FLAC/PFC coupled numerical simulation of AE in large-scale underground excavations

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Abstract

Acoustic emission (AE) and microseismic (MS) events are indicators of rock fracturing or damage as the rock is brought to failure at high stress. By capturing the AE/MS events, underground excavation induced rock mass degradation or damage can be located and evaluated. A better understanding of the extent and shape of the excavation damaged zone (EDZ) or yield zone around caverns helps to arrive at safe and economic design and construction of the caverns. For this purpose, one needs to understand the AE mechanism associated with the excavation process.

In the present study, a coupled numerical method is used to study AE at the Kannagawa underground powerhouse cavern in Japan. Two codes, Fast Lagrangian Analysis of Continua (FLAC), a finite difference code and Particle Flow Code (PFC), a distinct element code, are coupled. The motive to apply the FLAC/PFC coupled approach is to take advantage of each modeling scheme while at the same time minimizing the requirement for computational resources. The coupling is realized through an exchange of displacements, velocities, and forces in each cycling step. The rock mass surrounding an AE sensor is modeled using PFC and the remaining rock mass is modeled with FLAC to consider the geological complexity and the excavation sequence. In this manner, the AE activities at AE sensor locations of the Kannagawa cavern were simulated and found to be in good agreement with field monitoring results. This approach takes account of stress redistribution and provides stress and displacement patterns in the rock mass that are consistent with AE observations for excavation design. The observed AE activities in the rock mass can thus be utilized to assess the effectiveness of the rock support system and the overall stability of the cavern.

Keywords: AE; Crack initiation; Crack propagation; Coupling; Numerical simulation; Cavern

1. Introduction

Acoustic emission (AE) and microseismic (MS) monitoring techniques are non-destructive evaluation methods (NDE) that can be used to study the damage initiation and propagation processes in rocks under stressing. A detailed discussion on the similarity and difference of AE and MS activities is presented in Section 2. One of the advantages of using AE/MS monitoring techniques compared to other NDE techniques is the possibility to observe damage processes during the entire load history without any disturbance to the structures. Measurement can be performed from remote locations, adding another distinct advantage. AE/MS sources emit similar signals as earthquakes but on a much smaller scale. The monitoring data provides valuable information for rock mass stability assessment in that it highlights areas of the rock mass that are highly stressed or failing. In addition, in contrast to other NDE methods, AE/MS methods are usually applied during the loading, while most other methods are applied before or after the loading of a structure. AE/MS monitoring technique can thus be used to detect the onset of failure at a very early stage, long before a structure fails completely and damaging deformations occur. They can be
used for tunnel and cavern health monitoring within a predictive maintenance program. For this purpose, the AE mechanism associated with the excavation process must be understood to design large-scale underground excavations safely and economically.

The initial development of the AE/MS monitoring technique was associated with studies in the geotechnical field [1]. AE/MS techniques have been used by many, e.g., in mining for rockburst risk assessment [2], roof fall prediction [3], and in civil engineering for rock slope stability, rock damage evaluation, and large-scale underground cavern stability monitoring [4,5]. Areas where research and development of AE applications is currently being pursued, among others, are deformation process monitoring and global or local long-term integrity monitoring of civil-engineering structures (e.g., bridges, pipelines, off-shore platforms, tunnels, powerhouse caverns, etc.). The disadvantage of AE monitoring technique is that it can only provide limited quantitative measures such as AE counts and center frequencies for the assessment of damage. Therefore, other methods such as numerical simulation techniques are needed to perform thorough examinations of the rock mass conditions in order to provide quantitative assessments of larger volumes. Furthermore, AE signals are usually very weak, rendering data acquisition as a challenge in a services environment that is generally very noisy. Signal discrimination and noise reduction are very difficult, yet extremely important for the successful application of AE technique. Lastly, due to the high-frequency content, AE signals attenuate very rapidly so that only a small volume (<2 m³) of rock can be covered by an AE sensor. Despite these limitations, AE monitoring techniques have been applied successfully for rock damage evaluation in some underground excavations.

