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Modelling shakedown demand on rockbolts

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Abstract

Shaking due to remote seismic events places a demand on ground support that can result in damage or failure of support elements. This demand cannot be fully quantified by any single ground-motion intensity measure such as peak ground velocity/peak particle velocity (PGV/PPV). An alternative approach, inspired by practices in earthquake engineering, is to simulate shakedown loading using the simple zero-dimensional (0D) model proposed by Malovichko & Kaiser (2020). In this 0D model, shaking of a block of rock supported by a bolt is represented as shaking of a mass connected to the surrounding rock by an elastoplastic spring (representing the bolt) and a viscous damper (representing energy dissipation to sources such as friction). Four verification cases are presented that compare results from a 0D model with those determined from two-dimensional dynamic modelling of shakedown loading using the finite-discrete element method (FDEM). These demonstrate that 0D models can be used to estimate bolt deformation for near-ideal cases. In addition to these verification cases, results are presented from a more realistic FDEM simulation where a circular tunnel with a pre-existing notch of stress-fractured rock in the back is subjected to strong shaking. While a 0D model cannot capture the full complexity of the notch's movement and the corresponding bolt loading, it is demonstrated that important characteristics can be reproduced such as the final bolt deformation. Lastly, it is shown that 0D models can be used to develop simplified parameterisations of shakedown demand. This is of practical relevance for support design because it allows for shakedown analysis without explicit simulation of the tunnel-failure process.

Keywords: *shakedown demand, numerical modelling, rockburst hazard*

1 Introduction

Shakedown is one of the primary damage mechanisms caused by mining-induced seismicity (the other being strainbursting; Kaiser et al. 1996). Often, the potential for shaking to cause damage to an excavation is quantified in terms of peak ground velocity (PGV). However, it is not possible to fully characterise the complexity of potentially damaging ground motions through PGV (or any other single scalar parameter) alone.

An alternative approach to assessing the potential of shaking to damage ground support is to use the zero-dimensional (0D) model proposed by Malovichko & Kaiser (2020). As pictured in Figure 1a, this model considers a block of rock that is connected to the surrounding rock mass by one or more bolts. As shown in Figure 1b, this system can be approximated by 2 masses – one representing the ground/rock mass and the other the block of interest – that are connected by elastoplastic springs in parallel (each representing a bolt) and a viscous damper. Note that this model resembles single-degree-of-freedom models used in earthquake engineering. It is referred to as a 0D model here due to there being no discretisation of the bolt along its length. The forces on the block can be summed to give

$$m\left[\ddot{u}_g(t) + \ddot{u}(t) - qg\right] + c\dot{u}(t) + \sum_i F_i[u(t); u_{\max}(t)] = 0 \quad (1)$$

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where:

m = the block's mass

u_g = the ground displacement (positive into the tunnel)

$u_\Sigma(t)$ = the total block displacement (positive into the tunnel)

$u(t)$ = $u_\Sigma(t) - u_g(t)$ is the displacement of the block relative to the ground (positive into the tunnel)

q = 1 for this case of a block in the back (q = 0 for the sidewall and q = −1 for the floor; in general, $q = \boldsymbol{n} \bullet \boldsymbol{d}$, where $\boldsymbol{n}$ is a normal vector pointing from the block into the tunnel and $\boldsymbol{d}$ is a vector pointing down)

g = acceleration due to gravity

c = the damping coefficient

F_i = the force imposed by the i-th spring (bolt)

$u_{\max}(t)$= the maximum relative displacement of the block (to the surrounding ground) up to time t.

The force provided by a given bolt can be written as

$$F[u(t); u_{\max}(t)] = \begin{cases} ku(t) & \text{if } u_{\max}(t) < u_y \\ \min\{F_y, F_y + k[u(t) - u_{max}(t)]\} & \text{if } u_y < u_{\max}(t) \le u_{\text{ult}} \\ 0 & \text{if } u_{\max}(t) \ge u_y \end{cases} \quad (2)$$

where:

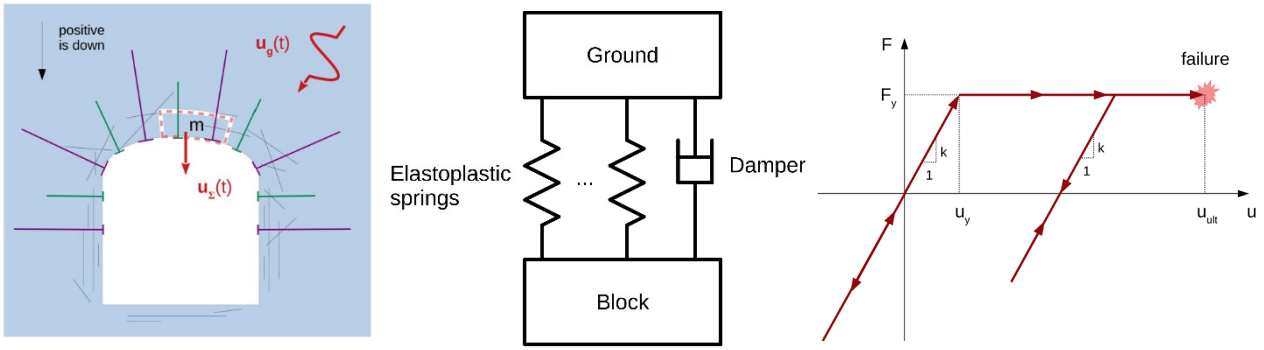
k = F_y/u_y is the spring's stiffness

u_y = the yield displacement

F_y = the yield force

u_{ult} = the ultimate displacement.

This is shown graphically in Figure 1c. For given time histories of ground motion u_g, the 0D shakedown model can be used to determine the relative displacement of the block and to assess the consumption (and possibly failure) of ground support elements (this involves solving Equation 1).



(a) (b) (c)

Figure 1 (a) Considered scenario of shaking in the back of a tunnel. A block of rock with mass m is attached to the surrounding rock mass/ground by 2 bolts. The motion of the surrounding ground u_g and of the block u_Σ are shown with red arrows; (b) Simplified description of the 0D model showing the block of rock connected to the surrounding ground via parallel elastoplastic springs (representing the bolts) and a viscous damper; (c) Elastoplastic force–displacement relation used to approximate bolt behaviour

In Section 2, the 0D model is tested across 4 verification cases against results obtained from dynamic discontinuum simulations using the finite-discrete element method (FDEM) as implemented in Irazu (Mahabadi et al. 2016; Geomechanica Inc. 2024). Section 3 presents FDEM simulation results for a more realistic case of tunnel shaking, with it being shown that the 0D model can provide a reasonable approximation of the demand imposed on bolts. In Section 4, 0D models are used to develop a parameterisation of shakedown displacement demand. Conclusions are presented in Section 5.

2 Verification cases

2.1 Case 1: undamped block in tunnel back

As shown in Figure 2a, the first verification case (Case 1) simulated in Irazu involves a block in the back of a tunnel that is supported by a single bolt. The mass of the block is 2,500 kg, and its contact with the surrounding rock mass/ground is frictionless. It is supported by a single 2.4 m-long bolt that has a yield displacement of u_y = 8 mm, yield force of F_y = 220 kN, and ultimate displacement capacity of u_{ult} = 90 mm. The ground velocity given by the black curve in Figure 2b is applied in the vertical direction to the boundaries of the model. Note that, as described in Section 1, the positive direction is into the tunnel (i.e. down in this case). The velocity pulse has a peak amplitude of 3 m/s and a frequency of 5 Hz.

