

Reliability Assessment and Maintenance Optimization of Hydraulic Rotary Drilling Rigs Used in Geotechnical Projects

Suraj Chapagain¹, Jagdeep Kumar¹

¹Department of Mechanical Engineering, Swami Devi Dyal Institute of Engineering & Technology,
Barwala, Panchkula, Haryana

Abstract - Hydraulic rotary drilling rigs play an important part in geotechnical engineering works but due to constant exposure to hostile and unpredictable working conditions are extremely susceptible to wear, leak, overheat and mechanical decay, the resultant frequent failures, downtimes, and expensive maintenance. This research measures the reliability performance and maintenance requirements of hydraulic rotary drilling rigs by analysing real time and historical operating data such as frequency of breakdowns, Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), type of failures, and availability of sub-system. The Failure Mode and Effects Analysis (FMEA) was used to classify failures as critical failure modes and assign Risk Priority Numbers (RPN) to every subsystem. The results showed that hydraulic and mechanical systems had the most significant proportion of failures and downtime whereas structural system had a lower proportion of failures and downtime. Longer repair times were also recorded on electrical and hydraulic components which impacted a great deal on the general availability of a system. On these findings, a Reliability-Centered Maintenance (RCM) framework was suggested to optimize the inspection periods, give more priorities to the high-risk components, and enhance the condition-based monitoring tradition. The research shows that reliability-based maintenance planning would allow considerable improvement in equipment availability, unplanned failures, and cost-effectiveness and safety in geotechnical drilling activities

Key Words: Hydraulic rotary drilling rigs, Reliability assessment, Failure Mode Effects Analysis (FMEA), Mean Time Between Failures (MTBF), Reliability-Centered Maintenance (RCM), System availability

1. INTRODUCTION

Hydraulic rotary drilling rigs are unique machines in geotechnical engineering in as they are applied in the foundation work, site investigation, tunnelling, slope stabilization, as well as ground improvement [1]. The quality of subsurface data, safety, and stability of constructed structures, and field operations productivity directly depend on their performance [2]. The more complicated and time-constrained the project is, the more dependable and prepared these rigs are [3]. Unexpected failure and malfunction may lead to work delays, money loss, safety and poor-quality project results [4].

These drilling rigs consist of interaction of hydraulic, mechanical, and control sub systems that work in harsh and varying site conditions [5]. Wear, fatigue, and unforeseen breakdowns are caused by constant working at high loads, vibration, and abrasive substances [6]. Maintenance is still practiced in a reactive manner or on a fixed time schedule in most projects without the consideration of the actual health of the components [7]. This will result in unnecessary maintenance or severe failure because of late intervention [8]. Hence, better, reliability-driven maintenance methods are required to streamline maintenance plans and enhance the performance of equipment [9].

The reliability assessment assists in knowing the frequency of failures, which parts are more likely to fail and the dynamic nature of the failures [10]. Failure Mode and Effects Analysis (FMEA), Mean Time Between Failures (MTBF), reliability modelling, and hazard rate analysis are the methods that allow the engineer to determine the components that are critical and predict them to deteriorate [11]. These assessments used with predictive and reliability-focused maintenance strategies promote proactive decision-making that leads to a more efficient result and decreases the maintenance cost in the long-term [12]. Despite the enhancement of digital monitoring technologies and real-time data recording that allow tracking the machine health [13], the research dedicated to the reliability and optimization of hydraulic rotary drilling rigs, in particular, in developing areas, is limited [14]. This paper fills that gap with the analysis of real-life operational data to determine major failure modes and reliability patterns. The final objective is to work out the optimization of the maintenance measures which would contribute to the equipment availability, lessen the unavailability, improve the cost-effective character, and assist the performing geotechnical works safely and effectively.

The research objectives of the study are:

- To determine reliability and significant failures of hydraulic rotary type drilling rigs in geotechnical projects.
- To streamline maintenance plans to minimize failures, reduce downtime and enhance rig performance and availability.

2. REVIEW OF LITERATURE

Reiffsteck et al. (2018) [15] researched the application of drilling parameters to improve geotechnical investigations and showed that drilling data including torque, rotation speed,

penetration rate, and energy consumption were useful in determining the conditions of the subsurface. They found that these parameters were useful to describe soil and rock properties more rigorously, and the interpretation of the ground behavior during site investigations. They also noted that the use of drilling parameter measurements minimized uncertainty and enhanced the consistency of geotechnical tests.