Two approaches, experimental and numerical methods, can be used for AE mechanism study. As will be discussed in details in Section 2, laboratory and in-situ experimental studies utilizing AE monitoring techniques have been carried out by many researchers. In laboratory, where the environment condition can be well controlled, there are fewer problems in AE signal recording and processing. For field application of AE monitoring technique to underground excavations, there are several challenges such as noise and volume coverage discussed above. Numerical methods are widely used for the design of construction works in rock engineering. An extensive review of the numerical methods in rock mechanics is provided by Jing [6]. The distinct element method (DEM) has been applied in a variety of situations for AE simulation, due to its ability to explicitly represent fractures and bond failure. The DEM methods, however, are computationally intensive because of the small time-steps imposed in explicit time-integration procedure and the contact detection routines that need to be executed at every step. Hence, hybrid numerical methods, such as DEM/FEM (finite element method), DEM/FDM (finite difference method), and DEM/BEM (boundary element method) hybrid models, have been developed for rock engineering involving rock damage procedures.

The efforts in coupling FEM, FDM or BEM method with DEM method are constrained by computation resource limitations, even today when the speed of computers has been drastically improved. These methods combine the advantages or strengths of each method while avoiding many of their disadvantages. For example, Lorig and Brady [7] presented a hybrid method for excavation analysis. In their model, the far-field rock mass is modeled as a transversely isotropic continuum by a boundary element scheme and the near-field rock mass is modeled as a set of discrete element blocks that are defined by joint sets. All components in the computational scheme are coupled in the solution process by satisfying continuity of tractions and displacement at interfaces. Recently, Hazzard and Young [8] and Potyondy and Cundall [9] used the FDM/DEM [10] coupled method to simulation microseismic activity near a tunnel excavation. The region of interest was modeled by an assemblage of PFC particles and this was then coupled to a continuum code, FLAC [11]. This allowed for high-resolution representation of the damage in the region of interest, i.e., investigating the damage initiation and propagation processes and related seismic activities.

In the present study, the FLAC/PFC coupled numerical method is used to study excavation-induced AE activities at the Kannagawa underground powerhouse cavern in Japan, where an extensive field AE monitoring program had been conducted during cavern construction. The rock mass surrounding an AE sensor is modeled using PFC and the remaining rock mass is modeled in FLAC. Means to exchange displacements, velocities, and forces between FLAC and PFC models in each cycling step were developed. The continuity of traction and displacement at interfaces between FLAC and PFC domains is satisfied at all times. The simulated AE activities at two sensor locations are compared to field AE monitoring results.

2. Rock mass damage and acoustic emission monitoring

AE/MS activities are low-energy seismic events associated with a sudden inelastic deformation such as the sudden movement of existing fractures, the generation of new fractures or the propagation of fractures. These events happen within a given rock volume and radiate detectable seismic waves. The main difference between AE and MS signals is that the seismic motion frequencies of AE signals are higher than those of MS signals, as illustrated by Fig. 1. The seismic waves propagate through the medium, and they are recorded by an acquisition system that continuously listens to the medium. Processing techniques, similar to those used by seismologists, are applied to determine the characteristics of the AE/MS events, e.g., location, source parameters and mechanism as well as AE/MS counts. In this manner, cracks that have created the AE/MS events can be studied indirectly. AE/MS counts and magnitudes
(energy release) show the amount and intensity of fracturing occurring in the rock. AE/MS locations delineate regions of damage. Micro-crack distributions, mapped three-dimensionally through time, describe damage accumulation, crack coalescence, and macro-fracture propagation. By analyzing the source parameters, fracturing mechanism can be revealed and the damage state can be quantified as demonstrated by Cai et al. [12,13] and Cai and Kaiser [14].

