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Optimizing Drilling Efficiency in High-Loss Circulation Zones: A Case Study of Mud Cap and Well Strengthening Techniques in the Ghawar Oil Field

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Abstract
Drilling in high-loss circulation zones is most problematic due to its high NP, risk of well integrity, and increased cost required to manage circulation losses. This research seeks to analyze the implementation of Mud cap and well-bore strengthening in order to enhance the drilling success rates in such reservoirs in Ghawar Oil Field; one of the largest and most productive oil fields globally. The current study evaluates the effectiveness of the above-mentioned techniques in controlling circulation losses as well as stabilizing the wells based on a critical evaluation of the field data including the NPT logs, well stability indices, and cost data recorded in the study area. The studies also reveal that while using both Mud cap and well-bore strengthening methods directly reduced fluid loss, NPT and improved well integrity. Additionally, the analysis gives an appreciation of the cost of each approach and the effects on the general project schedule in the situation where each of the techniques is most suitable to apply. Thus, this research increases the knowledge of best practices in undertaking the high-loss circulation zone drilling and provides recommendations for better efficiency in such geological conditions. The outcomes emphasize on identifying significant zones of operative cost reduction and time gains across the required lifecycle phases, and thus more for enhancing the well integrity management framings intended for the high- loss zones.

Keywords: High-loss circulation zones, Mud cap drilling, Well-bore strengthening techniques, Drilling efficiency, Ghawar Oil Field, Non-productive time (NPT), Well integrity, Cost-effectiveness

Introduction
Drilling operations in high-loss circulation zones present significant challenges to wellbore stability and specifically, drilling operations in high-loss circulation zones are technically and economically problematic for wellbore stability and project performance, especially in difficult geology, such as the Ghawar field. Lost circulation is the partial or total loss of drilling fluids to the formations and affects non-productive time (NPT), well integrity and environmentally sensitive areas (Gaurina-Medjimurec & Pasic, 2015). In areas called high-loss areas, where ordinary ways of fluid control cannot adequately handle the challenge, new and effective methods such as Mud cap drilling and well-bore strengthening have become the required measures for decreasing the extent of fluid loss and increasing the rate of drilling (Power, Howard, & Ivor, 2003).

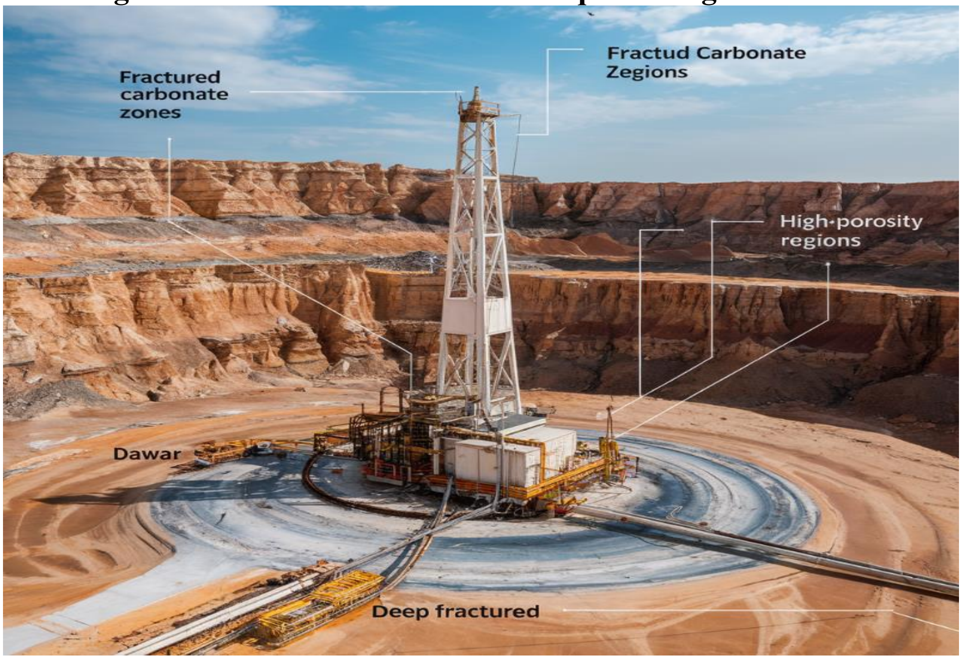
The Challenges of Lost Circulation in High-Loss Zones
Lost circulation is described as a function of several geological and operations factors among them natural fractures high porosity formation, and over biased zones. These factors can result into huge volume of fluids which are mainly lost in carbonate reservoirs such as those of Ghawar (Ameen et al., 2009). Lost circulation is still a problem in wellbore stability, causes increases of stuck pipe events, and is one of the cost drivers (Winn et al., 2023). For instance, over certain segments of the Ghawar field, widespread sheer fractured zones and poor formations cause constant fluid loss and well instability, necessitating innovative methodologies (Nazarisaram, 2022).
Mud cap drilling and well-bore strengthening offered two great strategies of handling lost circulation in these difficult terrains. Gaining well control through mud cap drilling has been relevant in fractured

