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Integrating rigid body methods with rockfall simulation to evaluate instability along Tegalrejo road, Gunung Kidul, Indonesia

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Abstract

Rockfall along transportation corridors is strongly controlled by slope geometry, discontinuity conditions, block size, surface material properties, and impact energy loss. This study integrates rock mass characterization, RMi-based block volume estimation, restitution coefficient calibration, and rigid body rockfall simulation to evaluate slope instability along Tegalrejo Road, Gunung Kidul, Indonesia. Field mapping, scanline measurements, and laboratory data were used to characterize interbedded tuffaceous sandstone and siltstone slopes. Rock Mass Rating (RMR) values range from 41 to 63, while Geological Strength Index (GSI) values range from 36 to 58, indicating fair to good rock mass quality. Potential block volumes estimated using RMi range from 0.000265 to 0.0588 m^3 and were used as rigid body inputs in RocFall3. The calibrated normal restitution coefficients are 0.315 for sandstone and 0.28 for siltstone, producing rebound heights of 4.96 cm and 3.92 cm from an initial drop height of 0.50 m. These values indicate low rebound behavior on weathered and rough slope surfaces. The unprotected simulation shows that several trajectories may reach the road corridor, with maximum kinetic energy, translational velocity, and total runout distance reaching 28.58 kJ, 31.17 m/s, and 332.05 m, respectively. A 6 m flexible rockfall barrier with an energy capacity of 111 kJ is proposed to reduce rockfall propagation toward the road.

Keywords

Rockfall simulation, Rigid body, RMi, RocFall3, Road slope mitigation.

1 Introduction

Rockfall is a common hazard on steep slopes and rock cuts, where detached blocks move downslope through free fall, bouncing, and rolling, potentially threatening roads and nearby infrastructure. Along Tegalrejo Road, Gunung Kidul, several rockfall and landslide events have disrupted traffic, including the 2023 incident that temporarily closed the road (Kompas.com, 2023). These events are closely related to the local geological setting, where the Kebobutak Formation, composed of breccia interbedded with sandstone and siltstone, is affected by structural controls associated with the Opak and Tegalrejo fault systems (Munandar et al., 2017; Surono, 2009).

Rock mass quality was evaluated using Rock Mass Rating (RMR) and Geological Strength Index (GSI) to characterize the general condition of the slope, while Rock Mass Index (RMi) was applied to estimate potential block volumes. The integration of RMR, GSI, and RMi provides representative geological and geometrical inputs for the rockfall simulation, particularly in defining rock mass condition, discontinuity-controlled instability, and potential rigid body block size (Hoek, 2007; Palmström, 1995).