2.1. Laboratory studies

The failure of brittle rocks in the laboratory has been extensively studied [16–20]. The monitoring of AE waves in the laboratory, usually in the 200–2000 kHz range, has been proven to be one of the powerful tools available to study the brittle failure of rocks in a controlled environment. One of the pioneering works in the determination of the spatial and temporal distributions of AE in a rock sample is attributed to Lockner et al. [21]. They located AE activities throughout the progressive stages from early loading, to peak strength and fault nucleation, and eventually fault propagation. Since there is generally a good correlation between AE rate and inelastic strain rate, the AE rate can be used to quantify damage initiation and accumulation in the rock sample [22]. In samples subjected to cyclic loading, with AE occurs during the reloading portion of a cycle until the load exceeds the level of the previous cycles. This phenomenon is known as the “Kaiser Effect” and has been applied to the estimation of in-situ rock stresses [23,24].

2.2. Field studies

Beside laboratory studies of AE in rock samples, there have been many works conducted to study AE/MS event activities in-situ. One of the best-known experiments is the Mine-by Experiment at the URL in Canada. Rock mass behavior and damage developments were monitored around a 3.5 m diameter test tunnel excavated, using a non-explosive technique by parallel hole drilling. Extensive state-of-the-art geotechnical and geophysical instruments, including extensometers, convergence arrays, triaxial strain cells and an AE/MS monitoring systems, were installed prior to the start of excavation to monitor the complete mechanical response of the rock mass surrounding the tunnel. An array of 16 triaxial accelerometers was installed to monitor excavation-induced seismicity near the advancing face. The accelerometers, with a frequency response from 50 to 10 kHz (±3 dB), were grouted in place at the end of diamond-drilled boreholes. The array was designed for focal sphere coverage and a source location accuracy of about ±0.25 m near the center of the tunnel. Over 25,000 events were detected and some 3500 events (or 14%) were source located. The AE/MS event locations delineate areas of rock damage in a distinctive fashion. The details of the project are presented in an extensive report by Read and Martin [25].

AE/MS monitoring and ultrasonic surveying techniques have also been utilized by SKB (the Swedish nuclear waste management company) for the experiments at the Åspö Hard Rock Laboratory (HRL) to investigate the response of the rock mass around the excavations [26,27]. AE/MS methods have also been used in a wide range of mining applications for rockburst risk assessment [2] and roof fall prediction [3]. In civil engineering, these techniques have been used for large-scale underground cavern stability monitoring [5], for example, for the evaluation of the excavation-induced EDZ zones during the construction of several large-scale powerhouse caverns [5,28–30].

In summary, AE monitoring can delineate regions of stress-induced fracturing in underground excavation. If the spatial and temporal distribution of AE events can be captured using an AE monitoring system and further analysis conducted using numerical methods, safe and
economic underground structures can be constructed with the assistance of AE monitoring and simulation techniques. In this study, we use numerical tools to simulate the AE activities during the excavation of the Kannagawa powerhouse cavern in Japan. The FLAC/PFC coupled method for AE simulation is discussed in the next section, followed by its application to the Kannagawa case study in Section 4.

3. FLAC/PFC coupled numerical method for AE simulation in large-scale underground excavation

The computational resource required to model a cavern excavation sequence using a distinct element code like PFC is enormous, especially when the particle size has to be sufficiently small to derive reasonable solutions at the scale of AE source size. As demonstrated by Potyondy and Cundall [9], the notch formation process at the URL Mine-by tunnel, simulated by the FLAC/PFC coupled method, is sensitive to the PFC particle size. Hence, for AE simulation during the cavern excavation, a coupled numerical approach is required to reduce computation time while ensuring solution accuracy and damage detail at the location of AE monitoring, i.e., within the zone of influence of the AE monitoring array.

The concept of coupling FLAC and PFC to study the AE activity during cavern excavation is illustrated by Fig. 2. The FLAC and PFC models are built separately. The geology and excavation step are considered in the FLAC model. The PFC model covers the coupling cell area surrounding an AE sensor, i.e., the size of the coupling cell in the FLAC model is the same as the size of the PFC model. The boundary conditions in the FLAC model and the PFC model are transmitted back and forth between the two models. The AE activity, represented by the bond breakage in the PFC model, can be tracked and presented in the form of AE rate versus excavation stages. In the present simulation, it is assumed that there is a one to one correspondence of PFC bond break and AE. The stresses and displacements in the FLAC model, combined with AE activities obtained by the PFC model, can be utilized for cavern stability assessment.