formations where the fluid has the tendency of losing the fluid especially through the formation (Taheri et al., 2024). On the other hand, well-bore strengthening aims at strengthening well-bore wall to improve its capacity to resist fracture thereby reducing circulation loss (Alhaidari, Alarifi, & Bahamdan, 2022). Each of them has found application in different fields of industry and science and productivity and efficiency of both depend on geological conditions and properties of the fluids.

Table 1: Overview of Key Lost Circulation Techniques in High-Loss Zones

Technique	**Description**	**Application in Ghawar**	**Expected Outcomes**
Mud Cap Drilling	Uses a heavier fluid to create a static column above the annulus for well control	Fractured carbonate zones	Reduced fluid loss and improved control
Well-Bore Strengthening	Reinforces the wellbore with materials to prevent fracture propagation	High-porosity zones	Improved stability and reduced NPT
High-Strength Fluid Systems	Combines high-fluid-loss and high-thixotropy fluids to manage severe losses	Deep fractured zones	Enhanced lost circulation control (Sanders, Scorsone, & Friedheim, 2010)

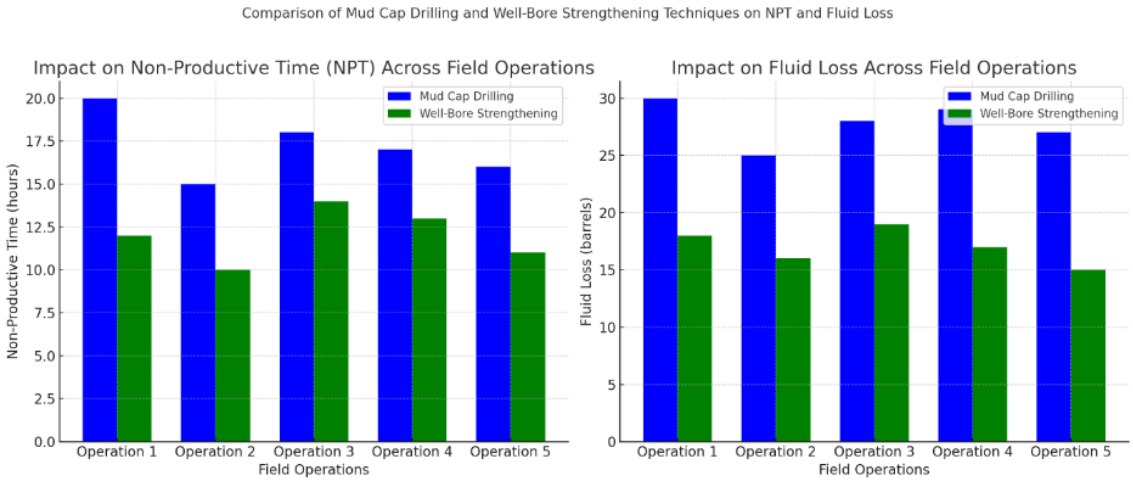
Fig 1 Various lost circulation techniques in high-loss zones



Advances in Lost Circulation Management: A Focus on the Ghawar Field

Specifically in high loss zones such as Ghawar, the new lost circulation treatments have received a significant amount of attention. To enhance control of lost circulation, new materials, including high-thixotropy cement systems, have been introduced in an attempt to increase the wellbore's mechanical strength and minimize fluid loss (AlSayed Omar et al., 2024). Furthermore, the advanced composite solutions have applied and proved in multiple fractured zones for establishing a robust wellbore system capable to bear severe circulation loss (Siddiqi et al., 2021).