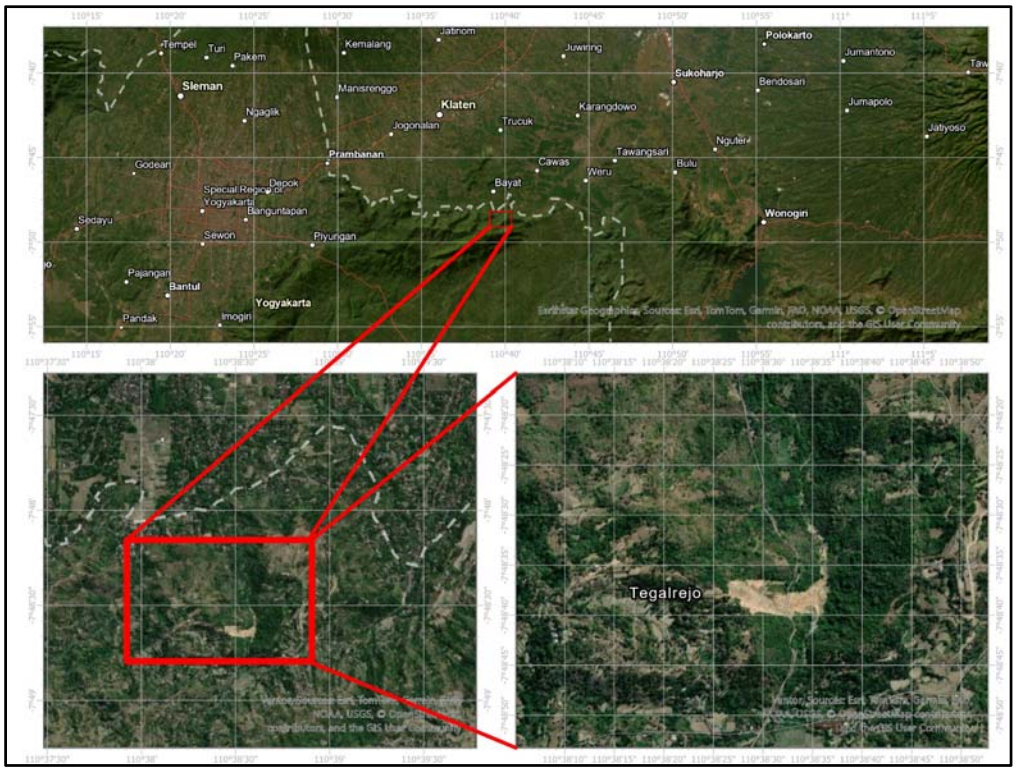


Fig. 1 Site Location of The Rockfall Along Tegalrejo Road (Google Earth Pro, 2026).

Identifying potential rockfall sources remains a primary challenge in hazard assessment because block movement is controlled by slope geometry, discontinuities, block size, and surface conditions. In this study, detached blocks are represented using a rigid body approach, where the blocks are treated as non-deformable objects with defined geometry, mass, and contact behavior. This approach allows the evaluation of rockfall trajectories, kinetic energy, velocity, bounce height, and runout distance. Therefore, this study combines rigid body methods with rockfall simulation to support hazard evaluation and mitigation planning along Tegalrejo Road.

2 Geological Setting and Rock Mass Characterization

The study area is located within the Southern Mountains Zone of Java and regionally belongs to the Kebobutak Formation (Surono, 2009). The rock mass consists predominantly of interbedded tuffaceous sandstone and siltstone with moderate to intense weathering conditions.

Geomorphologically, the area is characterized by structural hills and steep valley slopes with slope inclinations locally exceeding 70%.

Field observations identified several structural discontinuities, including paired joints, shear fractures, and minor strike-slip faults trending northwest–southeast. These discontinuities form weak zones that control potential block detachment and slope instability.

Rock mass characterization was conducted using scanline surveys and laboratory testing. Rock Mass Rating (RMR) values range between 41–63, indicating fair to good rock mass quality. Geological Strength Index (GSI) values range from 36–58, reflecting moderately fractured sedimentary rock masses. RMi analysis indicates potential block volumes ranging from 0.000265 m³ to 0.0588 m³.

The combination of moderate rock quality and highly developed discontinuities indicates that structurally controlled rockfall mechanisms dominate the study area.

Table 1. Summary of rock mass characterization.

Parameter	**Result**
Dominant lithology	Interbedded tuffaceous sandstone and siltstone
Main discontinuities	Bedding planes, joints, shear fractures, minor faults
RMR value	41–63
RMR class	Fair to good
GSI value	36–58
Estimated block volume	0.000265–0.0588 m³
Main rockfall control	Discontinuity, weathering, and steep slope geometry

3 Methods

This study combined field mapping, scanline measurements, rock mass characterization, RMi-based block volume estimation, and three-dimensional rockfall simulation. Field data were used to identify lithology, slope geometry, discontinuity conditions, groundwater, and evidence of previous rockfall activity. Rock mass quality was evaluated using RMR and GSI, while potential block volumes were estimated using RMi and used as representative rigid body inputs.

Rockfall modelling was performed in RocFall3 using simplified square and rectangular rigid blocks derived from field-based block dimensions. Seven release sources were selected from critical slope sections identified through field observation and hazard zonation. The model inputs included block volume, block shape, slope geometry, surface material type, normal and tangential restitution coefficients, and dynamic friction. Block deformation and fragmentation were not explicitly simulated, as the modelling focused on trajectory behavior, kinetic energy, velocity, bounce height, and runout distance.

The normal restitution coefficient was estimated using the rebound-height relationship:

$$R_n = \sqrt{\frac{h_2}{h_1}} \tag{1}$$

Where:

a. R_n : Normal coefficient of restitution

b. h_1 : Effective fall height of the rock before impact,

c. h_2 : Rebound height of the rock after impact

Simulation outputs were evaluated using kinetic energy, translational velocity, bounce height, and total runout distance. Only valid trajectories with “Stopped” status were used in the interpretation to avoid overestimating results from numerical errors. A flexible rockfall barrier was then placed at the critical section where the main trajectories intersect the road alignment, and protected and unprotected scenarios were compared to assess barrier effectiveness.