Rodgers et al. (2020) [16] concentrated on the use of measuring-while-drilling (MWD) in limestone in Florida to carry out geotechnical site studies. Their analysis has shown that the drilling responses in real-time including bit force, torque, and penetration resistance can be monitored better to identify lithological variations and weak sections. According to the findings, MWD technology was found to have improved the accuracy of the obtained data, decreased the reliance on the traditional sampling procedures, and helped to make decisions faster on the field.

Shen et al. (2022) [17] tested the performance of a percussive drill rig using a rate-energy ratio methodology by testing controlled rock drilling. Their findings revealed that rate-energy ratio was a good guide to the efficiency of drilling and the use of energy. The experiment demonstrated that the best drilling parameters delivered better penetration rates and minimized the energy expenditure. They also underscored that the performance evaluation designed on the basis of energy associated indices assisted in better performance planning of the drill rigs and their maintenance planning.

Sundaram et al. (2024) [18] surveyed the new developments in the current geotechnical investigation practice in India and indicated that the industry had been moving towards the modern testing methodology, digital data collection system and real time monitoring equipment's. Their research demonstrated that such developments increased the accuracy, speed, and reliability of characterizing the subsurface, as well as decreasing the uncertainty levels that are related to the conventional investigation methods. They also pointed out the increasing focus on the incorporation of technology-based methods and techniques into conventional geotechnical engineering practices so as to increase project safety and performance results.

Wang et al. (2018) [19] formulated a reliability-based optimization model on the tunnel boring machine (TBM) performance considering the geological uncertainties. Through their research, it was established that performance prediction was better, and this was through the inclusion of probabilistic modelling of ground conditions to predict performance and assist in making decisions in relation to TBM operational environments. The results showed that the optimization of machine parameters in the presence of uncertain geological conditions resulted in the efficiency of the performance of the machine and negative risk of operational failures and losses.

Wodecki et al. (2020) [20] was interested in process monitoring on heavy-duty drilling rigs and created an acquisition system and cycle identification algorithms to measure drilling processes. Their study revealed that operational parameters could be successfully identified by continuous monitoring and used to predict the phases of the

operation and could also easily identify abnormality. They determined that these automated monitoring systems improved the reliability of the operations, predictive maintenance as well as the overall safety and performance of the drilling rigs.

3. RESEARCH METHODOLOGY

The methodology of the research explained how the reliability and the maintenance requirements of hydraulic rotary drilling rigs were evaluated in geotechnical projects. An operational data of real-time and historic operation was used through a quantitative approach that was analyzed to determine failure modes, reliability indicators, including MTBF and MTTR, and critical components. They were then applied to create optimized maintenance strategies using Reliability-Centered Maintenance principles. The outcome was also confirmed by the expert reviews and historical comparison, and all data concerning the site were controlled in terms of confidentiality and ethical consideration.

3.1 Research Design

The research design applied in this study was a quantitative, analytical research design that was designed on real time and historical data of hydraulic rotary drilling rigs in the geotechnical project. It was concerned with measuring the level of rig reliability and enhancing maintenance to decrease failures and downtime. The use of reliability engineering and statistical analysis to determine the critical components, study the patterns of failures, and determine the system availability forms the foundation of optimization of maintenance.

3.2 Data Collection

Geotechnical sites where drilling rigs were frequently utilized were used as the sources of data. The data comprised the hours of operation, breakdowns, maintenance documentation, duration of downtime and replacements of various components, site and soil data. The data were obtained by CMMS reports, logbooks, manuals, and interviews with the staff. Every piece of data was sorted out to eliminate errors and provide accuracy prior to analysis.

3.3 Failure Mode Identification and Classification

The failures were categorized in subsystems (hydraulic, mechanical, electrical, structural, and control systems) and in type (wear, leakage, overheating, misalignment, etc.). The identification of critical failures was performed by the application of Failure Mode and Effects Analysis (FMEA). Risk Priority Numbers (RPN) were used to prioritize failure modes, with priority being placed on those components that needed maintenance and safety concern.

3.4 Reliability Analysis

Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), failure rate and availability were used to measure rig reliability. The failure data were also fitted on a reliability models like Weibull and exponential distribution to determine the trends. The hazard rate analysis was used to identify the kind of failures whether they were early-life failures, random

or wear-out related failures and this was used as an insight in the lifecycle behaviour of equipment.

