Investigating Nozzle Headwall Primary Support Performance during TBM Breakthrough: Insights from Various Sydney Rock Conditions

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Abstract

Nozzle tunnels are enlarged mined sections that connect TBM running tunnels to stations, commonly used in Sydney Metro projects. This paper presents an assessment of the impact of TBM breakthrough on the loads imposed on rock bolts installed at nozzle headwalls for various Sydney rock conditions. The nozzle ground support consists of shotcrete and a pattern of rock bolts and is analyzed using both 3D continuum finite element and discontinuum finite difference models. Three types of ground conditions —Sandstone III, Sandstone IV, and Shale III—are considered. Results indicate that while continuum models show slight increases in axial loads post-breakthrough, discontinuum models reveal a more significant load increase. This research emphasizes the importance of incorporating defect modeling in tunnel design when a more accurate assessments of rock bolt loads is required, such as in the case of the present study.

Keywords: TBM breakthrough, Headwall performance, Nozzles Enlargement Tunnel, Numerical Modelling, Primary Support.

1.0 Introduction

Major The assessment of stability conditions and the structural verification of the tunnel primary ground support during TBM breakthrough is a recurrent analysis scenario in the design of underground works for Metro projects in Sydney. Typically, the design of ground support systems often relies on established ground classification systems designed for the specific Sydney geology, which consists of the Triassic-aged Hawkesbury Sandstone, often interbedded with shale and siltstone layers. The rock mass usually exhibits horizontal bedding with vertical joints, creating a blocky structure. Beneath the sandstone, layers of Ashfield Shale are commonly found. However, in nonstandard cases, where there exist the interaction of multiple excavations and load/relaxation sources, a more detailed analysis of the ground-support interaction is often required.

The advent of numerical analysis techniques has significantly advanced engineer's capabilities to gain insights into the ground support interaction in more complex conditions. Continuum models are typically used to assess conditions where the rock mass can be treated as a homogeneous material, whereas discontinuum models allow for the examination of individual rock defects and their influence on rock mass behavior, stability conditions and loads on structural elements. Recent research on TBM breakthrough cases (Yu-feng, 2014), suggest that axial loads on rock bolts can increase after the TBM breaks through the primary ground support, underscoring the need for thorough evaluation of ground support systems. This paper investigates the impact of TBM breakthrough in the loads of rock bolts installed at the nozzle enlargement's headwall for various Sydney rock conditions. Results suggest that for these cases, it is convenient to incorporate defect modeling to accurately assess rock loads and mitigate risks.

2.0 Modelling Assumptions and Methodology

2.1 Ground condition

This study focuses on three specific ground conditions: Sandstone III, Sandstone IV, and Shale III. For Shale III and Sandstone IV, 3D continuum models in FLAC3D are employed using tunnel-scale ground parameters. For Sandstone III, both a discontinuum model with 1 to 2 m³ scale parameters in 3DEC and a continuum model with tunnel-scale parameters in FLAC3D are utilized. In the 1 to 2 m³ scale model, joints and defects are also incorporated to enhance accuracy. Discontinuum models effectively represent materials with joints and defects, allowing for a detailed understanding of how these features impact local stability and strength. Continuum models, on the other hand, simplify analysis by treating the material as a continuous medium, suitable for broader stress distribution assessments. By combining both approaches, the study captures the complexities of geological formations, improving stability predictions and facilitating tailored analyses for different rock types. This dual modeling approach also enhances validation and crossverification of results.

Rather than treating these formations as layered systems, they are analyzed as a single homogeneous ground layer. This approach provides a comprehensive understanding of overall ground behavior while minimizing the complexities associated with stratification. The parameters for the selected ground types are sourced from the article “Sydney Sandstone and Shale Parameters for Tunnel Design,” authored by Bertuzzi, R., 2014. By utilizing these parameters, the study aims to accurately reflect the conditions encountered in real-world applications, thereby facilitating a more effective evaluation of ground support systems.

2.2 Geometry

The Nozzle tunnel is excavated in four separate stages, including top-heading, bench 1 and 2 and invert. The nozzle top heading is 6 meters high and 8 wide. Benches are 3 meters high each, whereas the invert is 2.4 meters high. The primary lining of the heading is composed of 300 mm thick shotcrete, which is thickening to 500 mm at the elephant foot. Lattice girders spaced at 1-meter intervals are provided. The benches and invert feature a primary lining of 100 mm shotcrete, reinforced with 4-meter-long rock bolts installed vertically at 1.5-meter spacing.