3.1. Data transition and FLAC and PFC model controls

Recent versions of the Itasca codes (FLAC version 4 and above and PFC version 2 and above) have TCP/IP\(^1\) socket connection ability, which means that data can be passed rapidly between two or more codes running on the same machine or on separate machines with a network connection. The data transmission between codes is invoked by FISH functions that allow large arrays of data to be exchanged with single function calls. The data contained in FISH arrays may be passed in either direction between two codes (Fig. 3). During each step or cycle, the boundary node velocities in the FLAC model (server) are written to an array along with the updated coordinates. The data are sent to the PFC model (client) through the socket connections. The PFC model will wait until it receives the data from FLAC model and after that the PFC model uses the coordinates and velocities to update the wall coordinates and the resulting wall forces (and moments) are sent back to the FLAC model. In this fashion, the coordinates, velocities, and forces at the walls in both models are updated during the cycling and the coupling is realized. The data are transmitted in binary form with no

\(^1\)Transmission Control Protocol and (TCP) Internet Protocol (IP) are two distinct network protocols. TCP and IP are commonly used together, and the term TCP/IP is often loosely used to refer to the whole suite of protocols and applications that are based on these protocols.
loss of precision. Up to six data channels may be open simultaneously.

Several constraints have to be considered to ensure that the coupling process works properly. The large-strain mode must be used in the FLAC model (using set large command) and data must be exchanged at every cycle. The time step in both codes must be identical. This is achieved by running FLAC in static mode (by default) and PFC with differential density scaling (set $dt = dscale$). In this fashion, the time step is unity for both processes. Furthermore, the PFC's walls have to be slaved to FLAC's zone-segment movement. Some manipulations of forces sent from PFC to FLAC must be done, because each wall produces forces and moments relative to its center of rotation. FLAC grid point forces are derived from these data by using equations of moment equilibrium to determine the line of action of the resultant force.

Special FISH functions were used to realize the data exchange between FLAC and PFC and verified on simple examples (not presented here). The coupling technique is applied in the next section to simulate AE activities at the Kannagawa site and the simulation results are compared to field measurement data.

4. AE monitoring at the Kannagawa cavern site

4.1. Kannagawa underground pumped-storage powerhouse

The Kannagawa pumped hydropower project [5,31] in Gunma Prefecture in Japan is now under construction with a maximum output of 2820 MW. The powerhouse cavern at 500 m depth has a width of 33 m, a height of 52 m, and a length of 216 m (Figs. 4 and 5). The cavern excavation was started in 1998 and the last bench was completed in 2000. Top-down bench excavation method was used for the excavation of the powerhouse cavern as shown in Fig. 6. The arch pilot tunnel (A1) was excavated first, followed by widening of the arch abutment (A2 and A3). After the arch excavation and support system installation, the benches were excavated from top to bottom with bench heights of approximately 3 m (B1–B12). The rock mass at the site consists of conglomerate, sandstone, and mudstone. The rock masses are classified into eight major groups as shown in Fig. 9.

4.2. AE monitoring program at the Kannagawa cavern site

In order to understand the stress propagation and the damage mechanism in the rock masses, an extensive AE study program was executed during the construction of the Kannagawa underground powerhouse, which included AE monitoring of laboratory triaxial tests on samples taken from the construction site, and in-situ AE monitoring during cavern excavation. This in-situ AE monitoring program constitutes an extensive effort dedicated to the understanding of rock mass damage process during large-scale cavern excavation. Before cavern excavation was started, a total of 120 AE sensors were installed along 10 monitoring lines, equally divided in two cross-sections.
The layout of AE sensors in Section H is presented in Fig. 6. All sensors were 20 mm in diameter, 26 mm in height with a resonance frequency of 70 kHz. Due to late installation, the sensors located in the rock mass on the sidewalls (H4 and H5 monitoring lines) recorded event data only during bench excavations (B1–B12). Two hours of continuous data acquisition was conducted after each bench block blast. Data were processed automatically to eliminate noise [32]. AE events were then processed using fast Fourier transformation (FFT) and recorded on hard drives for later interpretation and analysis. Because the primary goal was to study AE activity caused by damage initiation and propagation along the monitoring line during cavern excavation, no effort was made to locate the AE event source locations. AE event source locating would require very dense sensor coverage.