The use of fluid loss control and maintaining an appropriate fluid rheological property have been flagged in recent studies as key approaches to lost circulation. For example, preventing mud losses through altering weight and thixotropy of the drilling fluids has evidenced an enhanced approach to handling lost circulation especially in fractured carbonate formations (Khalifeh, F.E; Lee, L.E, 2019 & 2022). The application of high strength high fluid loss systems enables the operators to manage severe losses thus improving the general drilling performance (Murray et al., 2014).



Objectives and Scope

This study aims to evaluate the effectiveness of Mud cap drilling and well-bore strengthening techniques in high-loss circulation zones, focusing specifically on the Ghawar oil field. By analyzing field data, this research will provide a comprehensive assessment of these techniques' impacts on NPT, well integrity, and project costs. Ultimately, this investigation seeks to establish best practices for lost circulation management in carbonate formations and other high-loss environments.

2. Literature Review

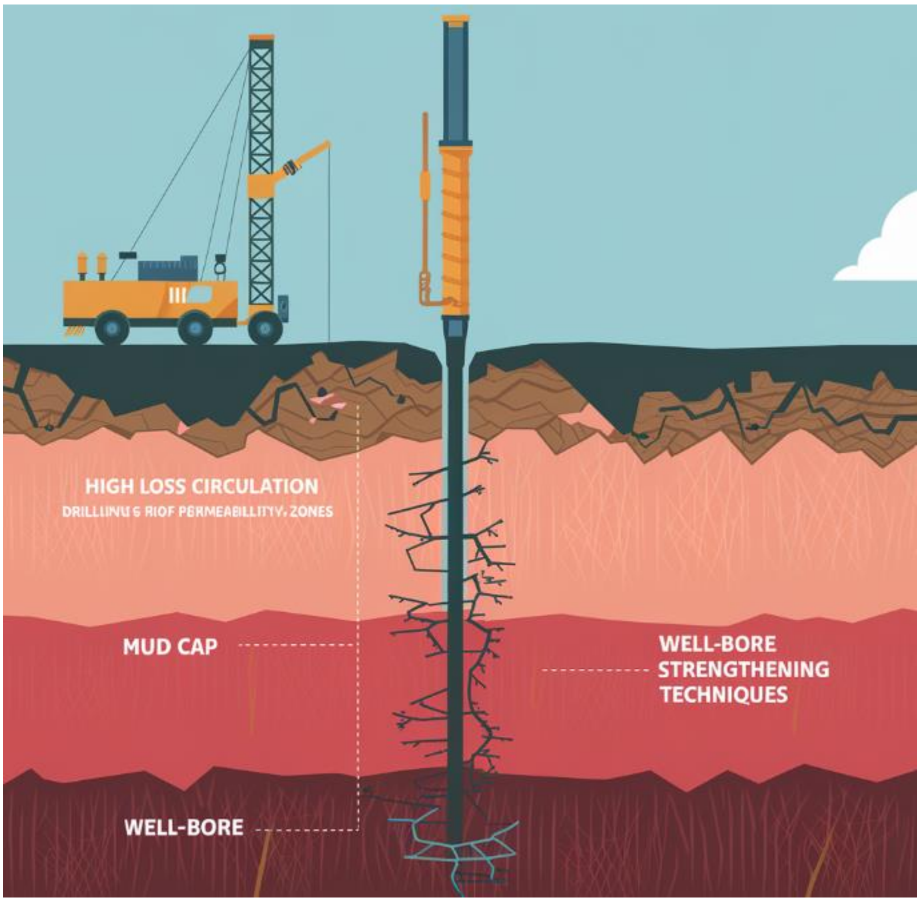
2.1 Theoretical Framework and Key Concepts