The Nozzle tunnel geometry, ground support, excavation stages and location of TBM breakout are shown in Figure 1. 3D geometry is illustrated in Figure 2, providing a clear visual representation of the geometry.

Figure 1: Nozzle geometry and primary lining

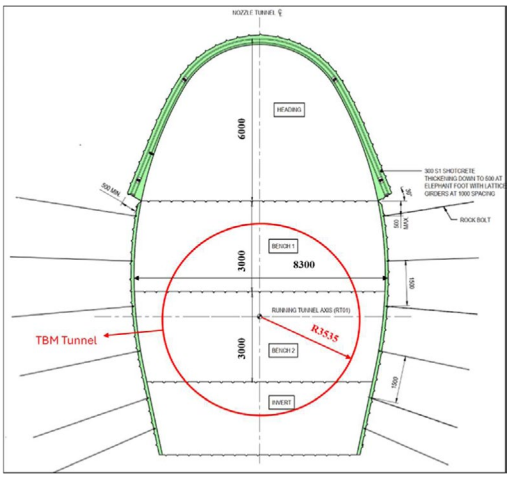
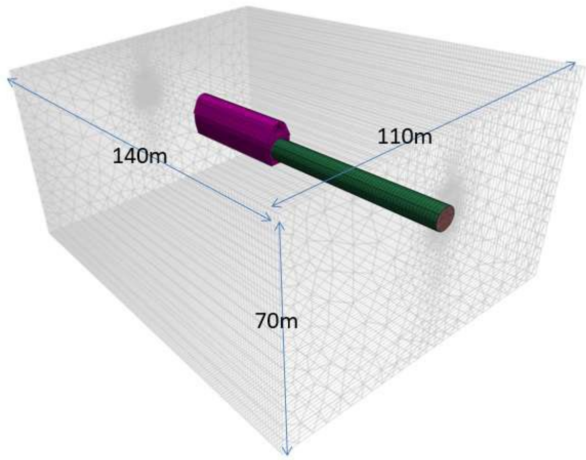


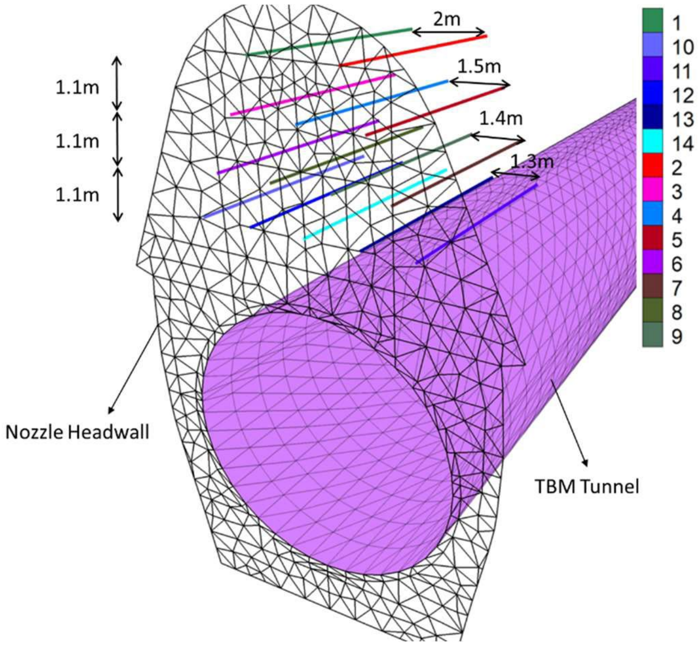
Figure 2: 3D Geometry of model



The nozzle headwall is reinforced with a total thickness of 100 mm of shotcrete and four rows of rock bolts, each 5 meters in length. From the top to bottom, rock bolt rows contain 2, 3, 4 and 5 rock bolts each in a total of 14 rock bolts. Figure 3 illustrates the rock bolt arrangement and their spacing.