Fig. 6. AE sensor layout in H section at the Kannagawa site. Sensors are numbered sequentially from shallowest to deepest locations.

Fig. 7. Evolution of AE events at measurement line H4 during bench excavation with interpreted damage initiation and propagation front locations (red dash and solid lines).
as the high-frequency AE signals cannot travel long distance. The layout of AE sensors shown Fig. 6 was intended to record all AE signals “within reach” regardless of signal arrival directions. Thus, the data were processed to determine the total AE event numbers and for each event the arrival time and some other AE parameters such as the rise time, event duration, and peak amplitude, center frequency, etc.

4.3. AE data characteristics

Fig. 7 shows the evolution of AE events along measurement line H4 during bench excavation. Damage initiation is defined by the systematic appearance of the AE events. The number of AE events recorded in each bench excavation is represented by the ball size. The ball colors indicate excavation steps. Damage initiation depth along line H4 reaches about 3 m when B1 is excavated. This zone does not change during B2 and B3 excavations. It jumps to 6 m during B4 excavation, and reaches a maximum of 7.4 m when B5 is excavated. Channels Ch6, Ch7, Ch10–Ch 12 record relatively large AE event numbers (compared to Ch1–Ch5) when B1 is excavated. Since the event number decreased during the subsequent excavation step B2, it was thought that they were not related to rock damage but to elevated noises.

The damage propagation front can also be examined by looking at the AE center frequency changes at each sensor location as the excavation advances. The center frequency is the frequency at the spectrum center after the FFT transformation of the waveform from the time domain to the frequency domain. In general, the AE center frequency reaches a maximum when the peak strength of the rock is reached. It is often associated with an AE event (rate) peak. After the event rate peaks, there is a tendency that the center frequency decreases as the event rate decreases. This is illustrated for Ch1, Ch3–Ch5 by Fig. 8, showing a distinct frequency drop after the AE event rate peaks are reached. In Ch2, a steady frequency increase trend is observed. The implication of this frequency increase is that the rock mass at this location may not be fully damaged (i.e., the peak strength is not yet reached), even though rock masses further away from the sidewall (Ch3–Ch5) must have exceeded the peak strength. This is possible if the rock, locally near these sensors, is stronger due to its heterogeneity. At other channels (>Ch5), the center

![Fig. 7. AE events along measurement line H4 during bench excavation.](image1)

![Fig. 8. Correlation between AE counts and center frequencies at measurement line H4.](image2)
frequencies show an increasing or constant trend throughout the excavation process, indicating that stresses in these areas and beyond increase but do not reach or exceed the rock’s strength. Hence, it is concluded that the damage zone depth at line H4 is about 7.4 m after B5 excavation and does not propagate deeper after B6 excavation.

Analysis of all remaining AE monitoring data supports the conclusion that the number of AE events is closely related to the cavern excavation sequence and related stress change in the rock mass. Correlation of the AE number and the displacement of the rock mass shows that AE initiation starts once a AE initiation threshold is reached [30,33]. Large rock mass deformations lag behind the AE initiation. Therefore, compared to displacement measurement, AE monitoring can be applied as an early damage detection technique. To achieve this goal, in the followings, numerical models are applied to explore this correlation of AE activity and rock mass response (stress and deformation) further. The FLAC/PFC coupled numerical method is applied to simulate AE activities at the AE sensor locations indicated in Fig. 6.

