Validation of Composite Geological Strength Index for healed rockmass structure in deep mine access and production tunnels

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ABSTRACT

Rockmass characterization is an essential component of geotechnical engineering design of underground excavations that requires an assessment of the microscale intact rock and macroscale structure. In complex rockmasses, mesoscale healed structure (intrablock structure) such as hydrothermal veins influences rockmass behaviour when intersecting with deeper modern excavations with complex stress paths, and should therefore be included in rockmass characterization. To address this need, the authors previously proposed a modification to the Geological Strength Index (GSI), the Composite GSI (CGSI) approach, which provides a more realistic estimate of strength for combinations of multiple suites of structure in complex rockmasses. In this paper, updates to CGSI are presented and the method, as applied to behaviour evaluation using equivalent continuum Finite Element numerical models, is used to analyze a validation case study of an adit at the El Teniente porphyry Cu-Mo mine in Chile. Three excavation faces along the adit were observed at 450, 550, and 600 m depths. Models with explicit structure were compared to equivalent continuum models with structure represented by CGSI and conventional GSI values for the worst case (lowest GSI) and joints only (highest GSI) estimates. The models are assessed using the depth of plastic yield from the excavation boundary as an analogue for overbreak. The results of the CGSI models show better representations than the conventional GSI approaches of both the explicit numerical models and the observed excavation faces. Models at numerous depths between 300 and 2000 m show that the CGSI models provide more accurate estimates of yield depth than the conventional worst case and joints only GSI models, when compared to the explicit model. The results of this case study provide evidence to support the effectiveness of the Composite GSI method for rockmass strength estimation of complex rockmasses with intrablock structure.

1 INTRODUCTION

Rockmass characterization is an essential component of pre-construction geotechnical engineering design of underground excavations. This requires an assessment of the microscale intact rock strength and macroscale rockmass structure to evaluate and quantify mechanical behaviour of the rockmass in terms of stiffness and strength characteristics. In complex rockmasses, mesoscale healed structures such as lithified sediment disturbance features, hydrothermal veins, veinlets, and stockwork (termed intrablock structure) exist within blocks bounded by macroscale structures such as joints, bedding, and other fractures (interblock structure). When intersecting with modern excavations in deeper environments with higher and more complex stress paths, intrablock structure can have a significant influence on overall rockmass behaviour and should, therefore, be included in rockmass characterization.

A distinguishing feature of intrablock structure is that it can behave as part of the “intact” rock in high-quality drill core, but influences rockmass shear and tensile strength at a larger scale and can control fragmentation after moderate disturbance and comminution. Examples of intrablock structure in fragmented blocks (observed in an underground drift) and drill core are shown in Figure 1.

The authors previously proposed a modification to the Geological Strength Index (GSI), the Composite GSI (CGSI) approach, to estimate a more realistic strength for combinations of multiple suites of rockmass structure, such as suites of interblock and intrablock structure found in a complex rockmass (Day et al. 2012).

In this paper, updates to the CGSI method for rockmass characterization are presented and the method, as applied to behaviour evaluation using equivalent continuum Finite Element Method (FEM) numerical models, is used to analyze a validation case study of an adit at the El Teniente copper porphyry mine in Chile. In addition, the possible risks of a lack of consideration for or an erroneous assessment of intrablock structure are discussed.
Figure 1. Three examples of hydrothermal vein types of intrablock structure from northern and southern Chile.

2 ACCOUNTING FOR INTRABLOCK STRUCTURE USING THE GEOLOGICAL STRENGTH INDEX

The conventional use of GSI dictates that when evaluating a rockmass that contains only interblock structure, the observed averages of the block size of structures and joint conditions are selected and represented by a single GSI value, for a given lithology. A typical use of GSI ignores intrablock structure when it is present, based on the conventional assumption that intrablock structure is not relevant. For deeper excavations in higher ground stress conditions, however, this would likely overestimate the rockmass strength. On the other hand, a conservative conventional approach to include another suite of structure with different properties (e.g. intrablock structure) would be to combine the worst cases from each block size and joint condition ranking to give an overall GSI value for the rockmass. Field observations indicate this approach underestimates the rockmass strength.