4 Result and Discussion

4.1 Rockfall Simulation

The rockfall hazard assessment along Tegalrejo Road shows spatial variation from low to high hazard levels. The variation is mainly controlled by slope geometry, lithological contrast, weathering degree, discontinuity condition, and previous rockfall evidence. The RHRS analysis indicates that moderate-risk zones dominate the study area, particularly on slopes composed of interbedded tuffaceous sandstone and siltstone with moderate weathering. These zones are characterized by fractured rock masses and slope segments that are sufficiently steep to promote block detachment.

Locally, high-risk zones occur on steep road-side slopes where discontinuities are well developed and previous rockfall activity has been observed. These zones are critical because detached blocks may directly reach the road corridor. Therefore, the RHRS map is used as the initial basis for identifying critical slope sections requiring further rockfall trajectory simulation.

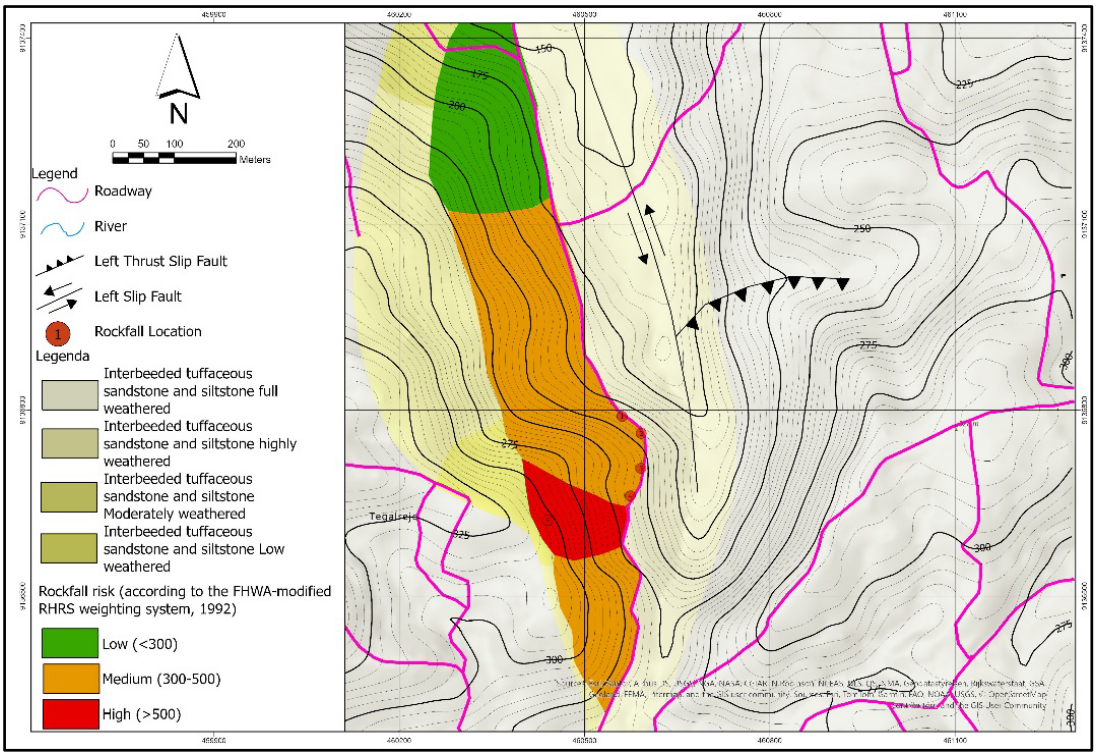


Fig. 2 Rockfall hazard zonation based on RHRS analysis along Tegalrejo Road.

4.2 Rockfall Simulation without Barrier

The unprotected rockfall simulation was carried out to evaluate the natural propagation behavior of detached blocks before the application of any mitigation structure. The simulation considered several release sources distributed along the critical slope sections, with different rigid block shapes representing field-based block geometry. The input parameters, including block volume, surface material properties, restitution coefficient, and dynamic friction, were calibrated using field evidence such as observed rockfall deposits, slope morphology, and impact traces along the road corridor.The restitution coefficient calculation indicates that sandstone and siltstone have relatively low rebound behavior. Using an initial drop height of 0.50 m, sandstone with Rn = 0.315 produced a rebound height of 0.0496 m, or 4.96 cm, while siltstone with Rn = 0.28 produced a rebound height of 0.0392 m, or 3.92 cm. These low rebound heights reflect significant energy loss during impact, which is consistent with the weathered and rough slope surface conditions observed in the field. Therefore, the calibrated restitution values support the simulated movement pattern, which is dominated by rolling, local sliding, and limited bouncing along several slope sections.