3.5 Maintenance Optimization Approach

Optimization of maintenance was based on the Reliability-Centered Maintenance (RCM) principles. Key elements that were being identified in the analysis were subjected to preventive and predictive maintenance. There were also possibilities of condition-based maintenance. The optimization was aimed at establishing maintenance intervals that minimized downtime and costs and maximized availability and life of equipment.

3.6 Validation of Findings

The analytical findings were confirmed by analyzing the trends of performance in history and by evaluating the analytical findings by the experts, who are the rig operators and maintenance engineers. To the extent possible, the results were compared with those of several rigs or project sites to render consistency and strength. This validation process made sure that the conclusions made using the data were realistic, practical as well as applicable to the actual geotechnical operations.

3.7 Ethical and Safety Considerations

The data utilized in the study were treated confidentially and only in the academic purposes. Authorization to access operational records was given by the owners of equipment and authorities of the site. There were no field activities pertaining to data collection that disrupted field operations or posed any safety hazards. It was highly confidential with organizations and personnel working anonymously.

4. RESULT AND DISCUSSION

The section provides and discusses the findings of the reliability study of hydraulic rotary drilling rigs. The results are the failure distribution by subsystems, the significant failure types, the major indicators of reliability like the MTBF and the MTTR and the availability of the systems prior to maintenance optimization. It also contains a criticality assessment that employs FMEA to determine the high-risk failure modes. The results are commented upon in order to outline the key aspects that influence the drilling rig reliability and the maintenance performance.

4.1 Failure Characteristics of Drilling Rigs

The section of Failure Characteristics of Drilling Rigs describes how the failures were distributed among the major subsystems of hydraulic rotary drilling rigs. The review indicated that the hydraulic, mechanical, electrical, and structural, and mechanical parts had the largest number of failures respectively. Table 1 corroborates this analysis as it gives the number and percentage of failures of each subsystem hydraulic, mechanical, electrical, structural, and control as well as the overall number of failures. In this comparison, it is obvious which subsystems were the most susceptible to failures and, consequently, should have been given more attention to maintenance in order to have a better overall rig reliability.

Table 1 results indicate that the hydraulic subsystem had highest number of failures (48 failures, 32%), meaning that hydraulic components are the most susceptible and give most significant contribution to system failures. This was succeeded by the mechanical subsystem that had 36 failures (24%), and electrical subsystem with 28 failures (19%) indicating that moving mechanical parts and electrical components are also a significant cause of system unreliability.

Table 1: Failure Frequency by Subsystem

Subsystem	Number of Failures	Percentage (%)
Hydraulic	48	32
Mechanical	36	24
Electrical	28	19
Structural	18	12
Control System	19	13
Total	149	100

The structural subsystem explained 18 failures (12%), and the control system 19 failures (13%), which is relatively low but still high. In general, the overall failures were 149 and the distribution shows clearly that hydraulic and mechanical subsystems should be the centre of focus of maintenance planning and reliability improvement strategies because they contribute the most in the downtime and loss of performance in hydraulic rotary drilling rigs.

As Figure 1 shows, the breakdown of failures in the major subsystems of hydraulic rotary drilling rigs is expressed in percentages. The hydraulic, mechanical, electrical, structural and control systems are the subsystems in the figure. The subsystems are represented by their percentage contribution to the total number of failures recorded and the variation in the occurrence of failures in the various components of the rig can be visualized.

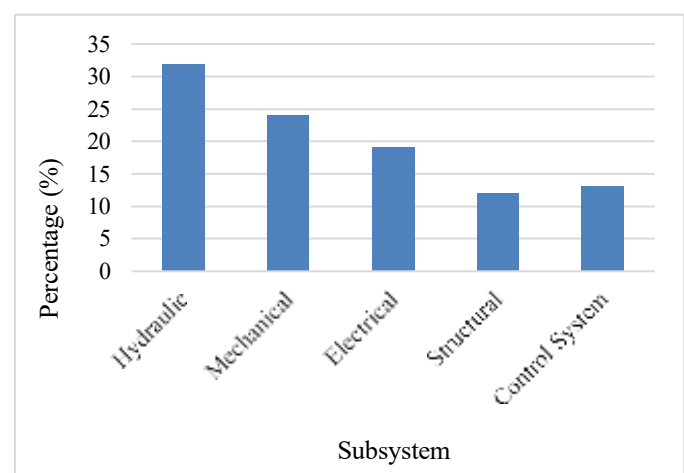


Figure 1: Percentage Distribution of Failures Across Major Subsystems of Hydraulic Rotary Drilling Rigs