The Composite GSI (CGSI) approach was designed to balance these conventional ideas to provide a more realistic estimate of strength for a complex rockmass with multiple suites of structure. The CGSI approach was first created to be used with the Hoek and Marinos (2000) version of the GSI chart and corresponding quantitative property estimates by Cai et al. (2004). New developments to CGSI use a modified version of the linearized and quantified version of the GSI chart by Hoek et al. (2013). A column has been added to the axis of discontinuity surface conditions for intrablock structure and descriptions of intrablock structure have been added to existing columns, as shown in Fig. 2. This new column is designed to reflect the rockmass strengthening potential of intrablock structure. For instance, hydrothermal quartz veins with a strong welded bond to the wall rock would be among the highest infill strengths in the new column, while weakly bonded calcite veins would fall in a modified existing column.

The GSI quantification by Hoek et al. (2013) proposed general scales for structure geometry (Scale A) and condition (Scale B) such that GSI is equal to their sum (see Eq. 1). Values for Scales A and B that describe the rockmass structure can come from direct field observations using the GSI descriptions for block size and discontinuity condition, and/or scaled quantities from alternative geotechnical classification or characterization systems. A modified version of the Joint condition rating (JCond) from the 1989 version of the Rock Mass Rating system (RMR) by Bieniawski (1989) is proposed here that includes intrablock structure as an alternative means to calculate values for Scale A (Eq. 2). Similar to the proposed column addition to the GSI chart for intrablock structure, the modifications to JCond are in the form of an added column for intrablock structure that considers the strengthening effects of healed structure when compared to open joints (see Table 1). Alternative quantified inputs used here for Scale B are based on the GSI quantification by Cai et al. (2004) using logarithmic considerations of rock block volume (Eq. 3).

\[
GSI = A_x + B_x \tag{1}
\]

\[
A_x = 1.5 \times JCond_89 \tag{2}
\]

\[
B_x = 20/3 \times \log_{10}(\text{Block Volume in cm}^3) \tag{3}
\]

To calculate CGSI for a rockmass that contains multiple, distinct suites of structure, weighted composite values for Scale A and Scale B of all structure suites present are calculated using Equations 4 and 5. \(A^*\) and \(B^*\) are therefore equivalent blended parameters for the composite rockmass.

\[
A^* = \left(\frac{A_1}{B_1} + \frac{A_2}{B_2} + \ldots + \frac{A_n}{B_n}\right) \div \left(\frac{1}{B_1} + \frac{1}{B_2} + \ldots + \frac{1}{B_n}\right) \tag{4}
\]

\[
B^* = 20 \log_{10}(10^{\frac{B_1}{20}} + 10^{\frac{B_2}{20}} + \ldots + 10^{\frac{B_n}{20}}) \tag{5}
\]

Where \(A_1\) and \(B_1\) apply to the first structure suite (e.g. interblock joints), \(A_2\) and \(B_2\) apply to the second structure suite (e.g. intrablock veins), and so on. The Composite GSI (CGSI) is then defined by Equation 6.

\[
CGSI = A^* + B^* \tag{6}
\]

In the following sections, the CGSI method is applied to a case study of an adit at the El Teniente mine, where its effectiveness as an input property for equivalent continuum numerical FEM models is compared to models.
with explicit structure and equivalent continuum models that use conventional interpretations of GSI.
Figure 2. The authors have created this extended version of the 2013 GSI chart to consider intrablock structure found in complex rockmasses. The added column is used to describe the infill quality of strengthening intrablock structure and descriptions of intrablock structure have been added to existing columns. A summary of equations to calculate the Composite GSI (CGSI) is also provided.

Table 1. Modified Joint Condition rating, Modified JCond, to include intrablock structure

<table>
<thead>
<tr>
<th>Condition of discontinuities</th>
<th>Strengthening intrablock structure</th>
<th>Very rough surfaces or moderately strong veins</th>
<th>Slightly rough surfaces or weak veins</th>
<th>Slightly rough surfaces</th>
<th>Slickensided surfaces or gouge &lt; 5 mm thick or separation &gt; 5 mm</th>
<th>Soft gouge &gt; 5 mm thick or separation &gt; 5 mm</th>
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</thead>
<tbody>
<tr>
<td>Overall rating</td>
<td>36.5</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>10</td>
<td>0</td>
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</table>