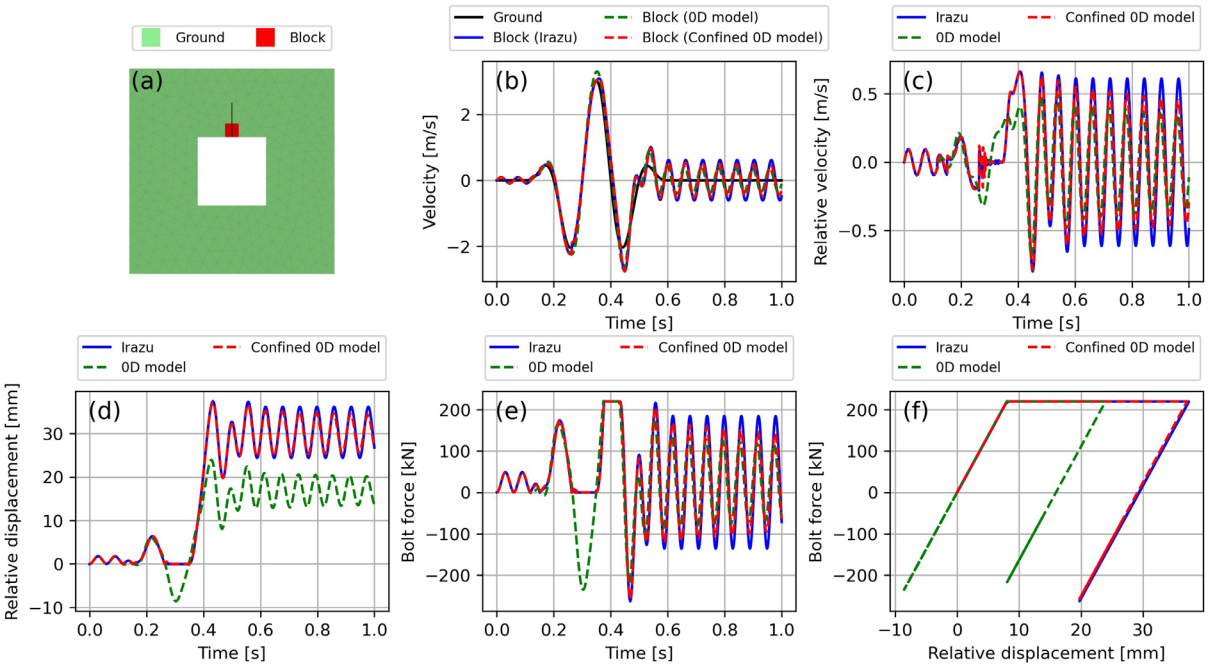


Figure 2 (a) Diagram of Case 1 model showing the rock mass (green), block of supported rock (red), and rockbolt (black line) in the back of a square-profile tunnel; (b) Time histories of ground velocity (black) and block velocity from the Irazu simulation (blue), unconfined 0D model (green), and confined 0D model (red); (c) Time histories of relative velocity of the block from Irazu and the 0D models; (d) Same for relative displacement; (e) Same for bolt force; (f) Force-displacement paths for the bolt

The blue curve in Figure 2 gives the velocity of the block as simulated dynamically in Irazu. Overall, it tracks the input ground motion closely, with the exception of the oscillations in the second half of the simulation that are a result of the undamped nature of the simulation. The green dashed curve gives the block velocity as determined from the 0D model with zero damping, i.e. by solving Equation 1 with c = 0 and q = 1, which appears to be in reasonable agreement with the results from Irazu. However, when looking at the relative velocity of the block in Figure 2c, it can be seen that the 0D model deviates from the Irazu simulation. The reason for this is that the block in the Irazu simulation is not free to move upwards into the surrounding

rock mass, whereas no such constraint is present in the 0D model of Equation 1. Hence, an additional term is added to confine the block, giving

$$m\left[\ddot{u}_g(t) + \ddot{u}(t) - qg\right] + c\dot{u}(t) + \sum_i F_i[u(t); u_{\max}(t)] + \begin{cases} 0 & \text{if } u(t) > 0 \\ k_g u(t) & \text{otherwise} \end{cases} = 0 \qquad (3)$$

where k_g is a large stiffness (a value of 1,000 times the bolt stiffness is adopted here; the exact value is not important). The red curve in Figure 2 shows the relative velocity as determined from the 'confined 0D model' of Equation 3, which is very similar to the relative velocities from Irazu. As shown in Figure 2d, the relative displacement of the block in the 0D model matches the Irazu values closely. Interestingly, the unconfined 0D model of Equation 1 underestimates the relative displacement. Figure 2e shows bolt force time histories, and Figure 2f shows force-displacement curves. The confined 0D model is in good agreement with the Irazu results.

2.2 Case 2: undamped block in tunnel sidewall

Compared to the Case 1, Case 2 differs in that the block is in the sidewall (see Figure 3a) and the applied ground velocity is horizontal (positive to the left). As shown in Figures 3b–3h, the confined version of the 0D model (Equation 3 with c = 0 and q = 0) again produces results that are in close agreement with the Irazu simulation. The unconfined 0D model significantly underestimates the relative displacement of the block (Figure 3d).

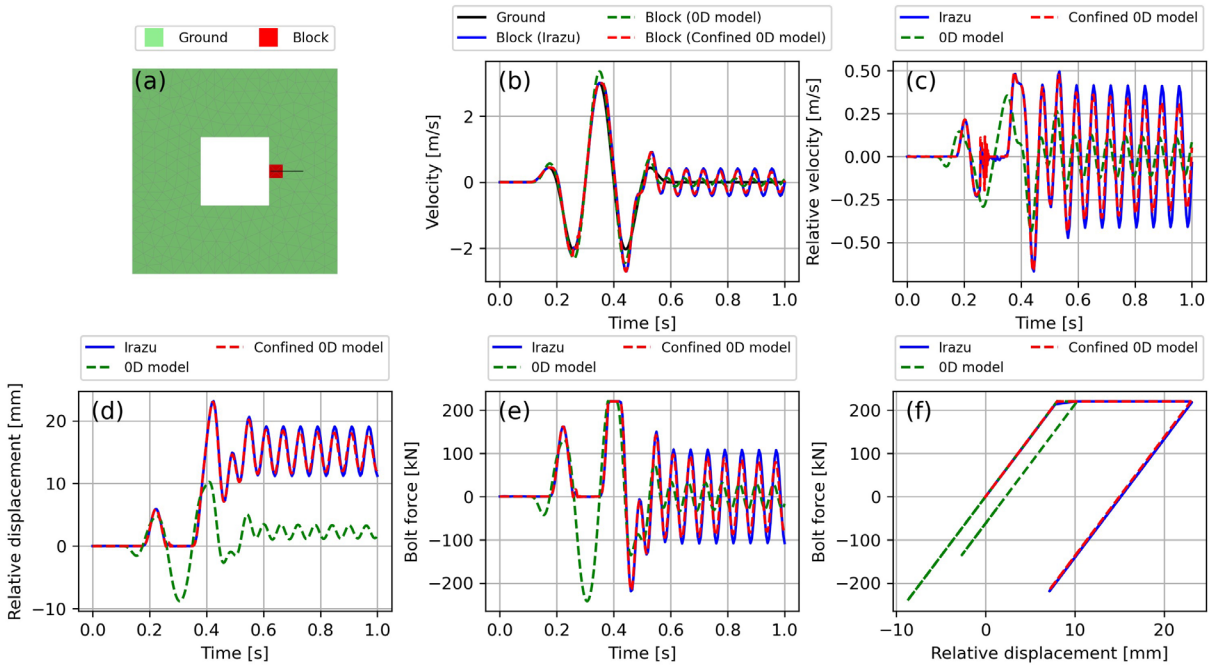


Figure 3 Same as Figure 2 for Case 2, where the block is in the sidewall as shown in (a)

2.3 Case 3: 2 bolts in tunnel back

Compared to Case 1, Case 3 differs in that the block in the tunnel back is twice as wide (giving a mass of 5,000 kg) and is supported by two bolts as shown in Figure 4a. One of the bolts (Bolt 1) is the same as used in Case 1 (u_y = 8 mm, F_y = 220 kN, and u_{ult} = 90 mm). The other (Bolt 2) is stiffer and less ductile, with u_y = 2 mm, F_y = 170 kN, and u_{ult} = 40 mm). The confined 0D model reproduces the Irazu results closely (see Figures 4b–4h). Interestingly, the unconfined 0D model is in closer agreement with the Irazu results than for the previous 2 cases. Furthermore, rather than underestimating the relative displacement, it provides a slight overestimate in this case (Figure 4d).