The figure 1 illustrates that the hydraulic subsystem had the largest percentage of failures at 32% then the mechanical

and electrical subsystem at 24 and 19 respectively. The structural subsystem and control system gave their 13 percent and 12 percent share of the failures respectively. These findings show that the most susceptible parts of the drilling rigs were hydraulic and mechanical components and therefore more attention needs to be given to these parts in the form of monitoring, emphasis on preventive maintenance and improving strategies that can reduce the downtime as well as enhance their operational performance.

4.2 Classification of Failure Modes

The Classification of Failure Modes section explains how the drilling rig failures were classified into categories, including wear, leakage, overheating, misalignment, sensor faults and others to define the primary reasons of the breakdowns. The results demonstrated that the most prevalent modes of failures were wear and leakage, next came overheating and misalignment, and sensor and other failures were seldom witnessed. This analysis is corroborated in Table 2, which gives number and percent of failures per type of failure, a easy comparison can be made on how frequently each mode took place. The findings in general suggest that the deterioration of components and hydraulic leakage were the most contributing components of the failures and should be the primary point of the maintenance enhancement.

Table 2: Distribution of Failure Types

Failure Type	Number of Failures	Percentage (%)
Wear	41	27
Leakage	36	24
Overheating	28	19
Misalignment	22	15
Sensor Fault	14	9
Others	8	6

It can be seen that wear-related failures were the most prevalent (41 failures, 27%), then closely exceeded by leakage failures (36 failures, 24%), meaning that parts and hydraulic system sealing were the most problematic in terms of reliability. The effects of thermal stress and mechanical imbalance were important with 19% and 15% of the failures caused by overheating and misalignment respectively. The sensor faults constituted 9 % of the failure whereas the rest 6 % were miscellaneous. On the whole, the trend shows that wear and leakage were the major causes of equipment failures, and thus, preventive lubrication management, inspection of seals, and tracking of conditions are the important factors to improve reliability.

Figure 2 demonstrates the distribution of various types of failures that have been seen in hydraulic rotary drilling rigs in percentages. Wear, leakage, overheating, misalignment, sensor faults, and other miscellaneous failures are failure categories presented. The data presented as a percentage share of total recorded failures is the representation of each type of failure, which made possible visual comparison of the contribution of each failure mechanism to the overall equipment unreliability.

The figure 2 indicates that wear had the highest percentage of failures with 27 % of all failures, next came leakage with 24 % and overheating with 19 %. Misalignment was a cause of failure of 15 % and sensor faults was 9 % and the rest 6 % were attributed to other minor causes. These findings reveal that component wear, hydraulic fluid leakage and thermal stress were the main cause of equipment failures. Hence, it is necessary to focus more on lubrication management, seal integrity check, and temperature control to minimize such reoccurring failure modes and enhance the overall rig reliability.

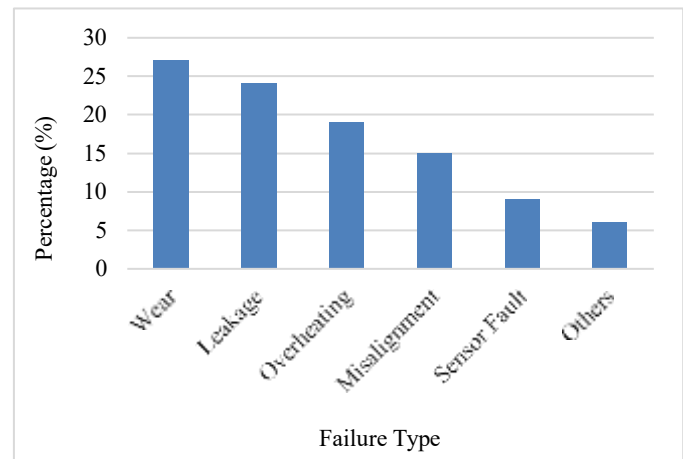


Figure 2: Percentage Distribution of Failure Types in Hydraulic Rotary Drilling Rigs

4.3 Reliability Performance Indicators

The Reliability Performance Indicators section describes the analysis of the reliability of the drilling rig subsystems based on the Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR). Findings indicated that structural, control and electrical systems were more reliable whereas hydraulic and mechanical ones failed more frequently. MTTR values also showed that electrical and hydraulic faults took the longest time to fix. These indicators were used to determine which subsystems were causing most of the downtime and where most of the maintenance efforts need to be directed.

