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Geotextile-Reinforced Haul Roads for Improved Hauling Speed in Open-Pit Coal Mining

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Abstract

Haul road rehabilitation should be assessed through both the distribution of road support and the transport components that constrain productivity. This study examined an approximately 1 km section of Jalan Mukmin at Gurimbang Mine Operation, PT Berau Coal, Indonesia, following combined nonwoven geotextile placement, aggregate addition, and compaction. A descriptive before-and-after comparison used penetration-derived California bearing ratio (CBR) estimates at ten stations and reported Komatsu HD785 speeds and cycle-time components. Station dispersion, a diagnostic exclusion of the highest post-rehabilitation estimate, and cycle-time sensitivity were evaluated. Mean CBR increased from 21.58% to 60.01%, while its coefficient of variation increased from 19.33% to 57.97%. Nine stations improved, but one decreased. Excluding the highest station for sensitivity analysis retained a mean increase from 21.92% to 51.78%, indicating that the direction of change was not dependent on that station alone. Cycle time decreased from 22.06 to 16.62 min; loaded travel accounted for 65.63% of the reduction. Under fixed volume and efficiency assumptions, calculated productivity increased from 115.46 to 153.25 bank cubic metres per hour. An illustrative additional 1 min of cycle delay reduced the post-rehabilitation estimate to 144.56. The contribution is a transparent joint assessment showing why a higher mean road-support estimate does not establish spatial uniformity, and why operational gains depend on preserving travel-time savings. Uncontrolled conditions and discrepancies between penetration logs and summary values limit causal attribution and the geotechnical magnitudes. The results support targeted station verification and component-based transport monitoring, rather than certification of long-term road stability or an isolated geotextile effect.

1. Introduction

Mine haul roads connect ground engineering with production performance. Their structural condition must support repeated heavy-wheel loads, while their surface and geometry affect travel speed and transport reliability. Recent comparisons of haul road design methods emphasize the importance of layer thickness, deformation, and mechanistic response [1]. Ercins and Bostancıoğlu further show that CBR-based sections can be insufficient under particular load and surface-stiffness conditions [2]. A higher road-strength index should therefore not be treated as a complete assessment of a haul road.

Operational evidence highlights a second assessment dimension. Alegre et al. use dispatch records and road grade to estimate segment rolling resistance [3]. Maior et al. assess geometry and rolling-resistance scenarios together with truck productivity and fuel use [4]. Road-roughness research likewise examines effects on travel speed, time, and haulage performance [5]. These studies support examining the transport process, but they also show why penetration resistance, roughness, rolling resistance, and productivity cannot be assumed to be equivalent outcomes.

Geosynthetics are a relevant option for weak-road rehabilitation. Singh et al. evaluated reinforced unpaved sections using laboratory CBR and field penetration methods [6], and reported further DCP-based comparisons of geotextile and geogrid sections [7]. Moving-wheel experiments evaluated surface

rutting directly [8], while full-scale stabilization research used control sections and traffic-related performance to calibrate design [9]. The evidence thus ranges from penetration-based indices to deformation under repeated loading. Each provides a different basis for assessing performance.

Longer-term performance requires additional evidence. Sarma and Dey examined geotextile-assisted unpaved-road behavior through a stress–deformation modeling approach with repeated loading [10]. Ho et al. evaluated geogrid-reinforced unpaved roads over five years, combining initial penetration and plate-load measurements with later roadway sensing [11]. These studies provide reasons to monitor durability and layer behavior; their materials, loads, and design conditions do not establish long-term benefits at another site automatically.

At Gurimbang Mine Operation in East Kalimantan, a previous case study already reported geotextile-assisted haul road improvement and HD785 productivity changes [12]. The research gap addressed here is consequently not first use of geotextile at this mine. It is the interpretation of station-level road-support changes together with the cycle components generating a modeled productivity gain. Separate average values can conceal local weak responses, whereas an aggregate productivity percentage can conceal dependence on travel time and unchanged operating assumptions.

This study evaluates a rehabilitated section of Jalan Mukmin using ten station CBR estimates and reported truck records. Its contribution is a joint descriptive assessment that combines spatial dispersion, sensitivity to a high station value, and transport-cycle decomposition. The resulting analysis makes two practical questions explicit: does improvement in the mean also represent a consistent response along the road, and how sensitive is the calculated production benefit to renewed cycle delay? The contribution is empirical and analytical; it does not establish a new design method or isolate the geotextile's causal effect.