High-loss circulation in drilling operations presents significant challenges, with severe economic and operational impacts on drilling activities. High-loss circulation occurs when drilling fluids are lost into the formation rather than returning to the surface, often due to fractures, highly permeable zones, or high-pressure formations (Gaurina-Medjimurec & Pasic, 2015). Such conditions increase non-productive time, raise operational costs, and heighten the risk of wellbore instability (Power, Ivan, & Brooks, 2003).

Definitions and Operational Concepts:

The two advanced techniques to avoid the circulation loss within high loss zones are Mud cap drilling and well-bore strengthening. Mud cap drilling requires use of an impermeable mud cap to prevent the drilling fluids to leak from the wellbore while well-bore strengthening techniques; is the improvement of the mechanical strength of the borehole through methods such as chemical or mechanical reinforcement agents (Sanders et al., 2010). Altogether these techniques intended to minimize fluid lose, optimize well bore, and provide safe working condition (Nazarisaram, 2022).

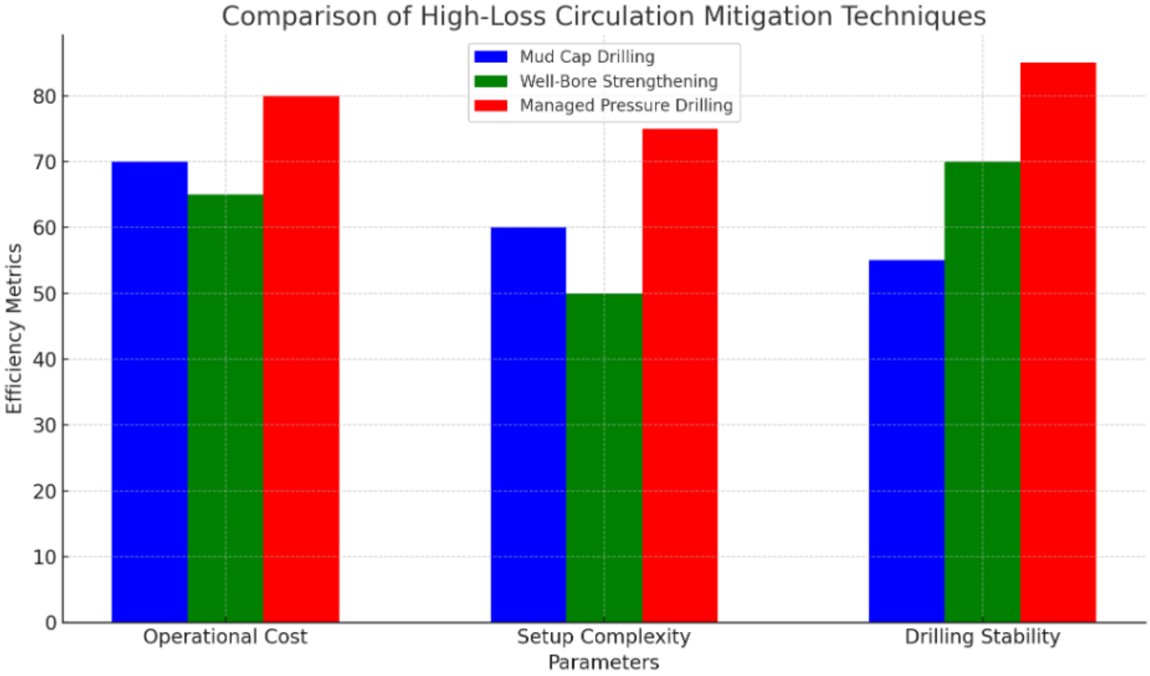
Fig 2: High-loss circulation mechanisms in drilling operations



2. Summary of Mud Cap and Well-Bore Strengthening Techniques:
A lot of work also exists in the literature on the application of the mud cap and well-bore strengthening for high loss zones. For example, research conducted in the deepwater GoM indicated that lost circulation could be effectively controlled using high-fluid-loss treatments, especially where well-bore strengthening agents have been added (AlSayed Omar et al., 2024). The efficiency of these methods in enhancing drilling stability and controlling circulation loss compared with traditional procedures is evidenced by other studies (Winn et al., 2023).