Table 3: MTBF for Major Subsystems

Subsystem	MTBF (Hours)
Hydraulic	120
Mechanical	145
Electrical	170
Structural	210
Control System	195

Table 3 indicates the Mean Time Between Failure (MTBF) of the big subsystems of hydraulic rotary drilling rigs. The subsystems are hydraulic system, mechanical system, electrical system, structural system and control system. MTBF is given in units of operating hours and measures the average duration that a sub system runs before it fails. This table enables one to compare the performance of

reliability across various subsystems by showing the frequency of failure to be experienced in each of them.

Table 3 results indicate that the highest Mean Time Between Failures (MTBF) was experienced in the structural subsystem at 210 hours meaning that it was the least prone to failure when compared to other subsystems. This was succeeded by the control system that had a MTBF of 195 hours and electrical subsystem that had 170 hours, which portrays a relatively high reliability. The mechanical subsystem had a lower MTBF of 145 hours, that is the failure happened more frequently than in the subsystems mentioned above. Hydraulic subsystem was the least resistant to failures with the lowest value of MTBF at 120 hours and, therefore, the component most likely to fail in the drilling rig. All in all, the pattern of the MTBF shows that hydraulic and mechanical subsystems demanded the majority of maintenance care, and structural components were the most stable in the course of operation.

Table 4: MTTR for Major Subsystems

Subsystem	MTTR (Hours)
Hydraulic	5.8
Mechanical	4.6
Electrical	6.2
Structural	3.9
Control System	5.1

Table 4 shows the Mean Time to Repair (MTTR) of the most important subsystems of hydraulic rotary drilling rigs. The subsystems are the hydraulic, mechanical systems, electrical systems, structural systems and control systems. MTTR is measured in hours and is considered to be the average time per subsystem of the overall system that is needed to diagnose, repair and put the subsystem back to working condition after a failure has been experienced. This table can be used to compare maintenance work and downtime which is caused by various subsystems.

It has been revealed that the greatest MTTR was in the electrical subsystem at 6.2 hours, so that the time when electrical failures needed the most time to fix may have been because of the difficulty in diagnosis or a time delay in replacing components. Hydraulic subsystem (hydraulic subsystem) was next with a hydraulic time of 5.8 hours, which implied that hydraulic failures also translated to significant downtime. The control system was characterized by the average of 5.1 hours of the MTTR and 4.6 hours of the average mechanical subsystem time spent on repairing. The structural subsystem was the least with 3.9 hours of the MTTR which meant that it restored faster than the rest. In general, the MTTR pattern demonstrates that electrical and hydraulic failures were the most significant causes of prolonged downtime, and such areas should be better equipped in terms of troubleshooting and planning preventive maintenance as well as stocking of spares.

4.4 System Availability Analysis

The System Availability Analysis part discusses the frequency of each subsystem in the drilling rig that was in

operation prior to optimization of maintenance. Table 5 contains the availability percentages of the hydraulic, mechanical, electrical, structural and control systems, which indicate what percentage of time each of the subsystems was in operation. It was observed during the comparison that the structural and control systems had the highest available, and the hydraulic system was the lowest available, that is, it was the most contributory to downtime. The above findings reveal that hydraulic parts needed more maintenance care to enhance the overall performance and reliability of the drilling rig.

Table 5: Availability of Subsystems Before Optimization

Subsystem	Availability (%)
Hydraulic	95.4
Mechanical	96.9
Electrical	96.5
Structural	98.2
Control System	97.5

The findings reveal that the structural subsystem was the most available (98.2) i.e. it was the system that stayed the longest and then the control system (97.5) and the mechanical subsystem (96.9) followed. Electrical subsystem was also slightly less available at 96.5. The hydraulic subsystem had the lowest availability of 95.4, which implies that it was related to the greatest amount of downtime. Comprehensively, these results indicate that the weakest component of the system before maintenance optimization was hydraulic components, whereas structural components were the most stable, which implies that it is necessary to pay even greater attention to maintenance of the hydraulic subsystem.