The primary lining for the nozzle, including rock bolts and shotcrete, has been designed for the worst ground type. For better ground conditions, the rock type was changed, however, the primary lining remains unchanged. Since the primary lining is effective for the worst rock type, it serves as a conservative approach for better ground conditions. However, the focus of this article is not to validate the design, but to analyze the variations in rock bolt loads following the TBM breakthrough.

Figure 3: Nozzle Headwall



An annular gap of 200 mm between the excavation and the segmental lining of the TBM tunnel is incorporated into the design. This gap, which is not immediately filled with grout in the surrounding rock media, has been modeled to evaluate the critical deformation of the ground after TBM breakthrough. The modeling process begins with the excavation and activation of the nozzle's primary lining. Following this, TBM breakthrough is modelled, enabling a detailed analysis of how the surrounding unsupported ground interacts with the annular gap before grouting.

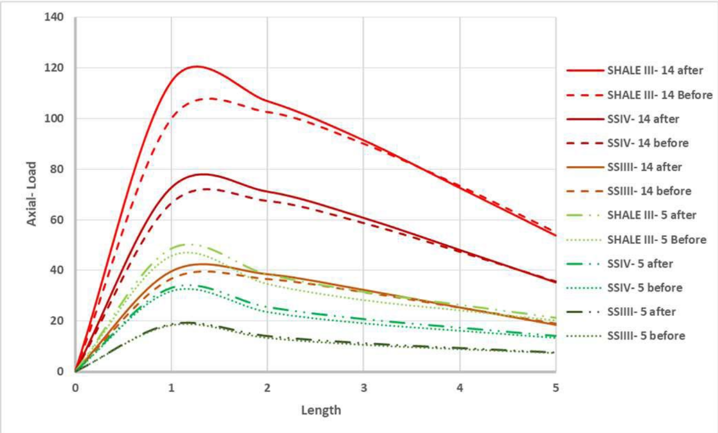
For Shale III and Sandstone IV, 3D continuum models in FLAC3D are employed using tunnelscale ground parameters. For Sandstone III, modelling is conducted with both a 3DEC discontinuum model with 1 to 2 m^3 scale parameters and a FLAC3D continuum model with tunnel-scale parameters. In the 1 to 2 m^3 scale model, joints and defects are also incorporated to cater for their impact on ground and ground-structure behaviors. By combining both approaches, the study aims at gaining insights into the relevant of modelling approaches and key assumptions on obtained results, providing a guidance for future investigations and practical design works.

3.0 Results and Discussion

3.1 Continuum models

After completing the modeling of all construction stages for the nozzle, the TBM tunnel excavation begins. The axial loads of the rock bolts are compared for two stages: first, after the completion of the nozzle excavation and before the excavation of the TBM tunnel, and second, after the TBM breakthrough. The axial load of Rock Bolt 14 represents one of the rock bolts with high axial loads, while Rock Bolt 5 represents one with low axial loads across all models, as shown in Figure 4 for three different rock types.

Figure 4: Axial Loads of Rock Bolts in Different Rock Types Before and After Tunnel Excavation



As observed`, comparing the axial loads while transitioning from Sandstone III to Sandstone IV and then to Shale III, the axial loads increase. The TBM tunnel breakthrough does increase the axial load on the rock bolts, but the increase is not significant. The maximum increase occurs in Shale III for Rock Bolt 14, reaching a maximum of 15%. The increase in Sandstone IV does not exceed 10%, and in Sandstone III, it is limited to 8%.

To understand the reasoning behind the above explanation, Figure 5 illustrates the horizontal displacement of the headwall before TBM tunnel breakthrough in Sandstone III, which reaches a maximum of approximately 11.8mm. Figure 6 shows that an additional horizontal deformation of about 2.3mm occurra at the headwall due to TBM tunnel breakthrough , indicating an increase of 20 percent in horizontal displacement.

