A Conceptual Assessment of Dynamic Analysis in RS3

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Abstract. Dynamic analysis is an important tool for assessing and managing the risks associated with seismic events. Seismic events result from ground ruptures. The magnitude of a seismic event depends on the size of the rupture and the stress drop, which respectively translates to displacement and released energy (work).

Modeling of dynamic analysis and ground response can contribute to forecasting seismic events in terms of their magnitude. It is important to have a good conceptual understanding of dynamic analysis in any software programs that is going to be used. Therefore, it is recommended to start with a simple scenario and fewer interacting parameters before moving forward to complicated cases. In this paper, a simple case was defined and analysed in RS3 to better understand the material response to dynamic loading under different conditions. The main goal is to find a correlation between dynamic load, material properties, displacement, and the resulted seismic event. Knowing such correlation, a calibrated data set can be generated and used for more complicated models. Then, the calibrated model can be used for forward and predictive modeling. Another focus of this research is on the energy release and the associated seismic events.

Keywords: Dynamic Load · Seismic Event · Seismic Magnitude · Seismic Energy

1 Introduction

A seismic event can be described as the rupture of a fracture or plane of weakness within a rock mass, which occurs in response to changes in differential stress. This rupture happens due to a decrease in the frictional resistance to shear slip on a generally rough surface and is typically part of an ongoing deformation process in the rock mass [1]. Seismic events can be caused by a variety of factors. Rockbursting is the most common cause of seismic events in mining. During a formal review of mining health and safety conducted by the Ontario Ministry of Labour from 2014 to early 2015, it was determined that seismicity and rock-bursting pose the most significant risk to the health and safety of workers in underground mines located in Ontario [2]. Rockburst occurs when stress builds up in the rock and causes it to fracture and release energy suddenly. This energy

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can cause the rock to burst and generate seismic waves that can be felt on the surface. Dynamic analysis involves simulating the behavior of rock and infrastructure during a seismic event, allowing engineers to identify potential hazards and develop mitigation measures.

Seismic event can be defined by seismic source parameters. Some of the most popular source parameters are moment magnitude, seismic moment, and seismic energy [3]. The most well-known metric for seismic magnitude is the Richter magnitude scale (M_L, Local Magnitude). However, this method underestimates large events and is most suitable for small shallow events with $M_L < 6.5$ [4]. The Moment Magnitude scale (M_w) has been introduced for large events and it corresponds with Richter magnitude for events $M_w < 6.5$ [5]. Total stored energy in a system can be released in a form of radiated seismic energy, heat generation from frictional factors and opening of tensile fractures. Seismic moment can be interpreted as the maximum amount of radiated energy.

Dynamic analysis refers to the process of studying the behavior of a system or structure in response to dynamic loads, such as vibration and seismic events. Modeling of dynamic analysis can help predictions about the magnitude and occurrence of seismic events. The goal of dynamic analysis is to understand the dynamic response of a system or structure and to identify potential areas of failure or weaknesses that could lead to safety hazards, reduced efficiency, or downtime.

With all that being said, it is important to find an appropriate tool to construct and verify a dynamic model. In this study, RS3 has been selected as a finite element based tool to build a dynamic model. The primary aim of this paper is to provide a clear understanding of the concepts underlying dynamic assessments. To achieve this goal, we focus on using simple models that help to elucidate the relationships between various parameters before delving into more complex scenarios.

2 Methodologies

2.1 Dynamic Analysis in RS3

RS3 [6] is a 3D FEM software to carry out numerical modelling of rock/soil in mining and civil engineering applications. Dynamic analysis can be performed using RS3 to simulate the response of rock/soil to seismic events and generate data on parameters such as displacement, velocity, and acceleration. The data can be used to analyze the behavior of the structure and to identify potential hazards and risks associated with seismic events.

Dynamic analysis in RS3 can be used to test the effectiveness of different mitigation measures, such as the use of support systems or reinforcement materials. Engineers can simulate the performance of these measures under different conditions and make informed decisions about the most appropriate measures to use in a given situation.

RS3 offers a range of dynamic boundary conditions, including Absorb, Transmit (Free-field), and Damper. When using the Absorb and Transmit conditions, the line segment is given a Lysmer-Kuhlemeyer dashpot boundary, which aims to simulate the infinite boundary behavior of the soil medium. This means that the boundary condition absorbs incoming shear and pressure waves as if the model were unbounded, providing a more accurate representation of the soil's behavior.