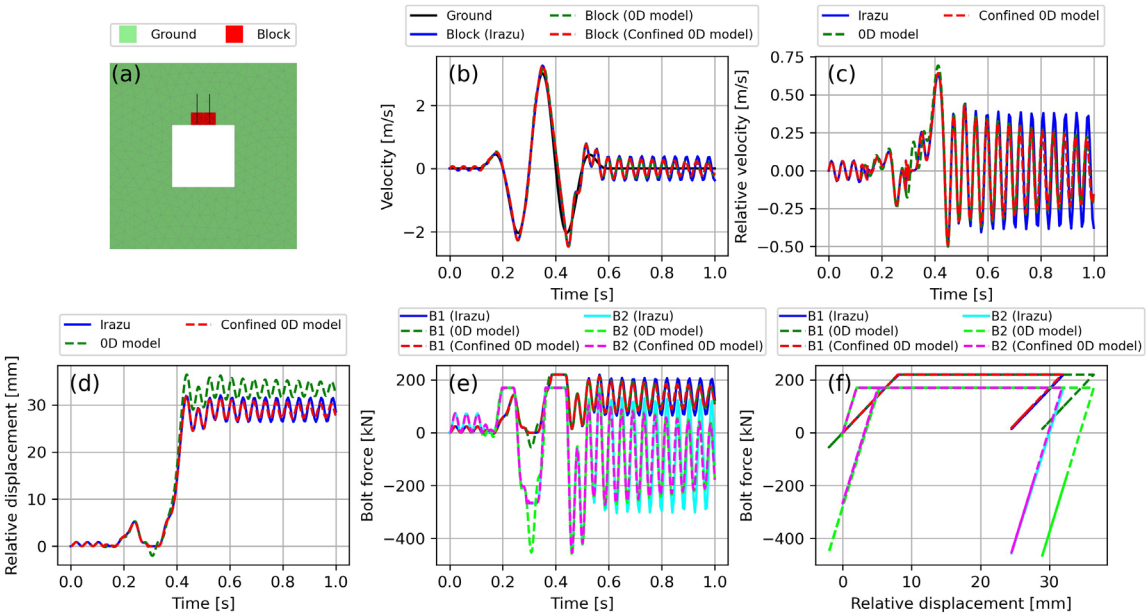


Figure 4 Same as Figure 2 for Case 3, where the block in the back is supported by 2 bolts. (e) and (f) show forces for Bolt 1 (B1) and Bolt 2 (B2) individually

2.4 Case 4: damped block in tunnel sidewall

Case 4 is the same as Case 2 (block in the sidewall supported by a single bolt) but with the addition of friction between the block and the surrounding ground. In particular, the block–ground contact remains cohesionless but now has a friction angle of 10˚. Unlike the viscous damping in the 0D models, this friction is not a function of velocity (it is a function of normal stress) and, as such, it its effect cannot be reproduced exactly. However, it is possible to select a damping coefficient c such that the confined 0D model provides a reasonable approximation of the Irazu results. This is shown in Figures 5b–5h, where the unconfined and confined 0D models use a damping ratio of 20% (i.e. $c = 0.2 \times 2\sqrt{mk}$).

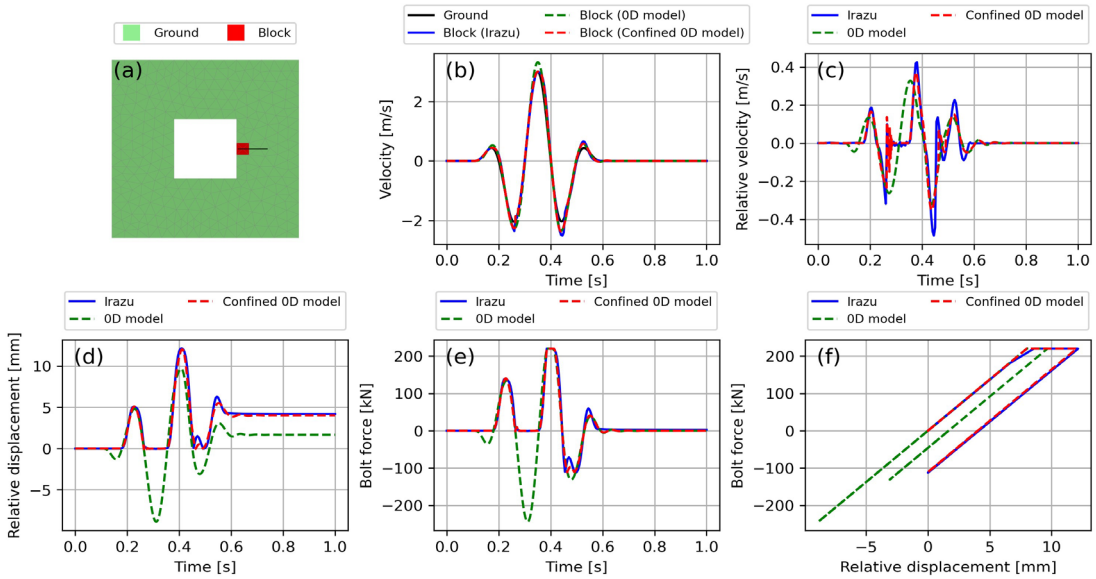


Figure 5 Same as Figure 3 for Case 4, where there is friction between the block in the sidewall and the surrounding rock mass

3 Tunnel shakedown simulation

3.1 Setup

The geometry of the verification cases considered in Section 2 was quite simple – a single rectangular block in the back/side of a square-profile tunnel. In this section, the more realistic geometry pictured in Figure 6 is considered. A notch of fractured rock has been formed in the back of a circular tunnel through a cycle of horizontal loading and unloading. The fractures induced by this loading/unloading can be seen in the 0 ms snapshot of Figure 7, where each fracture is coloured by failure mode (magenta for shear failure, cyan for tensile failure, and blue for mixed-mode failure). Note that the wedge-shaped 'block' as shown in red in Figure 6 is not a single, unbroken piece. Instead, it is composed of several pieces of fractured rock in the tunnel back that are gravitationally unstable (i.e. the pieces that would fall out if the tunnel back were unsupported). The block has a mass of 2,474 kg and is supported by bolts spaced at 1.05 m with the same properties used in Section 2.1 (u_y = 8 mm, F_y = 220 kN, and u_{ult} = 90 mm).