Figure 5: Horizontal Displacement before Tunnel Excavation

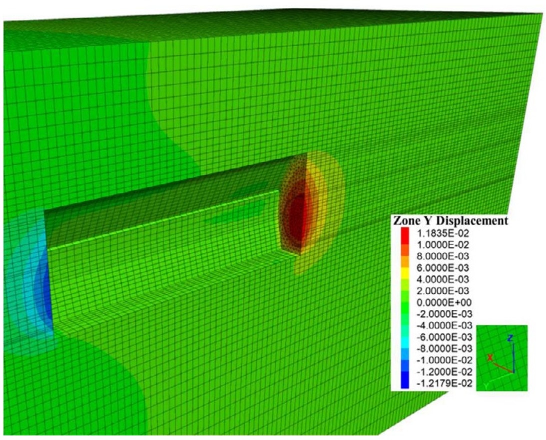


Figure 6: Horizontal Displacement Due to Tunnel Excavation (Previous Displacement Reset to Zero)

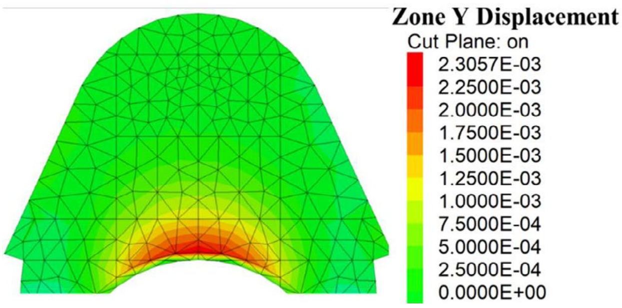
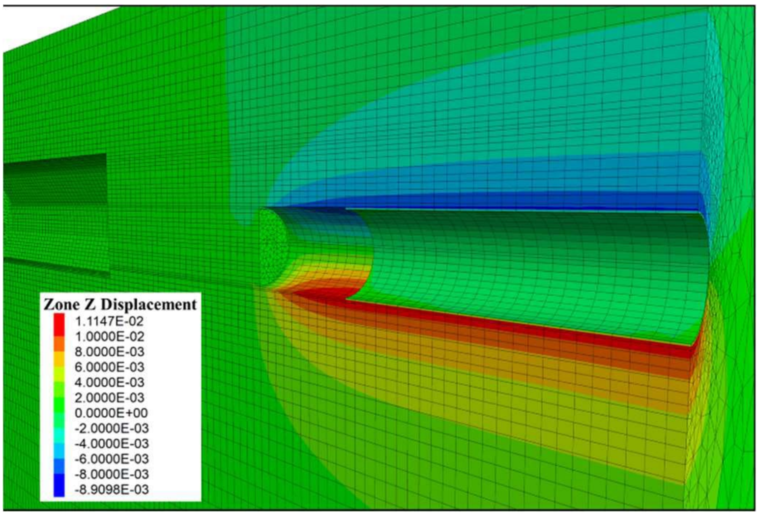


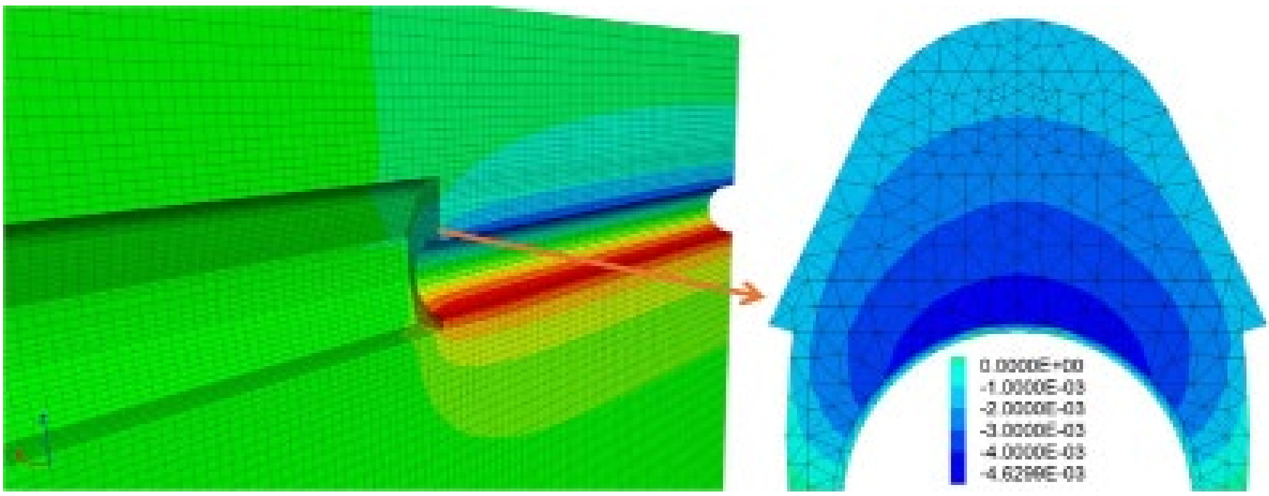
Figure 7 shows the vertical displacement caused by the TBM tunnel excavation in an area far from the nozzle (where the influence of the nozzle can be neglected). Maximum vertical displacement is about 9 mm at the tunnel crown, suggesting no overall stability problems (despite the 200 mm annular gap). It is important to note that the TBM tunnel excavation in the model begins by resetting the displacement caused by nozzle excavation to zero.