2. Methodology

2.1. Site and comparative design

The study concerned Jalan Mukmin in Pit West, Gurimbang Mine Operation, PT Berau Coal, Berau Regency, East Kalimantan, Indonesia. The road serves overburden transport between the mining front and disposal area. An approximately 1 km distressed section was selected purposively. Ten stations were designated at nominal 100 m intervals, from STA 0+100 to STA 1+000. Moisture-sensitive ground and visible surface distress motivated rehabilitation. The truck type was reported as Komatsu HD785.

A descriptive before-and-after design used field documentation, penetration results, and summarized operational records. No untreated control road was monitored. Road geometry, traffic, weather, operators, payload, and observation periods were not documented as controlled variables. The station calculations use the CBR values in the main results summary. Discrepancies with the underlying penetration logs require reconciliation; the geotechnical results therefore remain provisional. Operational sample sizes and variability were unavailable, so no confidence interval or formal intervention-effect test was calculated.



Figure 1. Field documentation of road distress (left) and geotextile placement (right).

2.2. Combined rehabilitation works

The works included clearing unsuitable surface material, addressing muddy areas and standing water, preparing and grading the formation, laying nonwoven geotextile, adding aggregate, and compacting the road profile in layers. Reported sheet dimensions were approximately 25 m by 4 m, placed across the prepared formation. Adjacent sheets overlapped by approximately 0.30–0.50 m, with stitching at some joints. These are reported construction practices, not independently verified design specifications. Figure 1 shows the original surface distress and geotextile placement. Certified material properties, layer thickness at every station, and compaction acceptance results were not available in the study summary. The intervention was therefore defined as the combined works. No attempt was made to allocate the change in road behavior to separation, aggregate thickness, compaction, drainage, or tensile reinforcement individually.

2.3. Penetration estimates and spatial summaries

Dynamic cone penetration index (DCPI) expresses penetration in millimetres per blow. DCP was used to estimate CBR, rather than to measure laboratory CBR or in-situ density directly. Research on DCP–CBR prediction examines the influence of density, moisture, and fines content [13]. Tests in clay–sand mixtures show moisture-state dependence [14], while instrumented DCP research integrates moisture information with penetration measurements [15]. These findings support recording material and moisture conditions when interpreting a conversion.

The study applied Eq. (1), where CBR is expressed as its numerical percentage. Indonesian DCP guidance provides the relevant field-test background [16]. The device configuration, tested depth, layer boundaries, and calibration range need confirmation before the estimated values are used for design.

$$\log_{10}(\mathrm{CBR}) = 2.8135 - 1.313 \log_{10}(\mathrm{DCPI}) \quad (1)$$

Station values were summarized using arithmetic mean, median, minimum, maximum, and sample standard deviation. Coefficient of variation (CV) was standard deviation divided by the mean, multiplied by 100. Paired changes were calculated as post-rehabilitation minus baseline CBR, in percentage points. To examine dependence on the highest post-rehabilitation value, a sensitivity analysis excluded STA 0+900 from both periods. This diagnostic comparison does not establish that the station is erroneous and does not replace the full dataset.

The empirical support index DDT was recalculated from each CBR value using the relation stated in the source study, Eq. (2). The cited Indonesian component-analysis guidance supplies its road-design background [17]. The reported average is the mean of the ten derived station indices, not the logarithmic transformation of mean CBR. DDT is retained as a secondary empirical indicator and is not equated to an allowable bearing pressure.

$$\mathrm{DDT} = 1.6649 + 4.3592 \log_{10}(\mathrm{CBR}) \quad (2)$$

2.4. Cycle decomposition and productivity sensitivity

Truck-cycle time was the sum of loading, loaded travel, dumping, and empty travel. Before-and-after differences were calculated for each reported component. Each travel component's share of the total time saving was its reduction divided by the total reduction. Loaded and empty speed records were summarized separately because measurement coverage was insufficiently defined to reconcile them with a reported route distance or derive times from speeds.

Productivity was calculated as bank volume per cycle multiplied by operating efficiency and cycles per hour, as expressed in Eq. (3). Q is bank cubic metres per hour (BCM/h), n is loading passes, Kb is bucket capacity (m^3), Ff is fill factor, Fb is bank-volume conversion factor, E is operating efficiency, and CT is cycle time in minutes.