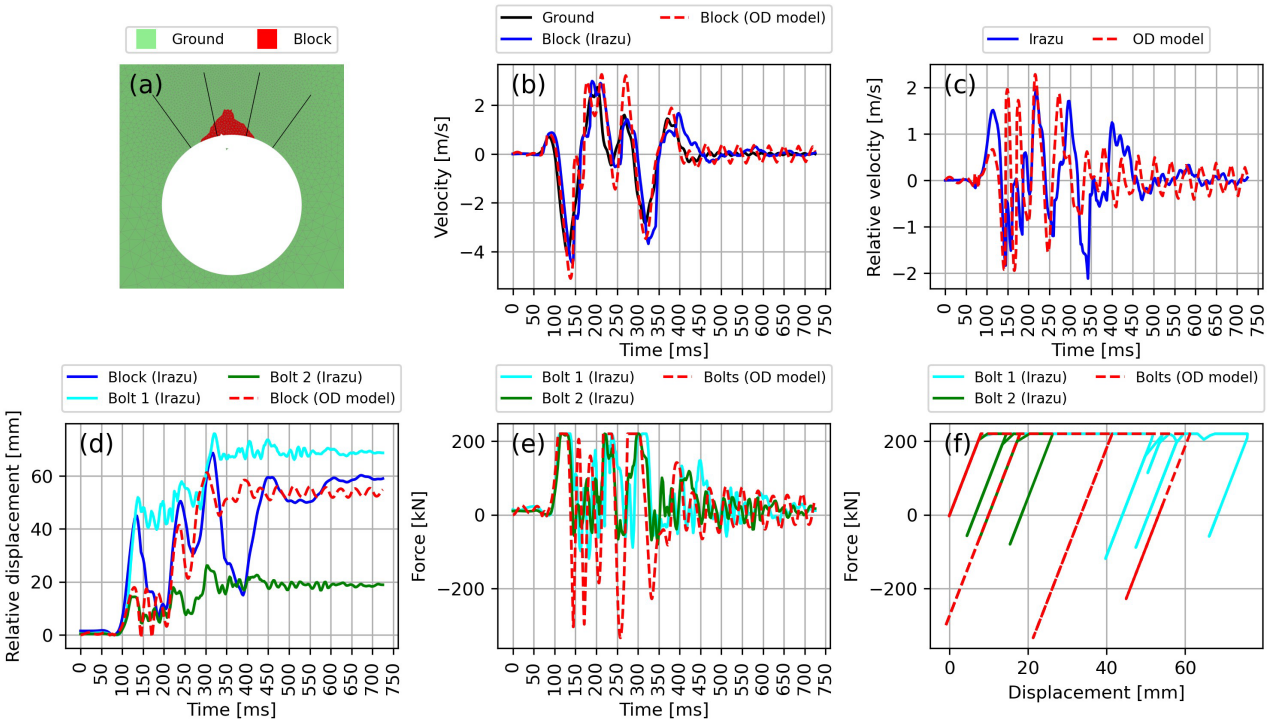


Figure 6 (a) Diagram of example shakedown case model showing the rock mass (green), block of supported rock (red), and rockbolts (black lines) in the back of a circular-profile tunnel; (b) Time histories of ground velocity (black) and block velocity from the Irazu simulation (blue) and confined 0D model (red); (c) Time histories of relative velocity of the block from Irazu and the 0D model; (d) Time histories from the Irazu simulation of relative block displacement (blue), axial displacement of Bolt 1 (B1; left bolt; green), axial displacement of Bolt 2 (B2; right bolt; cyan), and relative block displacement from the 0D model (red); (e) Bolt force time histories from the Irazu simulation (cyan and green) and the 0D model (red); (f) Force-displacement paths for the bolts

The ground velocity shown in black in Figure 6b is applied in the vertical direction at the boundaries of the Irazu model, which has a peak amplitude of 4 m/s (as noted in Section 1, positive displacements correspond to movement into the tunnel, which is down in this case). This time history of shaking has been constructed by modulating (at 8 Hz) and amplifying a strong ground motion recorded at a real mine. A frequency of 8 Hz corresponds to wavelengths on the order of 350–450 m for S-waves and 650–800 m for P-waves. At such low

frequencies, the entire tunnel and the rock mass within the modelling domain move essentially simultaneously.

3.2 Results

Figure 7 shows snapshots of the Irazu simulation in 50 ms increments (these correspond to the vertical grid lines in Figure 6b) with the rock coloured by vertical velocity and the bolts by axial force. It can be seen that the velocity in the detaching block is, at times, quite different to that of the surrounding ground (e.g. the 250 ms snapshot when the block and surrounding ground are moving in opposite directions). Furthermore, in some snapshots, there is a strong gradient in vertical velocity across the block itself (e.g. the 350 ms snapshot), which corresponds to rotation of the block. The blue line in Figure 6b shows the average velocity of the block in the Irazu simulation. The red line shows block velocities derived from a confined 0D model with q = 1 and a damping ratio of 1%. Note that, unlike the FDEM simulation, the block in the 0D model is a single, incompressible mass.