The dynamic load types in RS3 can be classified into two categories: external force loads and prescribed motion loads. External force loads are applied to the model in a manner similar to static line loads and are essentially time-varying external forces applied at nodes. On the other hand, prescribed motion loads including displacement, velocity, and acceleration loads define the motion of nodes during dynamic simulations. Nodes subject to prescribed motion loads are restrained in the relevant direction and moved by the necessary displacement amount dictated by the loading function.

2.2 Moment Magnitude, Seismic Moment, Seismic Energy

The Moment Magnitude (M_w) is a dimensionless number, and the subscript “w” stands for mechanical work [7]. M_w, is a static measure of the total mechanical work. A log scale is used, given as:

$$M_w = \frac{2}{3} log M_0 - 6 \tag{1}$$

Here, M_0 denotes seismic moment with dimensions of energy ($N.m$) [4]. Seismic moment is the total strain energy released during a seismic event [8]:

$$M_0 = \mu AD \tag{2}$$

Here, μ is the shear modulus of the rock, A is the shear-stimulated area, and D is the average shear displacement of the shear-stimulated area. Therefore M_0 has units of work ($W = F \cdot d = \mu \cdot A \cdot d$).

The size of a seismic event relates to the amount of radiated energy. The moment magnitude in terms of the seismic energy radiated by a seismic event is given by an empirical relationship developed by Gutenberg and Richter [9]. Using the following estimate and replacing it in M_w equation gives the magnitude-energy relationship as follows [10]

$$E_s = 1.6 \times 10^{-5} M_0 \tag{3}$$

$$M_e = \frac{2}{3} log E_s - 2.9 \tag{4}$$

where E_s (seismic energy) is in $N \cdot m$ and M_e is unitless.

M_w and M_e are both magnitudes, yet they may not have the same numerical values for the same seismic event. M_w and M_e define different physical properties of a seismic event. M_w, is a static measure of the total mechanical work and M_e is more of a measure of seismic potential for damage which is mostly controlled by the dynamic nature of the rupture (rapid, slow, etc.). In other words, M_w estimates the size of a seismic event and M_e indicates the strength of it, therefore both are relevant for studying the potential hazardous damage of a seismic event [11].

According to these equations, seismic radiated energy (E_s) is proportional to $10^{1.5\text{Me}}$.

$$log E_s = 1.5 M_e + 2.9 \rightarrow E_s \propto 10^{1.5 M_e} \tag{5}$$

As shown in M_e equation, for one unit increase of magnitude, the radiated energy increases by a factor of 32 [8]. In the same way, it would be increased by a factor of 1000 for two units' increase of magnitude.

$$\frac{E_2}{E_1} = \frac{10^{1.5(M+1)}}{10^{1.5M}} = 10^{1.5} = 32$$

Note that, only a small amount of the total stored energy is transformed into radiated seismic energy (E_s). The total stored energy can be calculated as:

$$E = \int_{t_1}^{t_2} F.v.dt \approx F(t)\Delta x \tag{6}$$

where $F(t)$ is the applied dynamic force from t_1 to t_2, v is velocity and Δx is the total displacement.

In reality, the total stored energy can be released in a form of radiated seismic energy, heat generation from frictional factors and opening of tensile fractures. This study does not account for tensile fractures and heat generation.

3 Assessments

The modelling steps are summarized as follows:

- Build geometries.
- Excavate openings (no material).
- Assign material properties and constitutive models.
- Define static and dynamic boundary conditions.
- Define initial stress state and dynamic loading.
- Create mesh.
- Solve the model to reach equilibrium.
- Interpretation.

In RS3, an elastic model with no initial field stress was created to study the response of the model to dynamic load. The initial stress was neglected to isolate the effects of dynamic loading on the model. The external box is 20.0 m in each direction. The excavation in the model has a spherical shape with a radius of 0.1 m and is located at the center of external box. The dynamic boundary condition is set to "absorb". The primary assumptions are dynamic load and loading time. Characteristics of the defined scenarios are listed in Table 1. Note that, exaggerated values were selected in this study to better explain the material behavior under dynamic loading.