Table 1. Station-level penetration-derived CBR and paired changes

Station	Before (%)	After (%)	Change (pp)
0+100	15.93	25.55	+9.62
0+200	27.97	26.30	-1.67
0+300	18.21	83.95	+65.74
0+400	22.06	87.94	+65.88
0+500	27.55	38.14	+10.59
0+600	20.53	37.15	+16.62
0+700	20.59	58.22	+37.63
0+800	18.75	72.68	+53.93
0+900	18.49	134.02	+115.53
1+000	25.69	36.11	+10.42

$$Q = n \times Kb \times Ff \times Fb \times E \times 60 / CT \quad (3)$$

The retained assumptions were n = 8, Kb = 6.7 m³, Ff = 1.10, Fb = 0.80, and E = 0.90, giving estimated volume of 47.168 BCM per cycle before efficiency adjustment. They were fixed between periods. Productivity is therefore a modeled consequence of cycle time, not an independently measured production gain. Sensitivity was evaluated by adding illustrative delays of 1 and 3 min to the post-rehabilitation cycle while holding all other assumptions constant. These scenarios are conditional calculations, not observed delays or forecasts.

3. Results and discussions

3.1. Spatial improvement and increased heterogeneity

Mean CBR increased from 21.58% to 60.01%, or 38.43 percentage points. Nine stations increased, while STA 0+200 decreased from 27.97% to 26.30% (Table 1). The median increased from 20.56% to 48.18%, and the median paired change was 27.13 percentage points. Thus, improvement occurred across most of the summarized stations rather than only in the overall average.

Improvement in the minimum was accompanied by a much greater spread (Table 2 and Figure 2a). Sample standard deviation increased from 4.17 to 34.79 percentage points, and CV from 19.33% to 57.97%. It is therefore inaccurate to describe the rehabilitated section as more uniform solely because its average was higher. A road with a strong mean can still contain locations whose response is weaker or inconsistent, requiring station-specific investigation.

The highest post-rehabilitation estimate, 134.02% at STA 0+900, influenced the mean. Excluding this station from both periods retained an increase from 21.92% to 51.78%. This shows that the direction of the summarized change does not depend on the peak station alone. It does not validate that peak or resolve differences between the penetration logs and the summary table. CBR is a reference-load ratio, so an estimate above 100% is not a degree of compaction. Confirmation of penetration increments, tested layers, and conversion applicability is particularly important for this value.

Table 2. Distribution of CBR estimates and sensitivity to the highest station

Statistic	Before	After
Mean CBR (%)	21.58	60.01
Median CBR (%)	20.56	48.18
Minimum CBR (%)	15.93	25.55
Maximum CBR (%)	27.97	134.02
Sample SD (pp)	4.17	34.79
Coefficient of variation (%)	19.33	57.97
Mean excluding STA 0+900 (%)	21.92	51.78

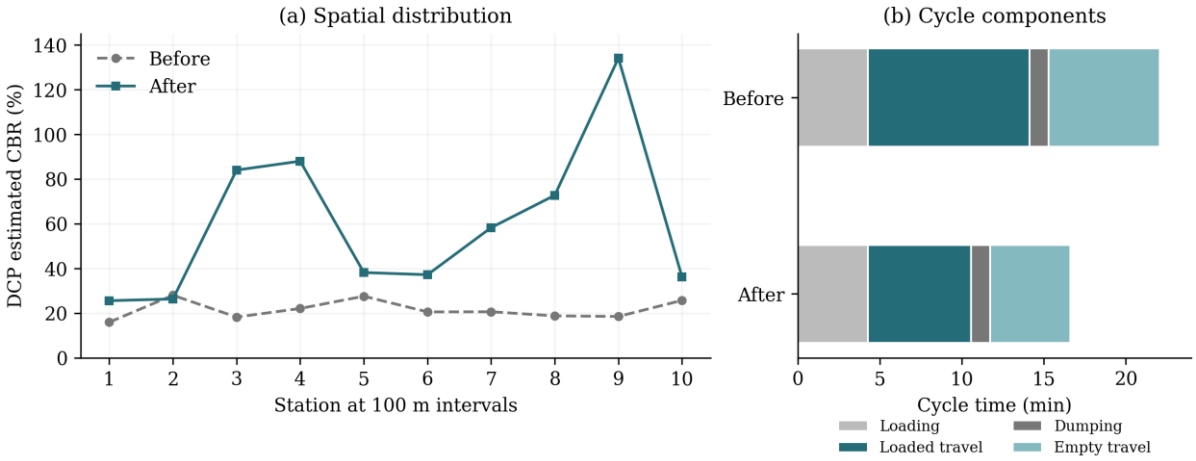


Figure 2. Spatial distribution of the summarized CBR estimates and reported truck-cycle components. Both datasets describe before-and-after conditions; the figure does not establish a station-level causal relationship between CBR and travel time.

These results provide a different assessment emphasis from reporting mean CBR alone. Singh et al. showed that penetration profiles can identify changes with depth in reinforced test sections [6]. In the present case, variation along the road is also consequential. The useful next step is to verify station layer profiles and construction conditions, particularly the station with a slight decline and those with large increases. A statistical distribution cannot identify the physical cause of the variation without those records.