4.5 Criticality Assessment Using FMEA

The Criticality Assessment Using FMEA section describes the way the most critical drilling rig failure modes were identified and rated with the help of Risk Priority Numbers (RPN). These failure modes, along with the subsystems and RPN values are provided in Table 6 with which one can compare which failure mode presents the greatest operational and safety risk. The findings indicated that hydraulic failures especially seal failure and hose burst had the highest scores in terms of RPN followed by overheating of the motor, and wear of gears and sensor faults were relatively minor. On the whole, it can be seen that the greatest threat of reliability is identified in hydraulic components, and special attention to their maintenance is necessary.

Table 6: Top-Ranked Failure Modes by RPN

Failure Mode	Subsystem	RPN
Seal Failure (Leakage)	Hydraulic	324
Hose Burst	Hydraulic	308
Motor Overheating	Electrical	286
Gear Wear	Mechanical	271
Sensor Malfunction	Control	248

The hydraulic components represented the most significant reliability risk with seal failure in the hydraulic subsystem (324) followed by hydraulic hose burst (308). The electrical system (286) also had a significant failure issue in

the form of motor overheating and the mechanical system (271) had a major failure issue in the form of gear wear. The control system sensor malfunctioned had the lowest RPN (248) but that still represented a significant risk. On the whole, the findings indicate clearly that hydraulic failures are the most severe and should be given the most important maintenance.

5. CONCLUSION

The research has revealed that failure behaviour at the subsystem level is strongly related to the reliability and maintenance performance of hydraulic rotary drilling rigs, and hydraulic and mechanical components are the most prevalent in the proportion of failures, downtime, and maintenance burden. The assessment of reliability based on the parameters of MTBF and the MTTR showed that hydraulic and electrical failures were more frequent as well as took a higher amount of time to repair, which decreased the availability of the system in comparison to other subsystems. FMEA also identified that hydraulic-related failures like seal leakage, hose burst and others were the most dangerous at the operation level, which is why special attention to reliability was needed in these directions. On the basis of these findings, the research indicated that Reliability-Centered Maintenance and condition-based strategies should be adopted in providing priority on vital components, optimization of inspection intervals and minimization of unplanned breakdowns. Comprehensively, the findings validated the idea that data-driven reliability testing has a potential to exponentially improve rig availability, operational security as well as cost-efficiency of geotechnical drilling processes.