From the given equations and assumptions for dynamic load and time, the following workflow can be used to back calculation seismic magnitude.

$$E = W = F \cdot d \rightarrow E_s = 1.6 \times 10^{-5} M_0 \rightarrow M_w = \frac{2}{3} log M_0 - 6 \tag{7}$$

dyamin load and displacement → *seismic energy* → *seismic moment* → *seismic magnitude*

Table 1: List of defined scenarios

Scenario #	Stiffness (MPa)	Dynamic Load (MPa)	Loading Time (s)
Scenario 1	4	6	0.1
Scenario 2	4	600	0.1
Scenario 3	0.4	600	0.1

4 Results

In order to collect outputs, a query line was introduced in the middle of the model with 25 monitoring points (Fig. 1). Point #12 was selected as a representative monitoring point in this study.

A dynamic load of 6 MPa has been applied to the outer boundaries of the sphere in the radial direction in a period of 1 s. Then, the load was released (set to zero) in 0.1 s and the unloading material behavior was assessed. Note that, damping values have been set to zero, to better observe vibration after unloading. Figure 2 shows vertical displacement vs time for monitoring point #12. As expected, displacement increases gradually over time for the first 1 s. Then unloading starts and continues for 0.1 s, and as a result displacement decreases. The dynamic behavior of the system after unloading was assessed for 0.5 s.

In order to have a better assessment of the overall behavior of the system, displacement was plotted for each monitoring point at different cycles of loading and unloading. As indicated in Fig. 3, the points that are closer to the source of load experienced higher magnitudes of displacement. Also, displacement is showing an increasing trend with loading time.

By zooming into the 0.1 s of the post-unloading phase, it can be seen how the released energy inside the material is causing vibration (Fig. 4). This is the natural frequency of the system. Therefore, having identical material properties and increasing the dynamic load, similar vibration frequency with higher displacement magnitudes is expected to be obtained. This was examined by increasing the dynamic force 100 times and it can be seen from Fig. 5 that displacement was also increased by two orders of magnitude.

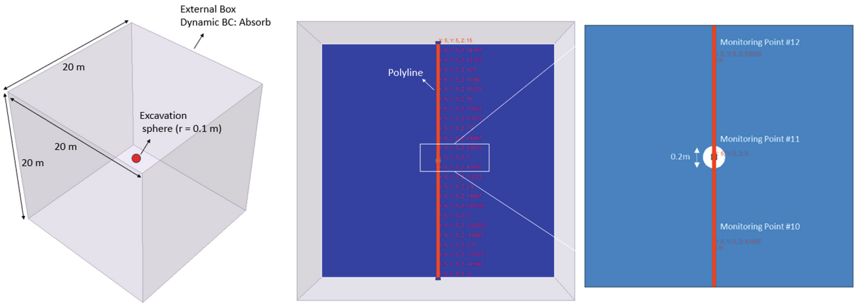

Fig. 1. The defined query line along the center of the model

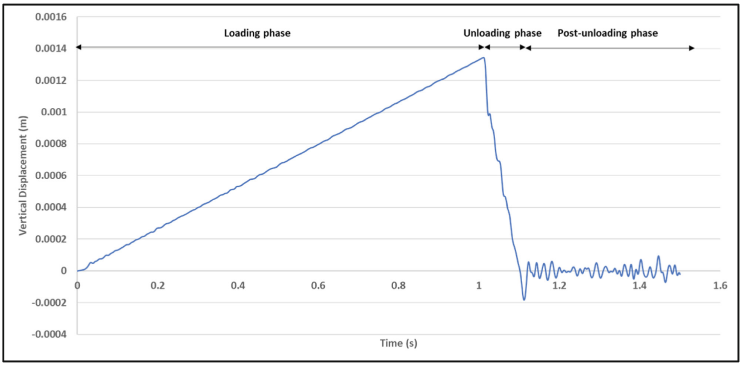

Fig. 2. Time history of vertical displacement for monitoring point #12 (scenario #1)