 Guidelines for classification of discontinuity conditions

<table>
<thead>
<tr>
<th>Discontinuity length (persistence)</th>
<th>Rating</th>
<th>7.5</th>
<th>6</th>
<th>4</th>
<th>2</th>
<th>1</th>
<th>0</th>
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</thead>
<tbody>
<tr>
<td>Separation (aperture)</td>
<td>Welded</td>
<td>None</td>
<td>&lt; 0.1 mm</td>
<td>0.1 to 1.0 mm</td>
<td>1 to 5 mm</td>
<td>&gt; 5 mm</td>
<td></td>
</tr>
<tr>
<td>Rating</td>
<td>7.5</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Roughness</td>
<td>Rough, undulating, irregular</td>
<td>Very rough</td>
<td>Rough</td>
<td>Slightly rough</td>
<td>Smooth</td>
<td>Slickensided</td>
<td></td>
</tr>
<tr>
<td>Rating</td>
<td>7</td>
<td>6</td>
<td>5</td>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Infilling (gouge)</td>
<td>Strong bonded vein (quartz)</td>
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<td>Hard filling &lt; 5 mm</td>
<td>Hard filling &gt; 5 mm</td>
<td>Soft filling &lt; 5 mm</td>
<td>Soft filling &gt; 5 mm</td>
<td></td>
</tr>
<tr>
<td>Rating</td>
<td>7.5</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Weathering</td>
<td>Strengthening by alteration</td>
<td>Unweathered</td>
<td>Slightly weathered</td>
<td>Moderate weathering</td>
<td>Highly weathered</td>
<td>Decomposed</td>
<td></td>
</tr>
<tr>
<td>Rating</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
3 CASE STUDY: ADIT AT EL TENIENTE

The El Teniente copper-molybdenum porphyry mine owned by Codelco is currently the largest underground block caving operation in the world (e.g. Stern et al. 2011). It is located in the Andean Cordillera in central Chile, approximately 70 km SSE of the capital city, Santiago. The main rock types in the deposit include breccia, andesite, diorite, and a stockwork mafic complex. The stockwork intrablock structure is known to affect rockmass behaviour (Brzovic & Vilaescusa 2007). The mine has been in operation since the early 20th century. Higher elevations of the deposit have been completely mined, leaving a large subsidence crater overlying current active mine levels.

The adit considered for this case study is planned to connect from ground surface to the new mine level, up to a depth of approximately 1000 m below ground surface.

3.1 Site Observations

The sections of the adit considered for this study are excavation faces observed at depths of approximately 450, 550, and 600 m, as shown in Fig. 3. The design profile for the adit is an arched geometry: approximately 6 m high and 6 m wide. All observed excavation faces occur in the stockwork mafic complex geological unit. Several joint sets (interblock structure) were observed in detail at the 600 m deep face in addition to a stockwork suite of hydrothermal quartz veins (intrablock structure). Annotated photos of the excavation face at 600 m (Fig. 6) show four joint sets highlighted by blue, green, pink, and yellow polygons. The approximate orientations of the joint planes and adit (eastward advance) are shown in a stereonet (Fig. 4). The average spacing of the quartz veins is defined by the fragmented block sizes of the excavated material, which are visible in the muck pile at the face (Fig. 6c). Vein spacing controlling fragmented block size is consistent with field observations by the authors and Brzovic & Vilaescusa (2007). The range of fragmented block sizes is shown in Fig. 5, where a normal distribution calculates an average vein spacing of 0.39 m.

All four joint sets are considered together as a single suite of structure, with the same surface condition ranked as "very good" quality on the GSI chart. The joint spacing is greater than 1 m, giving a "blocky" ranking on the GSI chart. The quartz veins comprise a second suite of structure, ranked as high quality "strengthening intrablock structure" and moderate "very blocky" on the GSI chart (Fig. 2). Based on these GSI assessments, Scales A and B (Eqs. 2-5) and corresponding calculated GSI values are listed in Table 2.

Ignoring intrablock structure would generate GSI for only joints (GSI = 80), which is considered an overestimate of rockmass strength. Likewise, a conservative conventional approach considers the worst case of the combined suites of structure (65), which is considered to underestimate rockmass strength. These scenarios are compared to the CGSI assessment (73) using FEM models in the following sections.

Table 2. GSI properties of observed rockmass structure
Figure 5. Histogram of selected block sizes as a measurement of average spacing of quartz veins.
Figure 6. Site observations from the 600 m deep excavation face of the adit at El Teniente. (a) Approximate excavation profile of adit approximately 5 m behind the face; (b) view of excavation face including immediate roof; (c) detailed view of excavation face with highlighted joint planes (4 sets) and average quartz vein spacing defined by the fragmented block size of the excavated material.
3.2 General Model Setup