5. AE simulation

5.1. Model description

Elasto-plastic stress analysis using FLAC was performed to calculate the stresses and deformation at each excavation stage. The model width and height are 640 and 610 m, respectively. In the zoomed-in FLAC model presented in Fig. 9, eight different rock types (zones) are shown together with the location of the access and observation tunnels. The top-down excavation sequence was reproduced in the FLAC model. The total excavation steps are 15 (three for arch and 12 for bench). The rock mass at the Kannagawa site was characterized using the GSI system [34] and the adopted rock mass deformation and strength properties are presented in Tables 1 and 2. The strain-softening model in FLAC is used. The residual strength parameters were obtained from the in-situ block shear tests. The material model is based on the Mohr–Coulomb failure criterion with non-associated shear and associated tension flow rules. The cohesion, friction, dilation, and tension are softened after the onset of plastic yield. They are represented by piecewise linear functions to approximate the nonlinear post-peak response. In the FLAC/PFC coupling simulation presented here, the rock support system (shotcrete, rockbolts, and anchors) is ignored. Thus, the response of an unsupported excavation is compared with measurements of a supported excavation. The influence of the rock support might be investigated in future studies.

The coupling area for AE sensor #5 in H4 measurement line (hereafter called as H4-5) in the model is a $0.5 \times 1 \times 1$ m zone surrounded by rock mass S1b. Because the high frequency AE sensors used at the Kannagawa site can only pick up AE signals in a rock sphere with a radius of 0.5–0.75 m, the PFC model size of $0.5 \times 1 \times 1$ m was chosen accordingly. A detailed enlargement view of the FEM mesh around the coupling cell is presented in Fig. 9 for sensor Ch5 in H4 line.

The PFC model shown in Fig. 10 contains 4721 disks. The PFC model assembly is first created and then loaded to the initial stress state of the virgin rock mass. The coupled model is then run with the FLAC model providing the velocities to the PFC model and the PFC model sending forces to the FLAC model. In each excavation step, the two models send and receive displacements and forces in every cycling step. The middle step results of both models are saved for later analysis. The PFC model parameters were obtained from uniaxial compressive test simulations with the targeted elastic properties listed in Table 1 and strength parameters in Table 2. These rock mass properties were determined using the GSI system and confirmed by

![Fig. 9. FLAC model for H4-Ch5 sensor coupling analysis.](image-url)
field testing and back analysis results [34]. The parallel bond model is used with the PFC model parameters listed in Tables 3 and 4 for the S1b and S1a rock masses, respectively. The PFC model parameters are calibrated using uniaxial compression tests.

The far field stress was obtained from overcoring tests at the cavern site. The principal stresses in the plane perpendicular to the cavern axis were determined as 12.5 and 4.8 MPa, respectively. The maximum principal stress is inclined at about 64° with respect to the horizontal direction (see Fig. 6).

5.2. Results and discussion

5.2.1. AE activities at H4-Ch5 sensor location

The stress path in the $\sigma_1$ and $\sigma_3$ space is known to be important for the evaluation of the rock mass damage state [35–37]. As can be seen in Fig. 11, the principal stresses around the coupling area rotated back and forth during the cavern excavation process. The principal stresses rotate first clockwise from the in-situ state at A3 excavation, and then rotate counter clockwise from A3 excavation to B4 excavation. From B4–B12 excavation, the principal stress again rotates clockwise to a state where $\sigma_1$ is sub-parallel to the cavern wall. This stress rotation sequence is extremely important for the simulation of AE activities in the PFC model as bonds are loaded and unloaded in shear or tension. The effect is captured by the FLAC/PFC coupled model.

The displacement inside the PFC model is governed by the displacement around the coupling boundary in the FLAC model. When B3 is excavated, the displacement vectors are pointing to the left side as shown in Fig. 12. The magnitudes and directions of the displacement vectors change as the excavation proceeds. At the end of the cavern excavation (B12), the displacement distributions in both models are presented in Fig. 13. The final displacement vectors are pointing to the right with a dip of about 45°. These two models show coupled displacements at the coupling boundary, an indication that the coupling between the FLAC and PFC models has been accurately implemented.