The results show that the rockfall trajectories vary significantly among the release sources. This variation is mainly controlled by the source location, slope inclination, local changes in slope geometry, and block shape. In the unprotected condition, several trajectories are able to reach the road corridor and continue downslope, indicating that the existing road section is located within the potential rockfall runout zone. The simulated movement is generally characterized by a combination of bouncing, rolling, and local sliding mechanisms.

To provide a clearer interpretation of the simulation outputs, the rockfall paths were statistically summarized for each seeder. Only valid trajectories with a "Stopped" status were used in the statistical analysis, while paths terminated by numerical error or maximum computation steps were excluded. The summary of the main simulation outputs is presented in Table 2.

Table 2. Summary of rockfall simulation outputs under the unprotected condition.

Seeder	Max duration [s]	Max kinetic energy mean/max [kJ]	Max translational velocity mean/max [m/s]	Total runout distance mean/max [m]	Design implication
Point Seeder 1	35.31	4.25 / 12.55	15.49 / 27.37	144.37 / 332.05	Long runout-dominant source
Point Seeder 2	39.29	1.62 / 22.48	7.90 / 20.60	51.94 / 294.41	High-energy and long-runout source
Point Seeder 3	27.36	1.32 / 28.58	4.11 / 21.44	19.91 / 183.06	Governing impact-energy source
Point Seeder 4	34.36	1.95 / 12.29	11.46 / 18.14	50.55 / 198.45	Moderate energy and runout
Point Seeder 5	14.91	0.21 / 0.99	4.71 / 14.43	12.23 / 66.77	Low-energy source
Point Seeder 6	0.77	0.12 / 0.69	2.14 / 3.39	0.30 / 0.68	Limited propagation
Point Seeder 7	29.68	3.38 / 8.20	15.41 / 31.17	123.42 / 322.49	Highest velocity and long-runout source

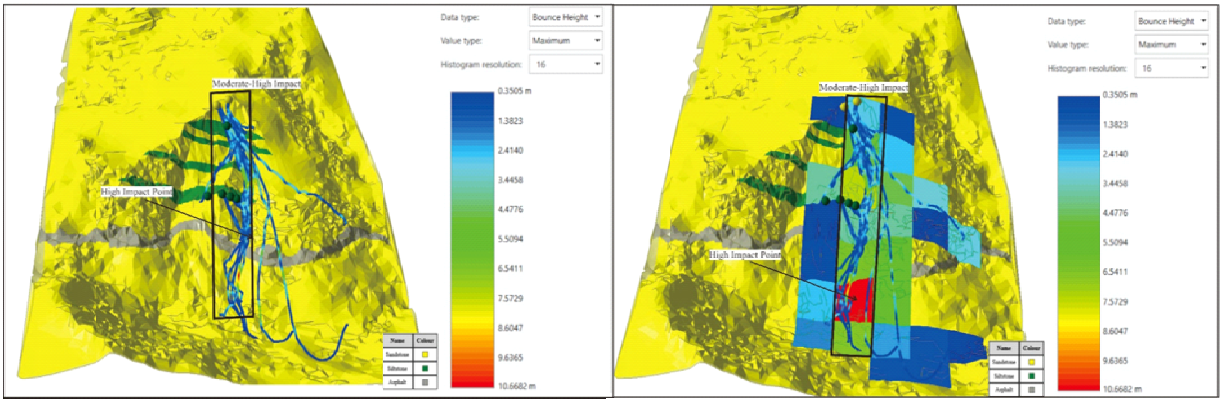


Fig. 3 Rockfall simulation without barrier: (a) trajectory path and (b) bounce height distribution.

4.3 Rockfall Simulation with Barrier and Mitigation

The simulation with a rockfall barrier shows a significant reduction in rockfall propagation toward the road corridor. The barrier acts as a passive protection system that intercepts falling blocks before they reach the road. Compared with the existing-condition model, the protected scenario shows a more controlled trajectory distribution and reduced bounce height beyond the barrier position.

The selected barrier model is based on a flexible rockfall protection system with an energy capacity of 111 kJ and a height of 6 m. The barrier is placed above the road alignment to intercept rock blocks before they enter the transportation corridor. This position is considered effective because it directly cuts the main rockfall paths identified in the unprotected simulation.