3.2. Mechanisms and limits of a support-index interpretation

The combined works are compatible with an increase in penetration resistance, but the mechanism remains unresolved. Geotextile at the soil–aggregate interface can help maintain separation, while added aggregate and compaction alter the profile and resistance encountered by the cone. Laboratory CBR research has investigated reinforcement position as a determinant of the response [18]. This indicates why thickness and placement should be documented rather than treating every post-construction increase as improvement of the original subgrade soil.

The average derived DDT index increased from 7.45 to 9.14 when Eq. (2) was applied consistently. Because DDT is calculated from CBR, the increase is not independent evidence of road improvement. It also cannot be directly compared with tyre contact pressure to demonstrate safety. The original tabulated DDT values did not reproduce the stated relation; the recalculation provides arithmetic consistency, but the intended correlation still requires confirmation.

Repeated-load research provides a more direct test of deformation performance than a converted penetration index. Singh et al. reported a 44.89% reduction in rutting for a geotextile test section after 350 vehicle passes, relative to the unreinforced comparison [8]. Sarma and Dey examined rutting and displacements under repeated loading through numerical analysis [10]. The Gurimbang CBR increase is an index change, whereas those endpoints concern surface deformation. Their percentages cannot be compared as equivalent effectiveness measures, and their results do not demonstrate the same rutting reduction under HD785 loading.

Full-scale stabilization tests by Cuelho and Perkins varied material and construction conditions and included controls to distinguish effects on operational performance [9]. The present combined works lack that separation. The observed response supports further assessment of the rehabilitated profile, but neither an isolated tensile-reinforcement benefit nor a general reduction in required aggregate thickness can be inferred. Mechanistic haul road studies further show that loads and surface-layer stiffness can matter beyond subgrade CBR [1], [2].

Table 3. Reported speeds and cycle-time decomposition

Indicator	Before	After	Difference
Loaded speed (km/h)	12.00	18.00	+6.00
Empty speed (km/h)	13.00	20.00	+7.00
Loading time (min)	4.27	4.27	0.00
Loaded travel (min)	9.86	6.29	−3.57
Dumping time (min)	1.17	1.17	0.00
Empty travel (min)	6.76	4.89	−1.87
Total cycle (min)	22.06	16.62	−5.44

3.3. Travel components as the source of cycle savings

Loaded speed increased by 50.00% and empty speed by 53.85%. The cycle decreased by 5.44 min, or 24.66% (Table 3). Loading and dumping were unchanged in the reported means, so the entire reduction came from travel. Loaded travel accounted for 65.63% of the saving, and empty travel for 34.38%. Combined travel decreased from 16.62 to 11.18 min, or 32.73%. Travel's share of the total cycle decreased from 75.34% to 67.27%.

This decomposition identifies where the modeled benefit originates. Monitoring the loaded leg is particularly relevant because it accounts for approximately two-thirds of the recorded time saving. That finding does not prove higher rolling resistance before rehabilitation: the study did not measure rolling resistance, and travel time also reflects grade, traffic, operating controls, and route coverage. Alegre et al.'s dispatch-based method explicitly combines segment grade and truck performance to estimate resistance [3]. Applying a comparable measurement approach would help test the proposed transport mechanism rather than infer it from CBR or speed alone.

Maior et al. reported scenario-based cycle-time reductions of up to 15% when evaluating grade and rolling resistance in an iron ore mine [4]. Road-roughness work also assessed travel and productivity responses for off-highway trucks [5]. The present 24.66% reduction is directionally consistent with better transport conditions, but its greater numerical value does not establish a superior intervention. Study designs, routes, trucks, and baseline constraints differ, and these comparisons do not supply the missing control condition at Gurimbang.

Asof et al.'s earlier Gurimbang study reported speed increases and higher monthly productivity following geotextile-assisted improvement [12]. The current analysis adds station dispersion and time-component attribution. It should not be represented as the first local demonstration of operational benefit. Its hourly model is also not directly comparable with a monthly production outcome, which includes operating duration and other production assumptions. Observation dates and any overlap in company records require confirmation to establish the independence of the current case evidence.

3.4. Productivity dependence and delay sensitivity

With load-volume and efficiency assumptions unchanged, calculated productivity increased from 115.46 to 153.25 BCM/h, a gain of 37.79 BCM/h or 32.73% (Table 4). The productivity ratio equals the inverse cycle-time ratio, 22.06/16.62 = 1.3273. This makes the relationship transparent: a 24.66% cycle reduction produces a larger percentage productivity increase because productivity is proportional to the reciprocal of cycle time.