Stresses or contact forces in the PFC model are updated as the coupling boundary is deformed. The contact forces

<table>
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<tr>
<th>Geological zone</th>
<th>Rock type</th>
<th>$\phi_0$ (°)</th>
<th>$c_0$ (MPa)</th>
<th>$\phi_v$ (°)</th>
<th>Dilation angle (°)</th>
<th>Tensile strength (MPa)</th>
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<td>57</td>
<td>0.5</td>
<td>49</td>
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<td>0.5</td>
<td>40</td>
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<tr>
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<td>57</td>
<td>0.5</td>
<td>49</td>
<td>5</td>
<td>0.4</td>
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![Fig. 10. PFC model for the FLAC/PFC coupling analysis. The model width is 0.5 m and the height is 1.0 m.](image)
in the PFC model at B3 and B12 excavation steps are presented in Fig. 14. At bench excavation step B3, there are very few cracks generated in the PFC model and the major principal contact force directions tend to be inclined, which correspond to the major principal stress directions in the FLAC model. At excavation step B12, the principal contact force directions are predominantly vertical with islands of low or non-existing horizontal contact force. As will be discussed later, this area is damaged due to the loading and stress rotation history that this zone experienced.

The development of cracks or AE events can be tracked in the PFC model as the cavern excavation proceeds and the results are presented in Fig. 15 for bench excavation stages B2, B4–B7, and B12. Systematic AE events start to appear at excavation step B4 but the AE rate increases drastically at B5 and approaches the maximum count at excavation step B6. Hence, the rock mass experiences peak load at this sensor location at excavation step B6, which agrees well with observations from the damage propagation front analysis shown in Figs. 7 and 8. Using the FLAC/PFC coupled modeling approach, the post peak AE activity can also be captured and the simulation process is stable. Because the PFC model size is relatively large, the stress on the right-hand side is higher than on the left-hand side and consequently, more cracks are developed on the right-hand side.

The simulated normalized AE numbers, defined as the ratio of the number of AE events (bond breaks) in one excavation step to the total AE event number, are plotted along the stress path in Fig. 16. The stress path was obtained by a FLAC model without the PFC coupling cell. The reason to use the normalized AE numbers for comparison is that the simulated number of AE activities in the PFC model depends on the number of disks so that the absolute AE number cannot be compared with field records. Furthermore, more damage events occur in the field than are recorded. Hence, it is necessary to compare normalized event numbers. Compared to the field monitoring data shown in Fig. 17, the simulated trend is in good agreement with the field data. The AE activity after the event peak is also well captured by the simulation.

Kaiser et al. [38] suggested that, under low confinement conditions, material heterogeneity can generate local tensile stresses that may result in fractures parallel to the maximum compressive stress direction. Further propagation and coalescence of the tensile fractures can lead to spalling type failure of the rock masses. Based on field observation and numerical model simulation, the spalling limit [38] was defined as $\sigma_1/\sigma_3 = 10–20$, with the constant

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<tr>
<td>$k_{n}/k_s$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>20</td>
</tr>
<tr>
<td>$k_{n}/k_s$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1.2</td>
</tr>
<tr>
<td>$\delta_0$ (mean)</td>
<td>10</td>
</tr>
<tr>
<td>$\delta_0$ (stddev)</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma_t$ (mean)</td>
<td>15</td>
</tr>
<tr>
<td>$\sigma_t$ (stddev)</td>
<td>3</td>
</tr>
</tbody>
</table>
depending both on the modeling approach and the rock mass type (e.g., the constant was established to be 5 for the Lac Shortt Mine [39]). The spalling limit depends on factors promoting internal tensile stresses and hence on rock and rock mass heterogeneity and the level of natural jointing. For intact rocks, the spalling limit is higher than for massive to blocky rock masses. Based on the data shown in Figs. 16 and 17, the spalling limit for the Kannagawa cavern can be defined as $s_1/s_3 = 5–10$ for the jointed rock mass under consideration. This range is shown in Figs. 16 and 17. Accordingly, the sudden increase in AE counts (at B5–B6) can be interpreted as a sudden transition from distributed damage to localized damage propagation when the spalling limit is reached and exceeded. This is supported by the crack pattern in Fig. 15 showing spalling on the right of the PFC zone.