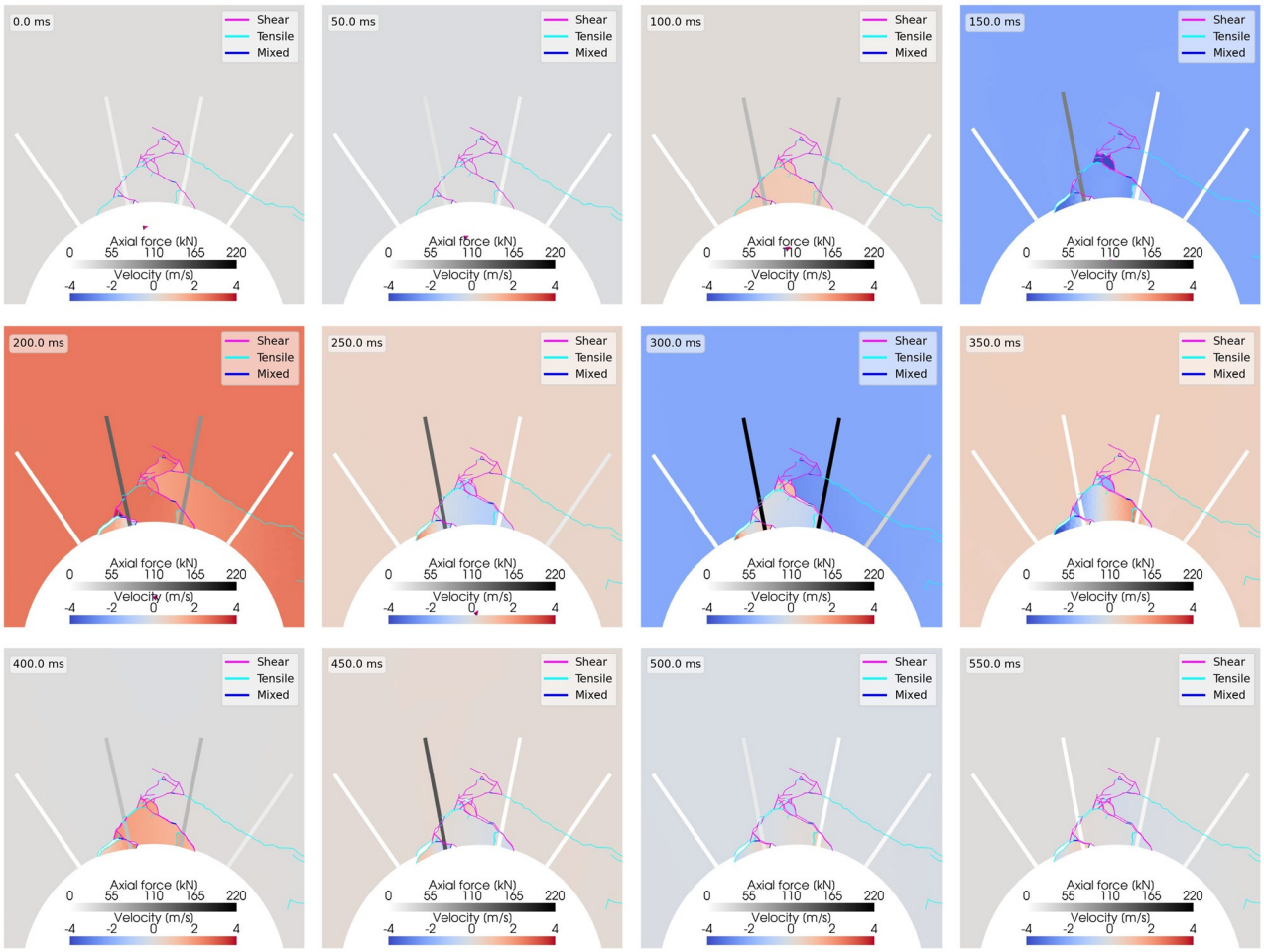


Figure 7 Snapshots in 50 ms increments with rock coloured by velocity in the vertical direction (positive down), fractures by failure mode, and bolts by axial force

Figure 8 shows snapshots from the Irazu simulation with the block coloured by relative velocity. A time history of the average relative velocity across the block is shown in Figure 6c (blue), which also shows the relative velocity of the block derived from the 0D model (red). The 0D model is unable to capture the full complexity of the Irazu simulation results because it doesn't explicitly account for behaviour such as interaction between fractured pieces of rock or rotation of these pieces. However, it does reproduce several important features (e.g. similar peak velocities in the positive and negative directions).

Figure 9 shows snapshots from the Irazu simulation with the block coloured by relative displacement. This clearly demonstrates the previously mentioned rotation of the block, with the left-hand side of the block experiencing significantly greater displacement than the right-hand side over the course of the simulation (60–80 mm compared to 0–20 mm). A time history of average relative displacement from the Irazu simulation is shown in Figure 6d (blue) along with the relative displacement derived from the 0D model (red). As was the case for relative velocity, the 0D model does not reproduce all features of the Irazu results, but it does capture some of the peaks (e.g. around 240 and 315 ms) and the final displacement of approximately 55 mm. Figure 6d also shows the axial displacement of the 2 bolts in the tunnel back. Bolt 1 (cyan) is on the left side of the notch and Bolt 2 (green) is on the right side of the notch. As can be seen in the snapshots of Figure 9, Bolt 1 experiences significantly greater displacement than Bolt 2 (70 mm compared to 20 mm; both are still within the ultimate displacement capacity), which is consistent with the rotation of the block. Note that this difference in bolt displacement is not captured by the 0D model, which assumes that the block and all bolts are displaced simultaneously by the same amount.

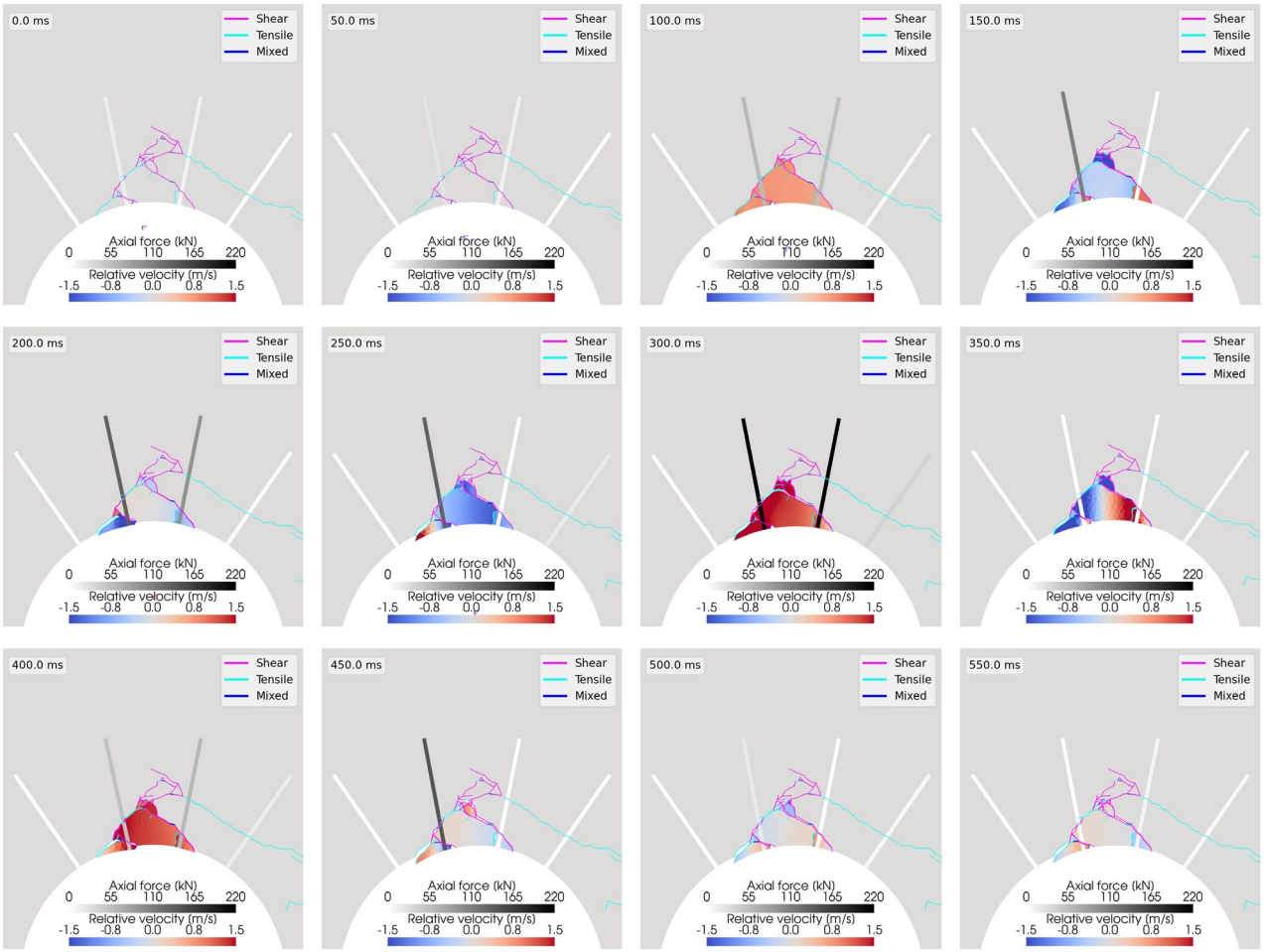


Figure 8 Snapshots in 50 ms increments with block coloured by relative velocity in the vertical direction (positive down), fractures by failure mode, and bolts by axial force

Figure 6e shows a time history of the axial force in each of the bolts supporting the block (cyan and green for Bolt 1 and Bolt 2 in the FDEM simulation, respectively). Also shown is the force time history derived from the 0D model (red), which does not differentiate between the 2 bolts (i.e. the 0D model produces identical force time histories for the 2 bolts). It can be seen that the 0D model again reproduces some features of the FDEM-simulated time histories, including the periods where there is plastic deformation of the bolts (i.e. where the bolts are yielding at 220 kN). Figure 6f presents force–displacement curves, which show periods of both loading and unloading for both Bolt 1 and Bolt 2. Loading and unloading cycles can also be

seen in the bolts of the 0D model (red), which exhibit behaviour in between Bolt 1 and Bolt 2 from the Irazu simulation (more deformation than Bolt 2 but less than Bolt 1).