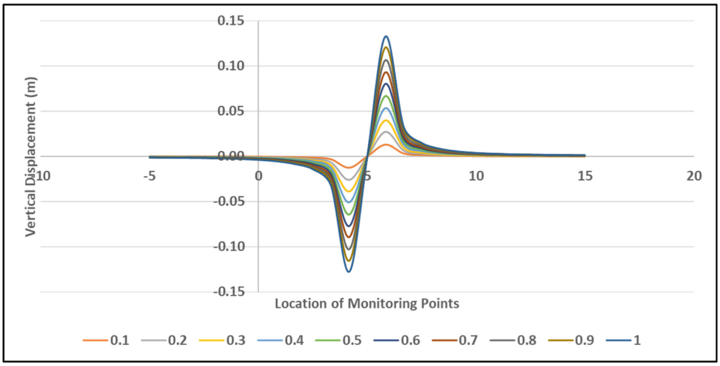

Fig. 3. Vertical displacement for each monitoring point during the loading phase

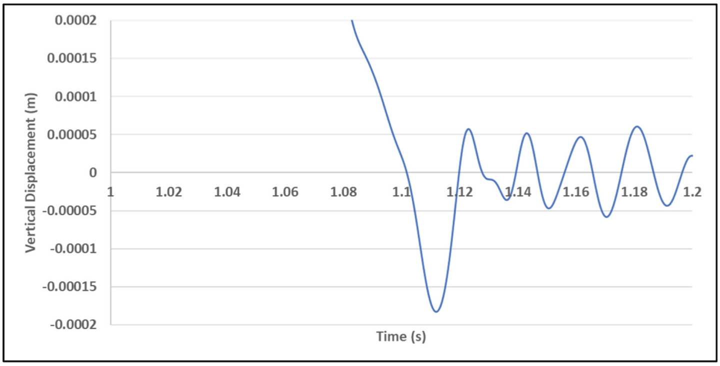

Fig. 4. Vertical displacement vs time for monitoring point #12 within 0.1 s of post-unloading phase (scenario #1)

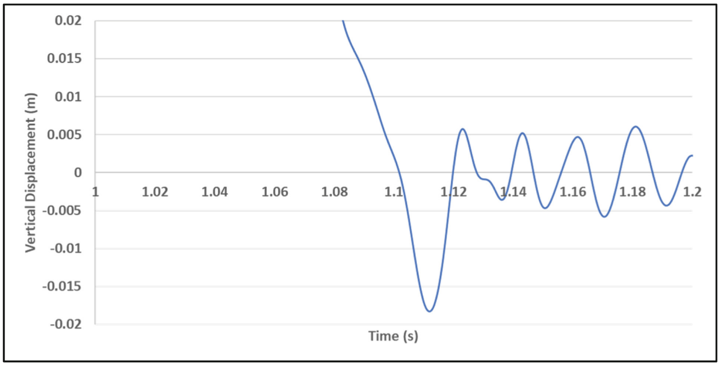

Fig. 5. Vertical displacement vs time for monitoring point #12 within 0.1 s of post-unloading phase (scenario #2)

By decreasing the stiffness (softer material), natural frequency of the system reduces, which means the released energy inside the material vibrates more slowly. Another way to explain this is to calculate P_{wave} velocity from elastic properties of the material using the following equation.

$$V_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{8}$$

There is a linear correlation between the velocity of the P_{wave} and Young's modulus (which represents stiffness). Therefore, higher stiffness results in higher velocity and higher velocity leads to higher frequency. This was tested by creating a similar model with lower stiffness (scenario #3). Figure 6 indicates only one cycle of vibration over 0.1 s for scenario #3.

The post-unloading phase was assessed by plotting displacement for each monitoring point at different cycles. Displacement graphs at two different times of post-unloading

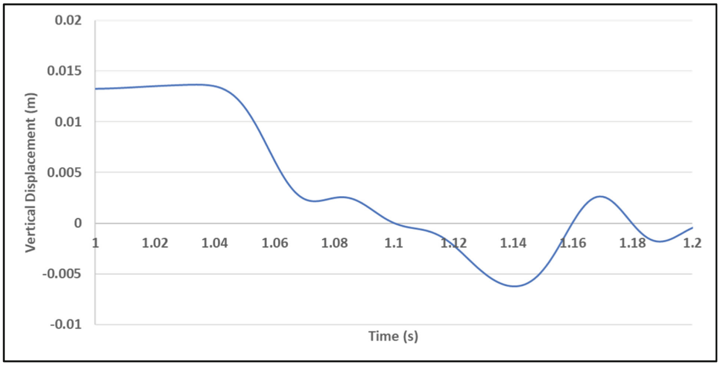

Fig. 6. Vertical displacement vs time for monitoring point #12 within 0.1 s of post-unloading phase (scenario #3)

show opposite trends for each monitoring point (Fig. 7). This is due to the vibration of the residual energy in the system. In other words, each point is undergoing displacement in different directions based on the direction of the wave that hits it.