5.2.2. AE activities at H4-Ch11 sensor location

The AE events at Ch11 sensor location in H4 line were simulated by utilizing a FLAC model with a different PFC coupling cell. The PFC model is of the same size as in the previous model but with different material properties as the coupling cell is located in S1a rock mass. The development of cracks or AE events at this sensor location is presented in Fig. 18 for excavation stages B4, B6, B8, B10, and B12. At the sensor location, AE events start to appear again at B4 excavation and gradually increase in this case until step B11. The simulated relative AE numbers are plotted along
the stress path in Fig. 19. Compared to the field monitoring data (Fig. 20), the simulated AE trend is again in good agreement with the field data, except for the early AE events development during excavation step B1–B3, when the rock mass is still under high confinement. This AE activity is not captured by the PFC model. As indicated earlier, it is speculated that the early AE flurry can be attributed to noise at B1 and localized heterogeneity in the rock mass. A comparison between observation and model simulation results suggest that extra noise may have been recorded in Ch 6–Ch12 of H4 line during the excavation step B1 in the field (see also Fig. 7). Contrary to the large numbers of AE activities in excavation step B1, there are very few AE activities recorded in B2 excavation step in Ch6–Ch12. Furthermore, AE activities seem to be large at Ch 10 and Ch11 compared to the activities at Ch6–Ch9. Hence, one can only speculate what the reasons for this difference in predicted and observed behavior could be. Our best speculation is that natural local weakness or stiffness variations are not properly reflected in the numerical models.

Compared to observation and prediction for H4-Ch5 (Figs. 16 and 17), it appears that the spalling limit at this location is somewhat higher (between 10 and 15). Hence, crack propagation and coalescence is more gradual as the spalling limit is reached and then followed (towards $\sigma_l = \sigma_u = 0$). Fig. 18 shows that compared to Fig. 15, only localized spalling patterns appear. Consequently, the difference in behavior can be attributed to minor difference in AE sensor location relative to the yield zone front. H4-Ch5 is further inside the yield zone than H4-Ch11.
It follows that the coupled technique handles the stress rotation and the stress path in the post peak region well. The simulated relative AE numbers at different sensor locations agree very well with the field monitoring data, indicating that it can be used in combination with AE monitoring technique for cavern stability assessment.
6. Conclusions

The FLAC/PFC coupled approach is successfully used for AE simulation during the large-scale underground excavation at the Kannagawa site. In the simulation, full coupling between FLAC and PFC codes is made possible through built-in socket connections. The FLAC model, which considers various geological strata, in-situ stress, and excavation sequence, provides the excavation related stress change and stress paths. The PFC cell, which is approximately the size of an AE sensor coverage volume, when coupled with FLAC model through displacement or velocity constraints, provides a representational crack formation model that accurately captures the AE history. In this manner, the stress rotation and post-peak AE behavior are properly captured. The functionality of the method is demonstrated through the AE simulation at two sensor locations. The simulated AE activities are in good agreement with field monitoring results. The FLAC/PFC coupled approach was also used successfully to simulate the AE activities at other AE sensor locations and the results compare well with the field AE monitoring data. Due to space limitation, they are not all included in this publication.

The application of the FLAC/PFC coupled approach for quantitative AE simulation in large-scale underground excavation is robust. The simulation results are satisfactory and represent a significant advance for the application of numerical methods for the interpretation of monitoring data and for the design and construction of large-scale underground excavations. It provides the distribution of stresses and displacement in the rock mass required for excavation design, as well as the AE activity pattern anticipated in the rock mass for cavern stability assessment. In terms of routine design application for cavern construction, the most significant value of the work will eventually be realized through various simulations to aid the field AE data analysis, interpretation, and construction management.

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