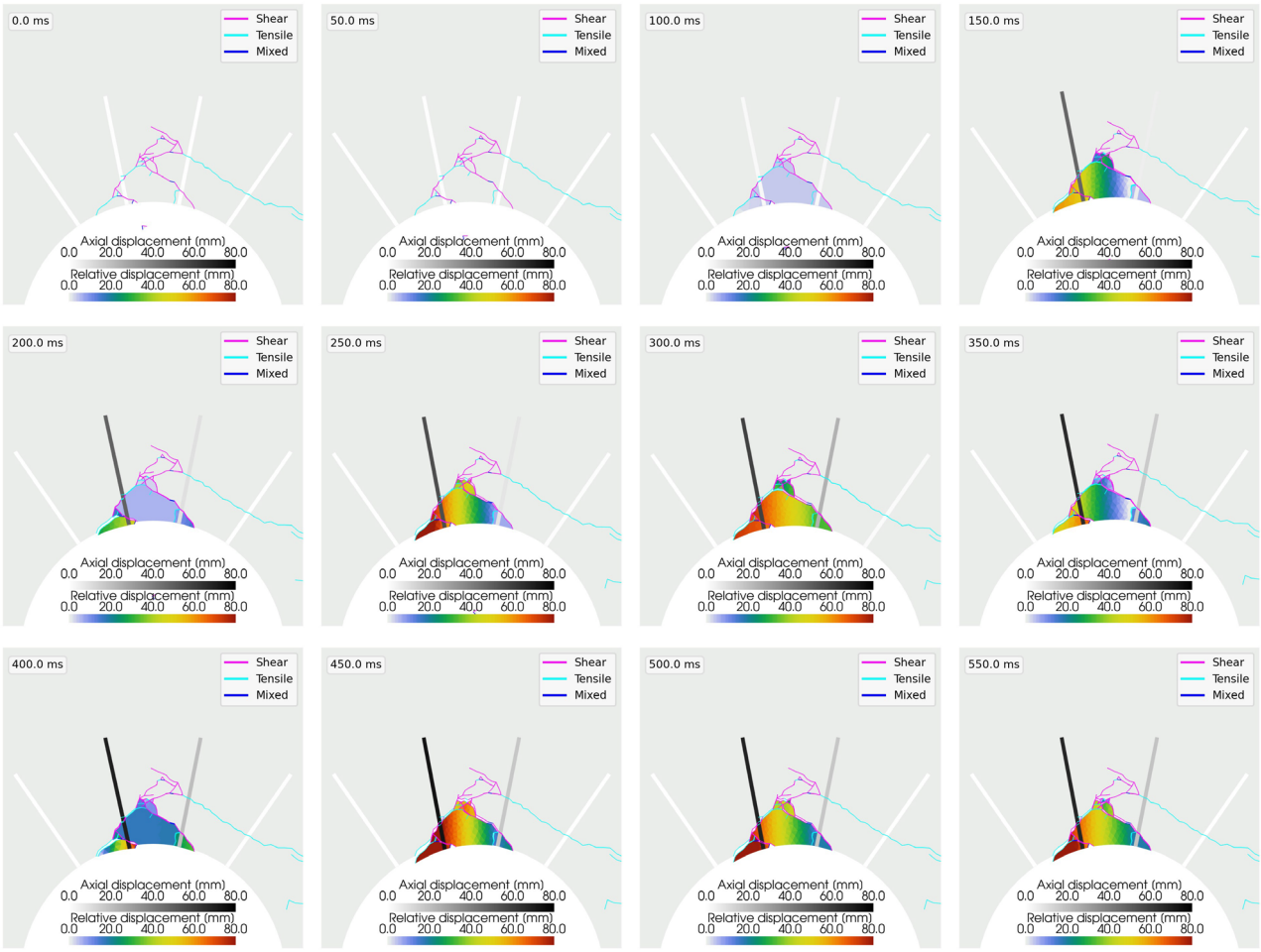


Figure 9 Snapshots in 50 ms increments with block coloured by relative displacement in the vertical direction (positive down), fractures by failure mode, and bolts by axial displacement

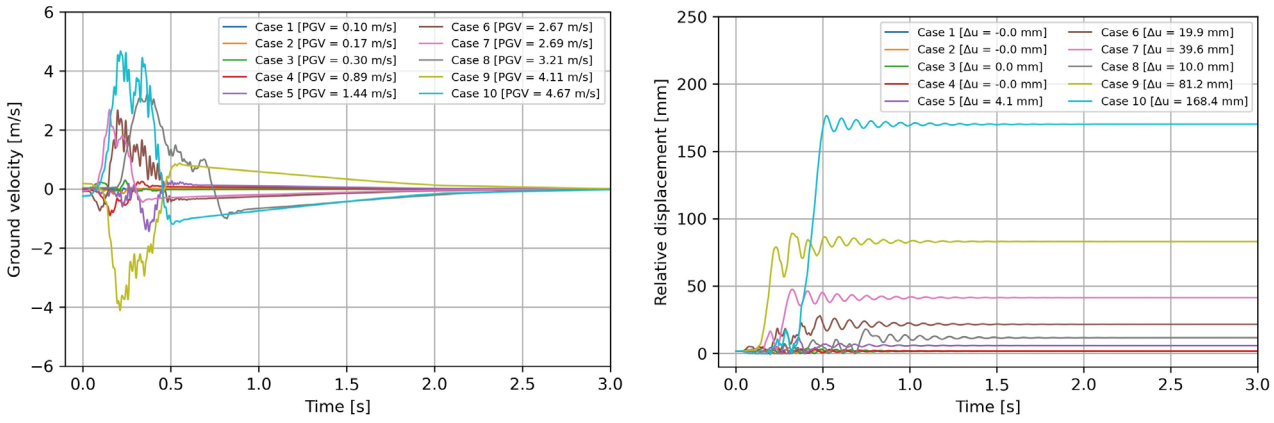
4 Parameterisation of shakedown demand

4.1 Introduction

For the purposes of support design/selection, a method is required for assessing whether ground motion of a given intensity can be 'survived' without bolts reaching their ultimate capacity. In this section, 0D model simulations are utilised to relate ground-motion intensity to the expected displacement increment Δu.

As an example, a 0D model is considered for a m = 5 t (5,000 kg) block in the back (q = 1) that is reinforced by a single bolt with u_y = 8 mm, F_y = 220 kN. Based on the results of Section 3, a damping ratio of 1% is used (further simulations like those in Section 3 should be conducted in future to better understand the reasonable range of damping ratios). This model has been subjected to a catalogue of ground motions derived from finite-source models of 2 damaging seismic events as described by Malovichko & Kaiser (2020). Of the 2,147 ground motion time histories used, 10 examples are shown in Figure 10a, which can be seen to vary significantly in amplitude (see PGV values listed in the legend) and frequency content. Figure 10b shows the corresponding relative block displacements, with the displacement increment Δu listed for each case in the legend. Note that in Cases 1–4, Δu = 0 mm, which means that there was no plastic deformation of the bolt. At the other extreme, a very large increment of Δu = 168 mm occurred for Case 10. Such large displacements

are possible because the ultimate displacement of the bolt has not been constrained in these simulations (i.e. $u_{ult} = \infty$).