Figure 7: Vertical Displacement of the Tunnel Far from the Nozzle



As the TBM tunnel excavation advances, the maximum vertical displacement at the nozzle headwall reaches approximately 4.6 mm. This displacement reflects the vertical movement of the ground at the headwall above the TBM tunnel, as the excavation approaches the headwall, indicating that the rock bolts and shotcrete at the nozzle headwall are effectively mitigating ground movements (Figure 8). Comparing the vertical displacement changes before and after TBM tunnel excavation reveals an increase of about 25 percent.

Figure 8: Vertical Displacement due to TBM Tunnel Excavation



3.2 Sensitivity Analysis

To assess the changes in rock bolt axial load due to the TBM tunnel breakthrough in Sandstone III, the geometry shown in Figure 3 has been modeled using 3DEC software, in addition to the model in FLAC3D. The properties of the defects and the specifications were selected based on the Bertuzzi 's study. Figure 9 displays the model in 3DEC. It should be noted that in the continuous FLAC3D model, tunnel-scale parameters were used to simulate rock behavior, while in the 3DEC discontinuum model, 1 to 2 m^3 scale parameters were employed to account for rock behavior, including joints and defects, to evaluate local instability.

As the aim of this article is to examine the changes in rock bolt load due to TBM breakthrough, the vertical load in the 3DEC and FLAC3D models has been configured to achieve a maximum rock bolt axial load of approximately 100 kN before the TBM breakthrough.

Figure 9: Modeling of joints in 3DEC model

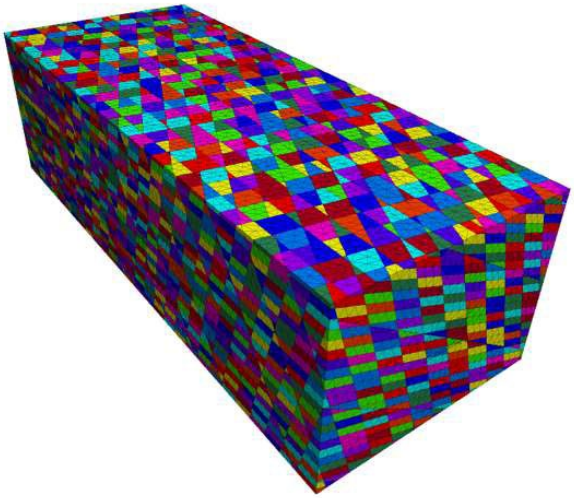
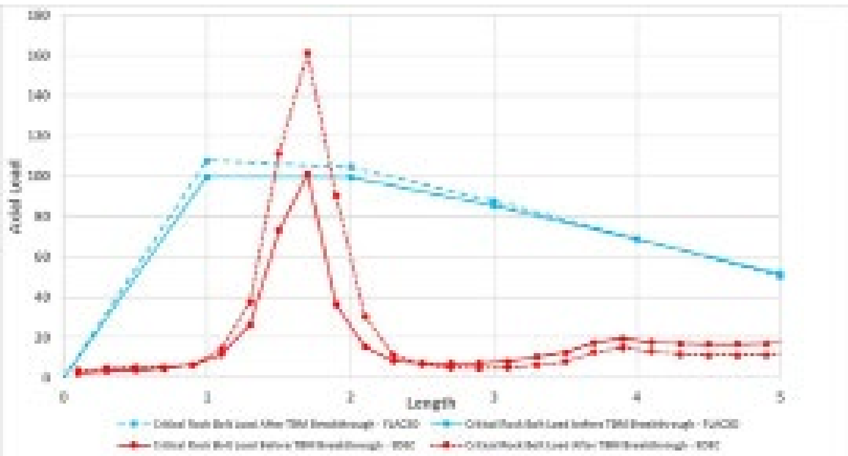


Figure 10 illustrates the changes in loads at the critical rock bolt location, for the FLAC3D and 3DEC models. The increase in rock bolt load in the FLAC3D model is approximately 9 percent, while the increase in critical rock bolt load in the 3DEC model is around 60 percent.