REFERENCES

- [1] S. Akhtar, S. M. Al-Otaibi, W. S. Algaraawi, N. M. Alsanabani, K. S. Al-Gahtani, and A. Fnais, "Assessment of the lifespan of a site drilling machine in Saudi Arabia and India using correspondence analysis," *Sustainability*, vol. 17, no. 9, p. 3865, Apr. 2025, doi: 10.3390/su17093865
- [2] S.-H. Chen, "Operation and maintenance of hydraulic structures," in *Hydraulic Structures - Theory and Applications*, Intech Open, 2020. doi: 10.5772/intechopen.91949.
- [3] A. A. I. Elrayah, "Enhancing drilling operations: prioritizing wellbore integrity, formation preservation, and effective mud waste control (case study)," *Journal of Engineering and Applied Science*, vol. 71, no. 1, Apr. 2024, doi: 10.1186/s44147-024-00383-0
- [4] P. Flegner, J. Kačur, G. Wittenberger, M. Durdán, and M. Laciak, "Identification and Evaluation of Vibration Sources from Experiments on Laboratory Drilling Equipment," *Machines*, vol. 13, no. 12, p. 1076, Nov. 2025, doi: 10.3390/machines13121076.
- [5] M. E. Hossain and A. A. Al-Majed, *Fundamentals of Sustainable Drilling Engineering*. John Wiley & Sons 2015.
- [6] Kattar, M., "Use of machine learning to optimize drilling equipment performance and life cycle focus: predictive maintenance" M.S. thesis, Dept. Petroleum and Mining Engineering, Polytechnic University of Turin, Italy, 2022
- [7] A. Khan, Y. Li, M. Shoaib, U. Sajjad, and F. Rui, "Utilizing Machine Learning and Digital Twin Technology for Rock Parameter Estimation from Drilling Data," *Journal of Intelligent Construction*, vol. 3, no. 2, pp. 1–23, Apr. 2025, doi: 10.26599/jic.2025.9180088.
- [8] M. Krechowicz, W. Gierulski, S. Loneragan, and H. Kruse, "Human and Equipment Risk Factors Evaluation in Horizontal Directional Drilling Technology Using Failure Mode and Effect Analysis" vol. 12, no. 2, pp. 45-56, Jun. 2021, doi: 10.24425/mper.2021.137677
- [9] P. F. Li, X. F. Wang, Z. Yang, Z. J. Zhang, F. Yang, H. P. Tang, B. B. Zhang, "Advancing drilling parameter reliability: A data-driven comparison of MWD and DPM for stratigraphic identification," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 18, no. 5, pp. 4094–4107, Jul. 2025, doi: 10.1016/j.jrmge.2025.06.005.
- [10] S. Mukhongo, J. Wakiru, P. N. Muchiri, and S. N. Mburu, "Risk-based Maintenance Decision Support for Geothermal Drilling Rigs: A Case Study for KenGen Drilling Rigs," in *Proceedings World Geothermal Congress 2020*, Reykjavik, Iceland, Apr. 2020
- [11] R. O. Muminov, D. A. Kuziev, V. V. Zotov, and E. S. Sazankova, "Performability of electro-hydro-mechanical rotary head of drill rig in open pit mining: A case-study," *Eurasian Mining*, pp. 76–80, Jun. 2022, doi: 10.17580/em.2022.01.16.
- [12] P. Pande, J. Giri, J. Raut, H. Sabeur, R. Bhagat, and M. Azizi, "Real-time prediction of soil bearing capacity in clayey soils using drilling parameters and statistical modeling," *Scientific Reports*, vol. 15, no. 1, p. 37770, Oct. 2025, doi: 10.1038/s41598-025-19767-0.
- [13] B. S. Prasad, V. M. S. R. Murthy, and S. R. Naik, "Challenges in Drill Equipment Selection vis-à-vis Underground Excavations—A Methodology," in *Proceedings of Geotechnical Challenges in Mining, Tunneling and Underground Infrastructure*, 2022, pp. 167–182, doi: 10.1007/978-981-16-9770-8_9
- [14] M. J. Rahimdel, M. Ataei, and R. Khalokakaiei, "Reliability analysis and maintenance scheduling of the electrical system of rotary drilling machines," in *Current Trends in Reliability, Availability, Maintainability and Safety: An Industry Perspective*, Lulea, Sweden: Springer International Publishing, 2016, pp. 623–632, doi: 10.1007/978-3-319-23597-4_45.
- [15] P. Reiffsteck, J. Benoît, C. Bourdeau, and G. Desanneaux, "Enhancing geotechnical investigations using drilling parameters," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 144, no. 3, Jan. 2018, doi: 10.1061/(asce)gt.1943-5606.0001836.
- [16] M. Rodgers, M. McVay, D. Horhota, J. Hernando, and J. Paris, "Measuring while drilling in Florida limestone for

geotechnical site investigation,” *Canadian Geotechnical Journal*, vol. 57, no. 11, pp. 1733–1744, Jan. 2020, doi: 10.1139/cgj-2019-0094.

[17] Q. Shen, Y. Wang, R. Cao, and Y. Liu, “Efficiency evaluation of a percussive drill rig using rate-energy ratio based on rock drilling tests,” *Journal of Petroleum Science and Engineering*, vol. 217, p. 110873, Jul. 2022, doi: 10.1016/j.petrol.2022.110873.

[18] R. Sundaram, S. Gupta, and S. Gupta, "Advances in the State-of-Practice of Geotechnical Investigation in India," *Indian Geotechnical Journal*, vol. 54, pp. 109–133, 2023, doi: 10.1007/s40098-023-00750-3.

[19] L. Wang, W. Sun, Y. Long, and X. Yang, “Reliability-Based performance optimization of tunnel boring machine considering geological uncertainties,” *IEEE Access*, vol. 6, pp. 19086–19098, Jan. 2018, doi: 10.1109/access.2018.2821190.

[20] J. Wodecki *et al.*, “Process monitoring in Heavy Duty Drilling Rigs—Data acquisition system and cycle identification algorithms,” *Energies*, vol. 13, no. 24, p. 6748, Dec. 2020, doi: 10.3390/en13246748.