FEM numerical models of the adit were created using RS2 software by Rocscience (2015). The adit is assumed to be far enough away from any other excavation such that it is not affected by other induced stresses. In situ stresses have been measured in the mine at various locations using multiple techniques including overcoring and borehole breakout observations, which were analyzed by Diederichs (2016). The minor principal stress ($\sigma_3$) is oriented vertically while the major ($\sigma_1$) and intermediate ($\sigma_2$) principal stresses are oriented horizontally. The K ratios between $\sigma_1$ vs. $\sigma_3$, and $\sigma_2$ vs. $\sigma_3$, tend to decrease with increasing depth (see Fig. 7). The maximum K ratio relationships are shown in Eqs. 7 and 8.

\[
\sigma_1 = \sigma_3 (1 + 60D^{-0.5}) \quad [7]
\]
\[
\sigma_2 = \sigma_3 (1 + 20D^{-0.5}) \quad [8]
\]

An estimated intermediate set of K ratio relationships were selected for this case study, however, to account for stress rotations caused by mining activities (e.g. McKinnon & de la Barra 2003), as shown in Eqs. 9 and 10.

\[
\sigma_1 = \sigma_3 (1 + 40D^{-0.5}) \quad [9]
\]
\[
\sigma_1 = \sigma_3 (1 + 10D^{-0.5}) \quad [10]
\]

The explicit rock mass structure in the models is based on site observations from the 600 m deep excavation face (see Fig. 6). The equivalent continuum region of the explicit models is implemented in the far field sections of the model, away from the adit (see Fig. 8), to alleviate the high computational requirements required for explicit structure. The geometries of the rock mass structure are visible in Fig. 8 inset, where the joints are modelled with parallel statistical elements and the veins are modelled with Voronoi polygonal elements. Joint set 2 is excluded from these 2D models because it is nearly perpendicular to the excavation.

The intact rock properties of the hydrothermal mafic complex (Table 3) are from laboratory testing conducted at the mine. The geometry of the modelled rock mass structure is based on site observations (Table 4). The mechanical properties of the joints and veins (Table 5) are based on results from the literature (Read & Stacey 2009) and previous work done by the authors (Day et al. 2014).

![Fig. 7. In situ stresses at El Teniente (Diederichs 2016).](image)

![Fig. 8. Relevant quadrant of FEM model with explicit structure, and a detailed inset of explicit structure and adit dimensions.](image)

<table>
<thead>
<tr>
<th>Parameter (Units)</th>
<th>Value</th>
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<td>Intact Young’s Modulus, $E_i$ (MPa)</td>
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</tr>
<tr>
<td>Poisson’s Ratio, $\nu$</td>
<td>0.18</td>
</tr>
<tr>
<td>Unconfined Compressive Strength, $\sigma_u$ (MPa)</td>
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</tr>
<tr>
<td>Hoek-Brown material constant, $m$</td>
<td>9.1</td>
</tr>
<tr>
<td>Hoek-Brown material constant, $s$</td>
<td>1</td>
</tr>
<tr>
<td>Hoek-Brown material constant, $a$</td>
<td>0.5</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Parameter (Units)</th>
<th>Joint Set 1</th>
<th>Joint Set 2</th>
<th>Joint Set 3</th>
<th>Quartz veins</th>
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<tr>
<td>Inclination (°)</td>
<td>12</td>
<td>-85</td>
<td>-15</td>
<td>-</td>
</tr>
<tr>
<td>Avg. spacing (m)</td>
<td>3</td>
<td>2.5</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>Avg. length (m)</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Persistence</td>
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<td>0.7</td>
<td>0.7</td>
<td>-</td>
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<td>Open</td>
<td>Open</td>
<td>Open</td>
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<tr>
<td>Voronoi regularity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Irregular</td>
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<table>
<thead>
<tr>
<th>Parameter (Units)</th>
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<th>Quartz Veins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal stiffness, $K_n$ (MPa/m)</td>
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<td>6,500,000</td>
</tr>
<tr>
<td>Shear stiffness, $K_s$ (MPa/m)</td>
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<td>6,500,000</td>
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<tr>
<td>Mohr-Coulomb Strength Criterion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak tensile strength, $\sigma_t$ (MPa)</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Peak cohesion, $c$ (MPa)</td>
<td>1</td>
<td>4.3</td>
</tr>
<tr>
<td>Peak friction angle, $\phi$ (°)</td>
<td>55</td>
<td>25</td>
</tr>
<tr>
<td>Residual tensile strength, $\sigma_i$ (MPa)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Residual cohesion, $c$ (MPa) | 0 | 0.2  
Residual friction angle, $\phi$ (°) | 25 | 40