The simulation results indicate that barrier installation reduces the exposure of the road to falling blocks. However, barrier installation should be combined with other mitigation measures, including scaling of loose blocks, local rock netting on highly fractured slope faces, drainage improvement, and periodic monitoring. These additional measures are important because the slope instability is structurally controlled by discontinuities and affected by differential weathering between sandstone and siltstone layers.

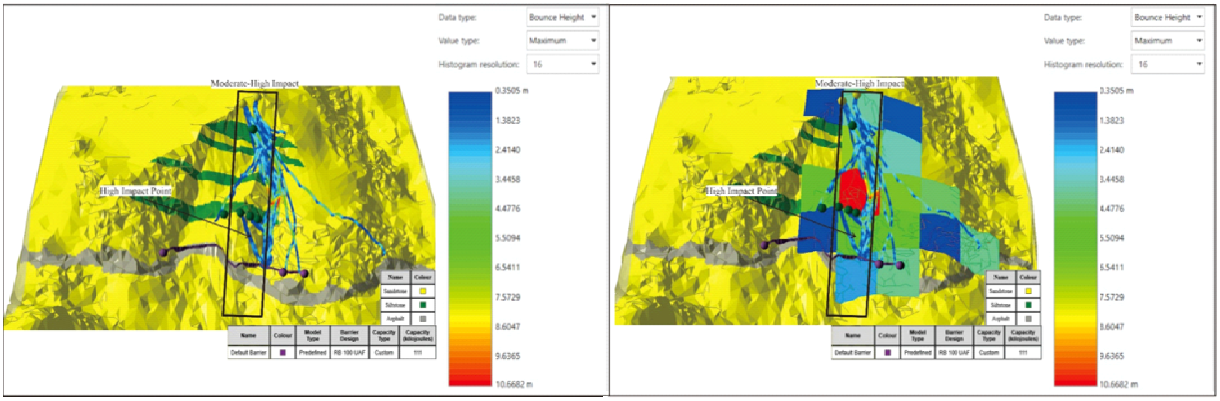


Fig. 4 Rockfall simulation with barrier: (a) trajectory path and (b) reduced bounce height distribution after barrier installation.

5 Discussion

The integrated results show that rockfall susceptibility along Tegalrejo Road is mainly controlled by steep slope geometry, interbedded tuffaceous sandstone–siltstone, weathering, and discontinuity networks. Although the RMR and GSI values indicate fair to good rock mass quality, bedding planes, joints, shear fractures, and minor faults form potential release surfaces for block detachment. The RMi-based block volume estimation provides representative rigid body inputs, while the low calculated rebound heights of sandstone and siltstone indicate significant energy loss during impact on weathered and rough slope surfaces. The unprotected simulation confirms that several trajectories can reach the road corridor, indicating that the road lies within the potential runout zone. The critical source varies depending on the evaluated parameter, with maximum kinetic energy, translational velocity, and total runout distance reaching 28.58 kJ, 31.17 m/s, and 332.05 m, respectively. Therefore, mitigation planning should consider not only kinetic energy, but also velocity, bounce height, and runout distance. The protected scenario indicates that a 6 m flexible rockfall barrier with an energy capacity of 111 kJ can reduce rockfall propagation toward the road by intercepting the main trajectories before they reach the exposed area. Because the instability is structurally controlled and affected by weathering, the barrier should be supported by scaling of loose blocks, local rock netting, drainage improvement, and periodic monitoring.

6 Acknowledgement

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References

Hoek E (2007) Practical rock engineering. Rocscience, Toronto.

Kompas.com. (2023). Longsor beberapa bulan yang lalu, akses jalan warga Gedangsari Gunungkidul. Kompas. https://yogyakarta.kompas.com/image/2023/06/22/110917278/longsor-beberapa-bulan-yang-lalu-akses-jalan-warga-gedangsari-gunungkidul?page=1 Accessed 30 April 2026.

Munandar A, Prasetyadi C, and others (2017) Geological structure analysis of the Southern Mountains, Gunung Kidul area. Geological Journal of Indonesia 12(1):33–45.

Palmström A (1995) RMi – a rock mass characterization system for rock engineering purposes. Rock Mechanics and Rock Engineering 28(1):49–66.

Samodra G, Sartohadi J, Chen G, Kasama K (2014) Automated landform classification in a rockfall-prone area, Gunung Kelir, Java. Earth Surface Dynamics 2:339–348.

Surono (2009) Litostratigrafi Pegunungan Selatan bagian timur Daerah Istimewa Yogyakarta dan Jawa Tengah. Jurnal Sumber Daya Geologi 19(3):209–221.