distance to blast.

1. Introduction

Rock excavation by blasting causes severe environmental impacts, namely rock projection, toxic gas, noise and vibration production. Of these impacts, vibrations are the hardest to control, since stress waves propagate through the rock mass and hit nearby structures and equipment. Moreover, good quality rock masses, where blasting is frequently the only available excavation method can be good conductors of vibrations, in particular when fractures are tightly closed.

The established method of vibration impact assessment in engineering projects is the calibration of semi-empirical laws that take instant charge weight (W) and distance to blast (R) as arguments and provide estimates of Peak Particle Vibration (PPV):

$$PPV = K\frac{R^m}{W^n}[m/s] \tag{1}$$

with K, n and m being constants found by curve-fitting. The major shortcoming of this method is that it requires a significant number of blasts before it can offer statistically sound results and cannot cope with variables other than charge and distance, such as geological singularities or excavation shape effects. The numerical models that represent the geometry of the excavation and surrounding structures, mechanical properties of the rock mass can complement traditional methods. These methods provide estimates of the vibration level ahead of the start of the excavation and predict vibration variation due to the evolution of the works or mitigation measures.

The most pressing research issues in this area are the dynamic properties of rock and the definition of dynamic testing methods for rock and rock fractures, since rock deformability and strength are strongly influenced by strain-rate, and feed all dynamic numerical models. There have been significant advances on study of rock fragmentation and rock-explosive interaction. Laboratory and field observation using sensors and cameras with high acquisition rates capture the instants after the blasts [1,2], and complex numerical methods that incorporate the explosive detonation, gas production, rock pulverisation, fragmentation and fracture growth are used to model this phenomenon in a small (up to a few metres) scale [3]. On the opposite end of the scale, work on vibrations' impacts on structures is mainly related to description of surface case studies, effect of mitigation measures, development and calibration of empirical laws. Field tests, which are scarce, are mostly done by the military and not available to the public, noteworthy exceptions are the US. Bureau of Mines extensive field tests [4,5], and some partially published military studies [6,7]. Railway generated vibrations are an important problem, under serious attention from researchers worldwide, but the ground materials, vibration duration, intensity and frequency content are rather different from rock blasting problems [8]. Models that bridge the small and large scales are under development but they are out of reach of the common engineering practice, demanding large teams with world class modelling skills and very powerful hardware and software [9,10].

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The practicing engineer is confronted with several difficulties when faced with a real situation where underground rock blasting may affect nearby structures. The uncertainty associated to empirical laws or artificial intelligence techniques, such as neural networks, is large and these techniques do not consider geological features which can amplify or degrade vibration levels by factors of ten or more. The influence of excavations in the rock mass, fractures and faulting in real situations is still unknown. On the other hand, underground three dimensional dynamic simulations are relatively uncommon and carry a number of difficulties related to rock properties or blast simulation.

This paper describes a vibration propagation test on an underground complex set in a good quality rock mass, followed by 2D and 3D dynamic numerical modelling. The motivation for the test was the control of vibrations during the excavation of a new hydraulic circuit by drill and blast near a powerhouse that hosts three hydraulic turbines in continuous operation.

Low intensity test blasts were performed to define a vibration attenuation law for the site, which is the traditional approach for this problem. However, this method cannot take in account geological accidents in the path of the waves, namely contact zones, faults and dykes, schistosity and fracturing; geometrical effects such as the “shadow” effect of excavations; the reflection at the ground surface and the effect of transition of vibrations from the rock to the structure that supports the turbines. Realistic numerical models, if supported by good site characterisation or calibrated against in situ blast tests, can deliver useful insights and approximated quantitative results. The goal of this paper is, thus, to increase understanding of wave propagation in the underground environment, through the results of the field test, and then to develop the numerical simulation of this phenomenon, by describing some of the available paths and on how the final result is influenced by these choices, thus contributing to bring dynamic modelling of rock blast vibration into everyday practice.

One of the conclusions of this study is the quantification of the interference of vibrations with existing rock excavations. The influence of excavation geometry and its representation in the models is established, as well as the role of the excavation damaged zone around pre-existing excavations. Indications on methods for blast load application in the models and measurement of vibrations both on the field and on the model are also derived.