Using the introduced equations in Section 2, seismic energy was calculated using dynamic load and displacements as a direct output of a numerical model for scenario #1. Seismic moment and moment magnitude can then be estimated from seismic energy.

Figure 8 shows the estimated seismic energy. Although the remaining energy in the system after unloading is small, it vibrates in the system and causes displacement or micro-seismic events which are shown in Fig. 9.

Figure 9 illustrates the estimated moment magnitude. The size of seismic events is increasing during the loading phase and then they drop to small values as unloading starts and continues. Note that, negative values are permitted in magnitude scales. They are small seismic events that are hard to detect on surface.

Comparing to real seismic data, the estimated seismic energy from the corresponding seismic magnitude is within a reasonable range.

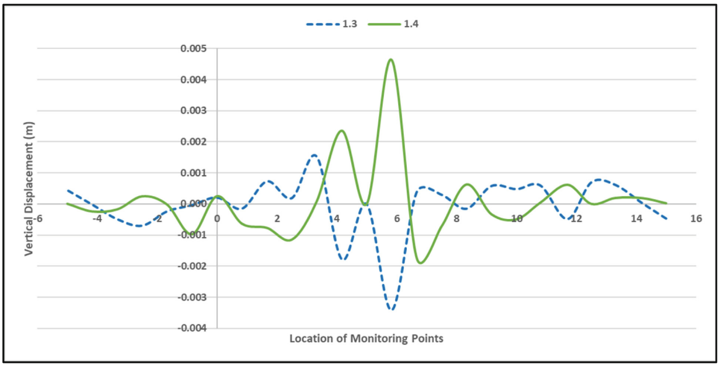

Fig. 7. Vertical displacement for each monitoring point during the post-unloading phase

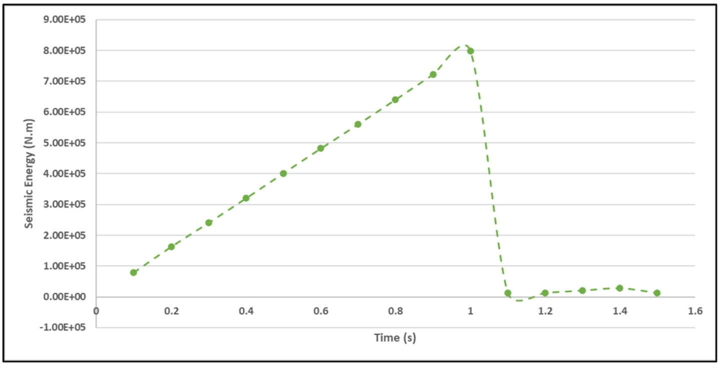

Fig. 8. Estimated seismic energy

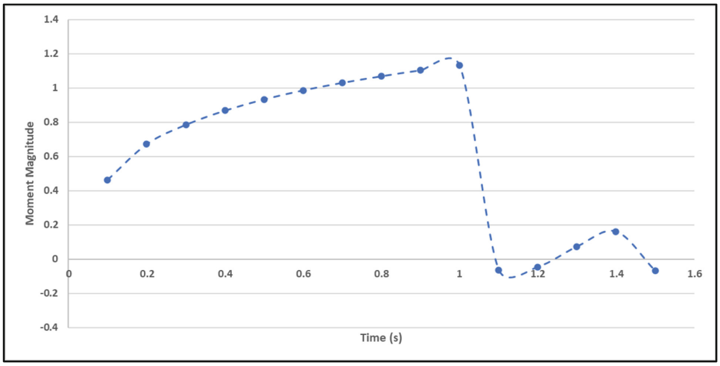

Fig. 9. Estimated moment magnitude from dynamic analysis

5 Conclusions

Dynamic analysis is an important assessment for ensuring the safety, efficiency, and productivity of underground operations. RS3 was proven to be an appropriate tool to perform dynamic analysis. There is a correction between the material properties and dynamic loading. The softer the material becomes, the longer it takes for the seismic waves to travel along the material and vibrate. Therefore, it is important to have a realistic assumption for material properties to achieve more accurate results. Displacement can be exported as a direct output from RS3. Having displacement, seismic energy and in return seismic magnitude can be estimated. This is an important understanding and can be used for predictive modeling to better manage hazard associated with seismicity. It is recommended to explore the effects of discontinuities and slip events in the model. With these proven concepts, a calibrated data set can be generated and used for more complicated models. The calibrated model can then be used for predicting future behavior of the material under different conditions.

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