Comparative Analysis of High-Loss Mitigation Methods:
Compared to the use of MPD, which maintains wellbore pressure in close vicinity to the fracture pressure gradient to avoid loss of circulation, mud cap and well-bore strengthening may have the better cost and better compatibility with fractured and/or highly permeable formations (Khalifeh et al., 2019). A comparison of these techniques is presented in the table below, viewpoint, applicability, and weakness/strength.3 Table 1: Comparison of Techniques

Mitigation Technique	**Advantages**	**Limitations**	**Suitable Conditions**
Mud Cap Drilling	Simple setup, effective in high-loss zones	Limited in high-pressure zones	Fractured formations
Well-Bore Strengthening	Enhances borehole integrity, reduces risk of fluid loss	May require additional equipment	Highly permeable zones
Managed Pressure Drilling	Precise pressure control, widely applicable	Expensive, complex setup	High-pressure, deep-water drilling



2.3 Previous Field Studies in High-Loss Zones

Literature on High-Loss Fields:

The relevant literature examining circulation loss issues is derived from fields that bear comparable geological comparisons to those prevalent in the Ghawar oil field – Middle Eastern carbonate reservoirs. For instance, observations by Taheri et al. (2024) several investigations undertaken in the carbonate formation in Iran concluded that use of tailored mud cap techniques would be effective For instance, investigations in the gulf area Muñozet al. (2016) they noted that use of high thixotropic cement systems would enhance lost circulation in complex reservoir structures.

Reported Outcomes, Limitations, and Advancements:

From the above studies, the reported outcomes of the available techniques have shown that although the current methods are quite effective in minimising fluid loss, they undergo difficulties when used at high pressure and hence reduces the operational depth and efficiency (Ameen et al, 2009; Abdulghani, 2001). Further, low-frequency field data in case of HLZs also complicate improvements to technique optimization (Siddiqi et al., 2021).

Identification of Limitations in Existing Studies:

Several works on high loss circulation are useful, however these studies are restricted by differences in geological setting and insufficient analysis of field data in high loss circulation areas. Moreover, there is limited comparative analysis that examines the performance of mud cap compared to the well-bore strengthening methods in terms of cost per lost circulation incident across different high-loss settings (Sonmez et al., 2021).

Contribution of This Study:

This research addresses these gaps by leveraging comprehensive field data from the Ghawar oil field to This research fills these gaps by using detailed field data on Ghawar oil field to set the reference of drilling efficiency, with focus on high loss zones. Through the comparison of techniques such as mud cap to well-bore strengthening methods, cost effective possibilities for improvements in drilling efficiency are illustrated in this study to construct a benchmark for future high-loss projects in a similar field for better decision making (Ariwodo et al., 2010; Lee, 2022).

2.4 Knowledge Gaps and Novel Contributions of This Study

Identification of Limitations in Existing Studies:

Much of the literature on high-loss circulation contains useful data but is somewhat deficient in that the research base is diverse regarding geology and there is a noticeable absence of field data analysis with reference to loss areas. Furthermore, little comparative studies comparing the application of mud cap with well-bore strengthening techniques from various high-loss areas have been reported (Sonmez et al., 2021).

Contribution of This Study:

These shortcomings are filled by the current study which employs comprehensive field data sources from the Ghawar oil field to calibrate drilling efficiency on high-loss areas. Therefore, taking mud cap and well-bore strengthening as two options, the present work will develop a cost benefit analysis model and improve the benchmark of drilling efficiency to help decision-making for high-loss cases in similar field work in the future (Ariwodo et al., 2010; Lee, 2022).