2. Underground blast test

2.1. Description of the site and test set-up

Bemposta dam was designed in 1957 and construction was finished in 1964. It is an 87 m high concrete arch-gravity dam set on a good quality rock mass, with an underground circuit and a powerhouse cavern on the right bank, shown in Fig. 1. The complex is owned by EDP, Portugal's major electricity operator. In 2008–2011 the complex was upgraded involving the excavation of a new hydraulic circuit and powerhouse [11].

A rock blast wave propagation test was planned to assess the effect of the new circuit drilling and blasting on the turbines and control equipment. The test was performed in the 6×4.5 m unlined auxiliary adits, built for the excavation of the original complex and not used since them Covering ranges from 25 m. The powerhouse is a concrete-lined, brick-shaped cavern connected to the surface by an elevator and stair shaft. The rock mass consists of migmatites with a schistosity that changes dramatically from place to place. There are two major discontinuity sets and some intercalations of pegmatites. RMR ranges from 30 to 80 with average values in the upper part of the range, fracturing is predominantly F3 and weathering classification yields mostly W2–3. The complex and images of the adits were the blasts took place are shown in Fig. 2.

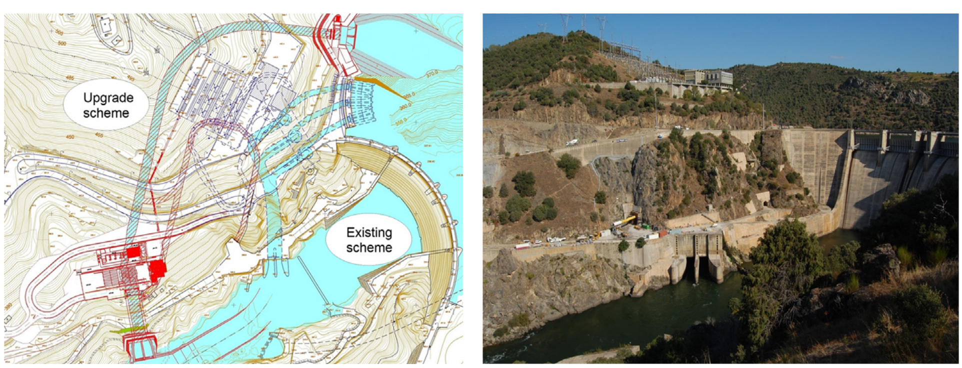

Fig. 1. Map of the surface, hydraulic circuit, powerhouse and auxiliary adits. (left), adapted from [11]. Photo of the dam and right bank during construction of the upgrade (right).

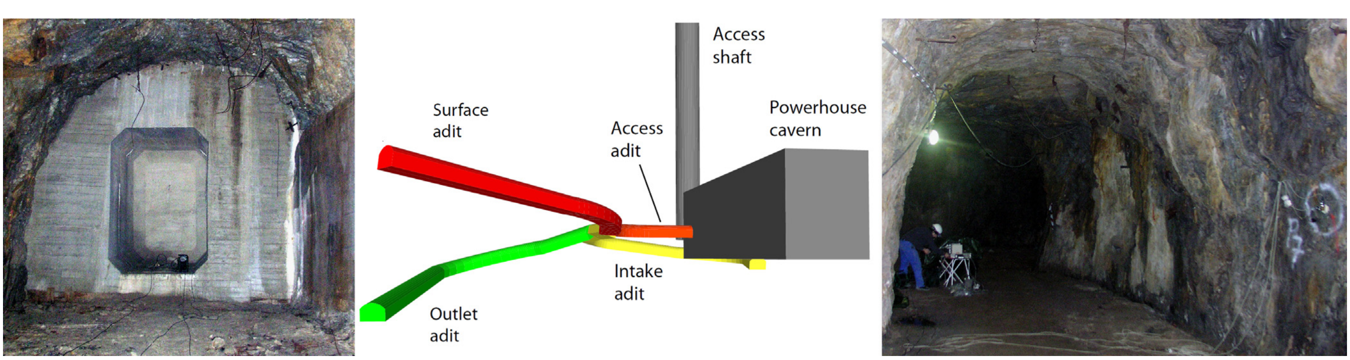

Fig. 2. Base P1 installed on the floor of the concrete plug at the end of the Surface adit (left); 3D representation of the underground complex (intake and outlet tunnels are not shown for greater clarity, centre); Access adit (right).