(a) (b)

Figure 10 (a) Ten examples of ground motion time histories derived from finite-source models; (b) Example responses of a 0D model in terms of relative displacement

4.2 Quantifying ground-motion intensity

Overall, there is a correlation between PGV and Δu for the 10 example cases shown in Figure 10b. Figure 11b shows this correlation across the entire dataset, with each point corresponding to one of the 2,147 ground motion time histories (note that cases where $\Delta u = 0$ have been excluded). This correlation is quantified by the Pearson correlation coefficient of $r = 0.59$ listed in the bottom right of Figure 11b. Figure 11 also shows correlations between Δu and other ground-motion intensity parameters. PGV is more strongly correlated with Δu than the other peak-amplitude measures of peak ground acceleration (PGA; Figure 11a; $r = 0.42$) and peak ground displacement (PGD; Figure 11c; $r = 0.39$).

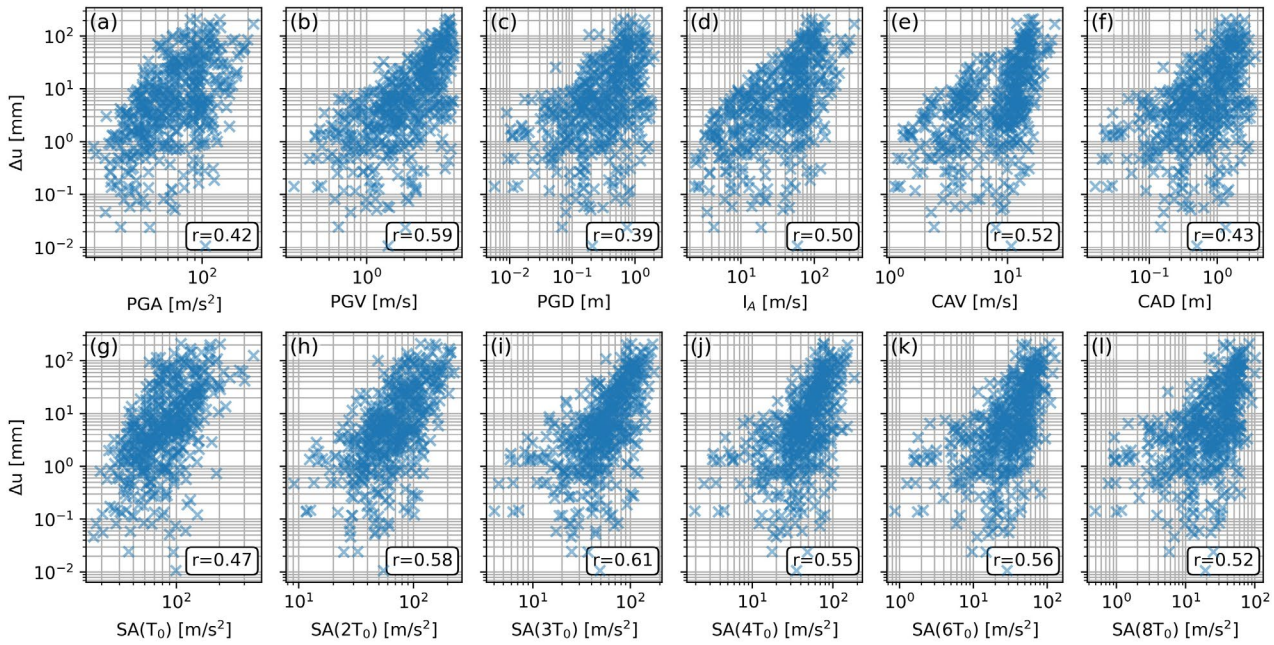


Figure 11 Correlations between bolt/block displacement increment Δu and ground-motion intensity measures as described in the text

Figures 11d and 11e present results from cumulative measures, which account for both the amplitude and duration of shaking. Arias intensity $I_A = \frac{\pi}{2g}\int_0^T a_g(t)^2 dt$ (Arias 1970), where T is the duration of shaking and $a_g(t)$ is the ground acceleration, shows a weaker correlation compared to PGV (Figure 11d; r = 0.50). Cumulative absolute velocity $\mathrm{CAV} = \int_0^T |a_g(t)| dt$ also has a weaker correlation (Figure 11e; r = 0.52). Cumulative absolute displacement $\mathrm{CAD} = \int_0^T |v_g(t)| dt$, where $v_g(t)$ is the ground velocity, has an even weaker correlation (Figure 11f; r = 0.43).

The second row of Figure 11 shows correlations for spectral acceleration (SA), which is the maximum acceleration of a damped harmonic oscillator subjected to a given time history of shaking. Figure 11g uses SA values for an oscillator with a natural period $T_0 = 2\pi\sqrt{m/k} = 0.085$ s equal to that of the bolt-mass system and a damping ratio of 1% (chosen to match the 0D model). Figs. 11h–11l use SA at longer periods of $2T_0$, $3T_0$, $4T_0$, $6T_0$, and $8T_0$, respectively. Of these, SA at a period of $3T_0$ has the strongest correlation with Δu (Figure 11j; r = 0.61).

In summary, these results demonstrate that PGV is a reasonable ground-motion intensity measure to use in estimating Δu. It has the advantage of being commonly used in the mining context while also providing a similar or better correlation with Δu than the other ground-motion intensity measures considered.

4.3 A one-parameter model

For the reference case of a 5 t mass (and a damping ratio of 1%), Figure 12b shows 2 fits of the form

$$\log_{10} \Delta u = \log_{10} c_0 + c_{\mathrm{PGV}} \log_{10} \mathrm{PGV} \tag{4}$$

which can alternatively be written as:

$$\Delta u = c_0 \mathrm{PGV}^{c_{\mathrm{PGV}}} \tag{5}$$

The solid red line is a median (Q50) fit Δu = 1.93PGV$^{1.89}$ mm, which has been determined using quantile regression. In theory, such a fit could be used for support selection by calculating the displacement increment Δu expected for an anticipated level of shaking (PGV) and comparing it with the remnant displacement capacity of the bolt. Importantly, this remnant capacity may be significantly less than the installed/ultimate displacement capacity u_{ult} if there is pre-shaking deformation due to bulking, squeezing, or prior shakedown loading. Note that using a median fit for such comparisons is nonconservative given that (by definition) there is 50% chance of greater bolt displacement. A more conservative/practical approach is to use a 95$^{\mathrm{th}}$ percentile (Q95) fit Δu = 8.71PGV$^{1.86}$ mm, which is the dashed red line in Figure 12b.