Figure 10: Comparison of Critical Rock Bolt Loads After TBM Breakthrough in FLAC3D and 3DEC Models

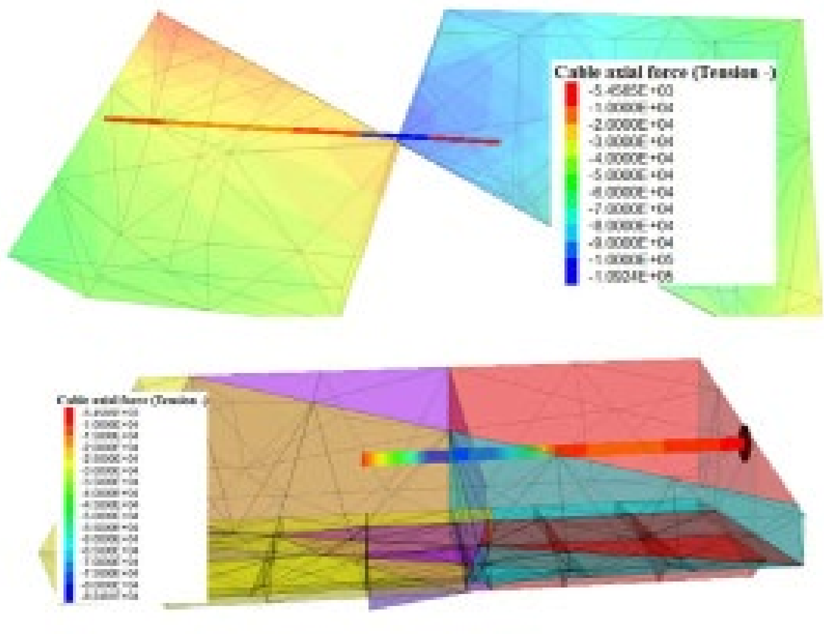


In the FLAC3D model, the average load is approximately 71 kN before the breakthrough, increasing to about 74 kN afterward. Conversely, the 3DEC model shows a lower average load, with values of around 39 kN before the TBM breakthrough and increasing to approximately 52 kN after the breakthrough. This data highlights that while the 3DEC model exhibits lower average loads, the changes in load are more pronounced, particularly due to joint movement. These differences underscore the varying responses of the rock bolts in each model.

It should be noted that the results from the 3DEC model are very sensitive and dependent not only on the parameters of the joints but also on the geometry of the joints. As shown in Figure 11, the primary load on the rock bolt is influenced by the movement of the defects. Therefore, if any other pattern is considered for the joint, the results may change.

While obtained rock bolt loads from both continuum and discontinuum models are within acceptable levels, obtained results highlight the significant impact of discontinuities in the axial loads of rock bolts. Therefore, it is convenient to incorporate explicit defect modeling to accurately predict rock bolt loads. In fact, different defect pattern could lead to different results, highlighting the need to model and consider the specific structural conditions anticipated for each specific project conditions.

Figure 11: Sensitivity of Rock Bolt Axial Load to Joint Geometry: Two Examples of Results



Conclusion

This paper has assessed the loads on rock bolts installed at the nozzle's headwall during TBM breakthroughs for three different ground conditions —Sandstone III, Sandstone IV, and Shale III— using both 3D continuum and discontinuum models.

Overall, the results obtained from the assessments outlined in this paper reinforce the need for detailed modeling of joints and defects to ensure a proper assessment of rock bolt loads at the headwall of Nozzle tunnels during TBM breakthrough. This allows not only a proper assessment of rock bolts loads, but also the establishment of more accurate trigger levels and need of contingency measures to mitigate risk.

In addition, since significant load increases along the rock bolts occur at their intersection with defects, the design should be accompanied by the monitoring of defects movement during construction to check on the integrity of rock bolts. By installing devices such as endoscopes and instrumented rock bolts, areas with excessive shear movement and potential damage to rock bolts and their protective sheath can be re-bolted to ensure adequate support and functionality during the project lifetime.

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