3.3 Model Analysis Using Depth of Rockmass Yield

FEM models of the adit with rockmass structure observed at the 600 m deep face were created using: (i) explicit rockmass structure, and three equivalent continuum models with implicit structure represented by: (ii) joints only (highest GSI), (iii) Composite GSI, and (iv) worst case conventional GSI values. The models are compared using depth of plastic yield from the excavation boundary, measured at the roof and the average of the two walls, as an analogue for overbreak. The detailed results are shown in Fig. 9. The yield of both the structural elements and intact rock are considered for the explicit model. Only yielded elements that can be traced to the excavation boundary through other yielded segments are included. Single yielded segments surrounded by otherwise intact rock and structure (typically far from the excavation) are assumed to have an insignificant influence on overbreak. In the model with explicit structure, most of the yield occurs through the structural elements instead of the intact rock. This is consistent with site observations (Fig. 6) where most failure at the

![FEM model results](image)

Figure 9. FEM model results of the 600 m deep excavation face of the adit at El Teniente, comparing maximum principal stresses ($\sigma_1$) and yielded elements, for the explicit and GSI equivalent continuum models.

![Estimated depth of yield measurements](image)

Figure 10. Estimated depth of yield measurements (normalized to 3 m tunnel radius) from FEM models at a range of excavation depths show a better fit between the explicit and CGSI solutions when compared to the conventional GSI approaches. The nonlinear data curves are best fits of the Carreau-Yasuda rheological model. The explicit rockmass structure and equivalent continuum GSI values in the FEM models are based on observations at the 600 m deep adit.
excavation face. The in situ stress conditions vary with depth (see Section 3.2). The inset excavations show yielded material elements for the 100 and 2000 m deep worst-case equivalent continuum GSI models. The overbreak observations at excavation faces at 450, 550, and 600 m depths are best approximated using the CGSI equivalent continuum models. For the 600 m face occurred along the joints and veins, and further block fragmentation occurred along and/or through the veins. For the 600 m face, the CGSI model is a better estimate of yield in the models with explicit structure when compared to the two types of conventional GSI approaches (Figs. 9 & 10). This finding validates the use of CGSI for continuum modelling of complex rockmasses with intrablock structure at depth.

3.4 Extension of analysis to various excavation depths

The FEM models with rockmass structure based on the 600 m deep excavation face were exposed to numerous excavation depths between 100-2000 m below ground surface to investigate the applicability of the CGSI method for a range of stress conditions. The in situ stress conditions for these models vary according to the stress analysis by Diederichs (2016) discussed in Section 3.2. The model results for depth of yield measurements are shown in Fig. 10. The nonlinear curve fit selected for these data sets is the Carreau-Yasuda rheology model that is designed to describe pseudoplastic flow with asymptotic viscosities at zero and infinite shear rates. This model enables asymptotic behaviour toward zero depth of yield in shallow conditions. These best-fit functions were solved using the Levenberg Marquardt iteration algorithm.

The overbreak site observations at the 450 and 550 m excavation faces are plotted in Fig. 10 and, like the 600 m model, their explicit models are in good agreement with the CGSI models. The worst-case conventional GSI approach underestimates the rockmass strength, resulting in a significantly larger depth of yield when compared to the explicit models, CGSI models, and field observations. In contrast, the conventional joints-only GSI that ignores intrablock structure overestimates the rockmass strength, resulting in an underestimated depth of yield. The consequences for both conventional approaches must be considered in the design of primary support, where optimized bolt lengths are required to support the rockmass effectively and efficiently. The analyses at 450 and 550 m are further evidence for the validity of CGSI.

At the majority of excavation depths greater than 200 m, the CGSI models continue to show the best approximation of the explicit models (in terms of depth of yield). This observation is more consistent in the roof measurements than the walls, which is attributed to an in situ stress ratio of K > 1 and geometry effects of the arched adit with corners at the floor. The CGSI models deviate from the explicit models in shallow conditions at less than 200 m depth, which can be explained by structurally controlled behaviour at low confinement that cannot be captured by continuum models. Indeed, no GSI approach is intended for use in this scenario.

4 DISCUSSION AND CONCLUDING REMARKS

Further developments to the CGSI approach that considers complex rockmasses with multiple suites of complex rockmass structure have been presented in this paper. Updates have been made to the GSI chart by Hoek et al. (2013): a new column and modified descriptions of existing columns describe the infill quality of healed intrablock structure (Fig. 2).

In addition, a verification case study of an adit at the El Teniente Division of Codelco for their support of this research. This work has been financially supported by the Natural Sciences and Engineering Research Council of Canada, the Nuclear Waste Management Organization of Canada, the Ontario Research Fund, and the Centre for Excellence in Mining Innovation.

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