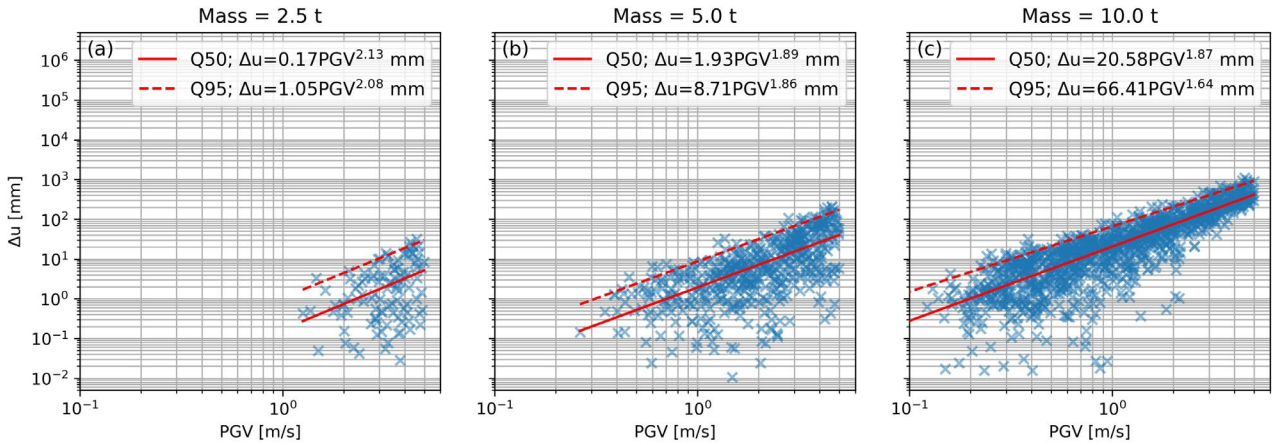


Figure 12 (a) For a 0D model with a mass of 2.5 t and damping ratio of 1%, the blue points give the simulated displacement increment Δu for shaking corresponding to different PGVs. The solid red and dashed red lines give Q50 (median) and Q95 (95$^{\mathrm{th}}$ percentile) fits respectively; (b–c) Same for a masses of 5 t and 10 t, respectively

Figures 12a and 12c show Q50 and Q95 fits for variants of the 0D model with masses of 2.5 t and 10 t, respectively. For the 2.5 t mass, there are significantly fewer cases of plastic deformation (leading to fewer plotted data points), and for the cases where there is plastic deformation, it tends to be small. This results in fits with much lower values of the coefficient c_0 relative to the 5 t mass, but interestingly, values of the PGV exponent c_{PGV} are similar to those for the 5 t mass. For the 10 t mass, plastic deformation occurs in more cases than for the 5 t mass (leading to more plotted data points), and these deformations tend to be larger, leading to fits with larger c_0 values. Values of c_{PGV} are again similar to the 5 t case (there is a slight decrease in c_{PGV} with increasing block mass, but it is far less pronounced than the trend in c_0).

4.4 A 2-parameter model

For the purposes of support design, the one-parameter model outlined in Section 4.3 is not particularly flexible. It requires

- defining a 0D model for a particular bolt/bolts (defining u_y and F_y), gravitational factor q, damping coefficient c, and block mass m
- simulating the response of this 0D model to a catalogue of ground motions
- determining a fit of the form given in Equation 5 to relate PGV to Δu.

To account for this, a 2-parameter model is considered of the form

$$\Delta u = c_0 \mathrm{PGV}^{c_{\mathrm{PGV}}} m^{c_m} \tag{6}$$

where m is the block mass in tonnes. Figure 13a shows data taken from Figures 12a to 12c for block masses of 2.5 t (blue), 5 t (green), and 10 t (red), respectively, and a damping ratio of 1%. The lines correspond to the median fit $\Delta u = 0.0093\mathrm{PGV}^{1.87} m^{3.35}$ mm. The dashed lines in Figure 13b correspond to the 95$^{\mathrm{th}}$ percentile (Q95) fit $\Delta u = 0.16\mathrm{PGV}^{1.68} m^{2.60}$ mm, which is more appropriate for design purposes.

For a given design PGV, a fit of the form given by Equation 6 can be used to test the effect of block mass on expected bolt deformation. From a practical point of view, this allows for the suitability of different bolt spacings (which will lead to different block sizes) to be assessed. For design purposes, this makes it a significantly more useful model than the one-parameter model of Section 4.3.

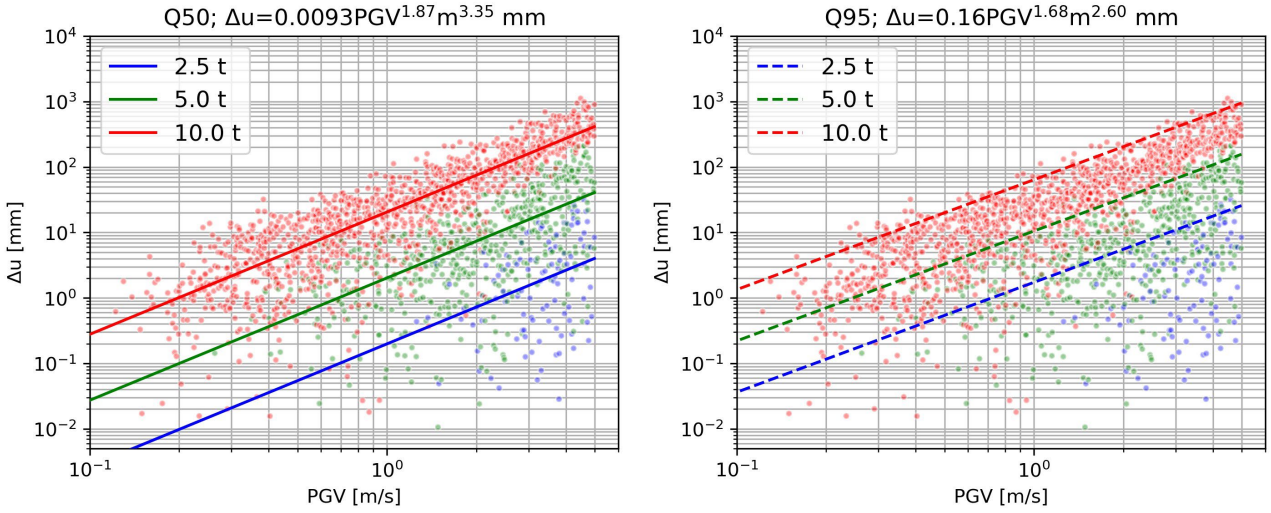


Figure 13 (a) Coloured points give displacement increments from Figures 12a–12c for block masses of 2.5 t (blue), 5 t (green), and 10 t (red), respectively. The lines correspond to the median (Q50) 2-parameter fit listed in the plot title; (b) Same data with a 95$^{\mathrm{th}}$ percentile (Q95) fit shown

5 Conclusion

The zero-dimensional (0D) model of shakedown loading proposed by Malovichko & Kaiser (2020) provides a means for assessing the demand imposed on a bolt supporting a block of rock that is subjected to a given time history of shaking. To test the accuracy of 0D models in estimating the consumption of bolt capacity, 2-dimensional dynamic simulations of shakedown loading have been conducted using the FDEM for 4 simple verification cases. The 0D model formulation of Malovichko & Kaiser (2020) did not fully reproduce the block motion and bolt deformation in the FDEM simulation, which is due to the confining effect of surrounding rock on a given block of rock being ignored (the block cannot penetrate into the surrounding rock). It has been shown that this confining effect can be incorporated into the 0D model, resulting in the FDEM simulation results being accurately reproduced. FDEM simulation results have also been presented for a more realistic case in which a tunnel with a stress-fractured notch in the back is subjected to strong shaking. This notch was composed of several pieces of rock supported by 2 bolts. While a 0D model is not able to reproduce the full complexity of notch movement (e.g. rotation of the notch, interaction between pieces, etc), it was shown that a 0D model can capture important aspects such as the peak relative velocity of the notch and the average bolt deformation.

Building on this capability, a methodology has been outlined for using them to develop simplified parameterisations for shakedown demand. This involves subjecting a representative 0D model to a catalogue of time histories of strong ground motion, determining the increment of bolt displacement in each case. These displacements are correlated with the PGV of shaking and the mass of the supported block. This correlation can be quantified by fitting the 95^{th} percentile of bolt displacement increments in terms of PGV and block mass using quantile regression. Such fits can then be used to compare the effectiveness of different bolt types and/or bolting patterns to withstand shaking for some design PGV without needing to perform explicit simulations.

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