Table 4. Calculated productivity and illustrative post-rehabilitation delay scenarios

Condition	Cycle (min)	Q (BCM/h)	Gain vs baseline
Before rehabilitation	22.06	115.46	Reference
After rehabilitation	16.62	153.25	32.73%
After plus 1 min delay	17.62	144.56	25.20%
After plus 3 min delay	19.62	129.82	12.44%

An illustrative additional 1 min of delay reduced the post-rehabilitation estimate to 144.56 BCM/h, 5.68% below its delay-free modeled value. Adding 3 min reduced it to 129.82 BCM/h, leaving a 12.44% gain over baseline. These are sensitivity scenarios, not measured losses. They show why preserving travel-time savings is important and why an average benefit may diminish if deteriorating road condition, queueing, or another source of delay returns.

The model does not distinguish those possible delay mechanisms. It also holds payload, fill factor, conversion factor, and efficiency constant, without independent validation against dispatch volume records. A future production assessment should measure the full distributions of cycle time and payload and distinguish efficiency already embedded in observed cycle means from any further adjustment. No reduction in fuel use, truck count, emissions, or operating cost is inferred from the present calculations.

3.5. Evidence needed for durable and transferable improvement

A durable-road assessment should connect construction records, layer response, surface deformation, and truck performance over comparable observation periods. The five-year study by Ho et al. illustrates the value of later sensing and repeated condition observations rather than relying on initial penetration results alone [11]. Its geogrid and aggregate system differ from a nonwoven-geotextile mine road; the transferable lesson is the monitoring design, not a specific service-life estimate.

Recent composite-geosynthetic studies also use multiple tests and a control section. Hasheminezhad et al. combined laboratory material characterization with field DCP, lightweight deflectometer, and CBR-related measurements [19]. Their conference study monitored full-scale sections exposed to traffic and recommended continued evaluation [20]. These composite systems include geogrid as well as nonwoven geotextile, so their mechanical benefits cannot be assigned to nonwoven separation alone. They nevertheless offer a stronger evidential structure for future assessment than a single converted index.

For Jalan Mukmin, immediate priorities are verification of station identities and penetration calculations, documentation of aggregate thickness and geotextile properties, and comparable measurements of moisture and compaction. Follow-up should record rut depth and settlement at the same stations, particularly after wet periods and accumulated truck passes. Segment-specific truck observations should document load state, road grade, route distance, traffic, and observation counts. This would permit examination of whether local road deterioration precedes renewed travel delay.

The joint approach is useful because it preserves distinctions between endpoints. Spatial summaries indicate where field verification is needed; cycle decomposition identifies which operational component contributes to a modeled gain. The available data cannot establish a numerical CBR–speed relationship at individual stations. Maintaining that distinction makes the analysis reproducible and avoids converting a descriptive road case into an unsupported pavement-safety or productivity forecast.

3.6. Study limitations

The purposively selected road section and uncontrolled before-and-after comparison limit generalization and causal inference. Rehabilitation combined several construction actions, and possible differences in alignment, weather, moisture, traffic, and driver behavior were not resolved. Missing material specifications and layer-specific test metadata restrict interpretation of the penetration estimates. The main CBR summary differs from appendix calculations, and the original DDT table differs from the stated equation. These issues require a raw-record audit before finalizing the geotechnical magnitudes.
The highest-value exclusion is only a diagnostic sensitivity check; it is not evidence for deleting a station or correcting its measurement. Operational values lack observation counts and uncertainty estimates, while reported route distance and speed–time combinations require clarification. The hourly productivity and delay scenarios are conditional calculations under fixed assumptions. No economic outcome, independent production measurement, or long-term safety assessment was available. The article's contribution is therefore the explicit interpretation of heterogeneous support estimates and component-dependent transport gains, subject to these verification limits.

4. Conclusion

The summarized CBR estimates showed improvement at nine of ten stations after combined geotextile, aggregate, and compaction works. Mean CBR increased from 21.58% to 60.01%, but its coefficient of variation increased from 19.33% to 57.97%. A sensitivity analysis excluding the highest station retained the direction of improvement. These findings demonstrate why an improved mean should be considered alongside spatial heterogeneity; discrepancies in the raw records still require reconciliation.

Reported cycle time decreased from 22.06 to 16.62 min, with loaded travel accounting for 65.63% of the saving. Under fixed assumptions, modeled productivity increased by 32.73%, while illustrative added delays materially reduced the gain. The joint assessment contributes a transparent basis for station-specific verification and transport-component monitoring. It does not isolate the geotextile effect, validate an allowable road bearing pressure, or establish long-term durability.

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