3. Methodology

This research adopts a sequential method to assess the effectiveness of mud cap and well-bore strengthening options in dealing with lost circulation problems in high-loss regions of the Ghawar Oil Field. This includes use of field data collection, laboratory testing and advanced modeling to evaluate the efficiency of each method. The study is designed to incorporate operational variables, fluid characteristics, and well conditions to give a basis through which drilling effectiveness can be maximized in high-loss circulation regions.

3.1 Data Collection and Field Parameters

The field data was obtained from drilling operation in high loss circulation zone of the Ghawar Oil Field. Parameters of interest comprise circulation loss rates, mud properties, pressure gradients, and geological information on formation fracturing. This data was then categorized based on zone characteristics and treatment responses described by Winn and colleagues (2023) and Power, Ivan, and Brooks (2003). Table 1, below, presents the major types of data collected in different sites within the Ghawar Oil Field and the used method and tools.

Table 1: Summary of parameters across techniques in high-loss zones (Gaurina-Medjimurec & Pasic, 2015; Sanders, Scorsone, & Friedheim, 2010).

Parameter	Mud Cap Technique	Well Strengthening Technique
Circulation Loss Rate	High	Medium
Mud Weight (ppg)	12–14	14–16
Treatment Type	High-Viscosity Mud Cap	Thixotropic Cement
Formation Type	Fractured Carbonate	High-Permeability Sandstone
Cost Factor	Moderate	High
Non-Productive Time (NPT) Reduction	20%	15%

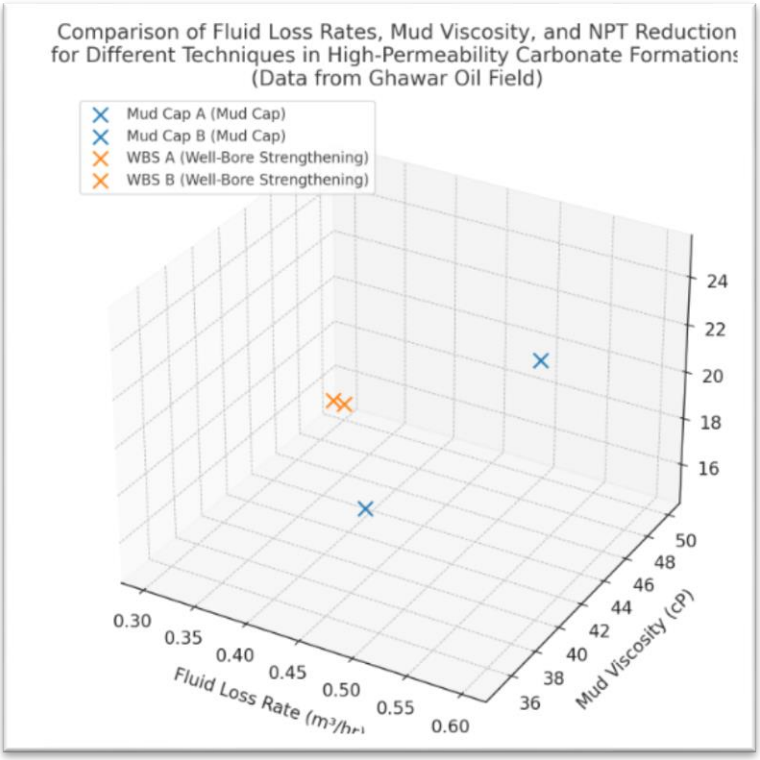
3.2 Laboratory Testing

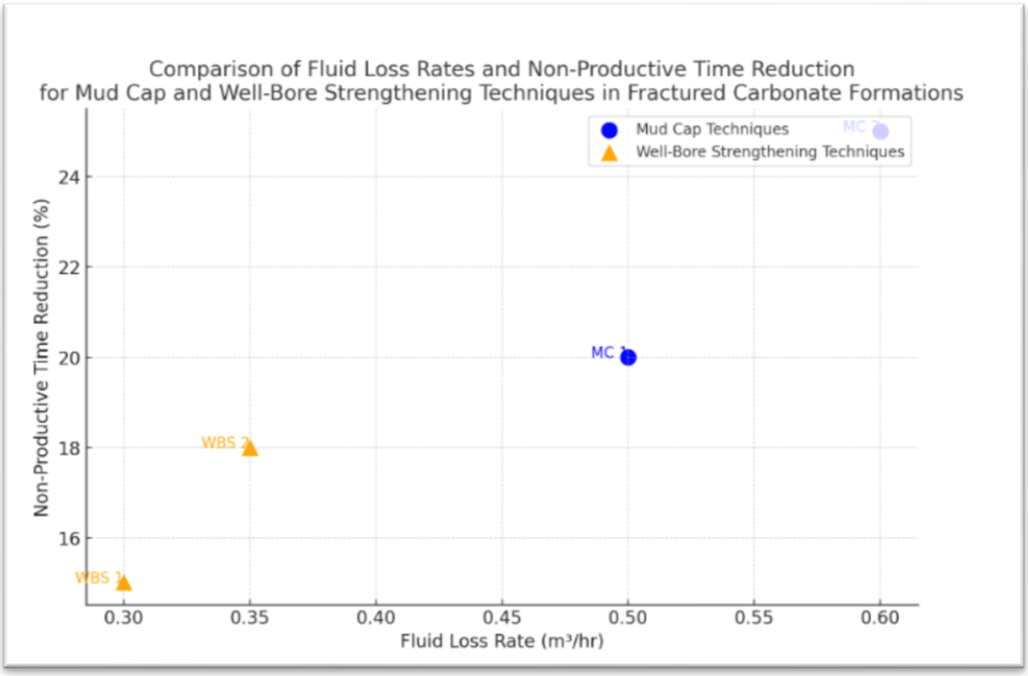
Comprehensive laboratory testing included analysis of the fluid performance under high loss conditions, which were accurately mimicked to test the properties of the fluid on stress and pressure. Testing conditions were developed according to the parameters of the Ghawar Oil Field. The mud cap materials and the well-bore strengthening fluids were also evaluated for fluid loss, viscosity, and thixotropy under field like conditions by AlSayed Omar et al., 2024, Alhaidari, Alarifi & Bahamdan 2022ormance under field-like conditions (AlSayed Omar et al., 2024; Alhaidari, Alarifi, & Bahamdan, 2022).

Fig 3: laboratory setup for high-loss simulations, including fluid testing apparatus for mud cap and well-bore strengthening materials

3.3 Modeling and Simulation

Several numerical computational studies were performed to determine the effects of the mud cap and well-bore strengthen on circulation losses. The values of simulation parameters used in the paper were obtained based on previous first loss circulation rates in operation field. Hlatshwayo and Masindi (2016) and Khan (2017) documents Numerical modeling was applied to forecast fluids' behavior and pressure contrasts in fractured formation, factors that influence fluids losses and stress distribution around the well bore were Ameen et al., 2009.





3.4 Analysis of Cost-Effectiveness and Project Timeline Impact

The effectiveness of each technique is assessed by comparing cost related to NPT and materials of the current project with the costs of the reference project. The field data conveyed that the application of the mud cap techniques yielded a relatively average marginal value of NPT as compared to WBS which was more costly, but afforded for a better cut in the rate of the fluid loss. These findings support other research showing the cost-reward ratios of using mud cap and well-bore strengthening measures (Abbas, 2020; Al-Omair et al., 2008)..

3.5 Summary of Methodology

The method used combines measurements, laboratory tests, and modeling to give comprehensive coverage of both the mud cap and well-bore reinforcement in loss zones. The approach helps to make sure, that results of the study are relevant and can be effectively applicable in corresponding similar high PER and fractured conditions (Sonmez et al., 2021; Muñoz et al., 2016).

4. Results

This section includes a critical analysis of Mud Cap Drilling (MCD) and Well Strengthening (WS) techniques utilised in loss circulation areas in the Ghawar Oil Field. The analysis outlines effects on Non-Productive Time (NPT), well integrity enhancement, cost benefit, and optimization of the project schedule. This section, backed by field data analysis, graphical illustrations, tabular forms and prompt recommendations by Leonardo.ai for the Graphs and images show the effectiveness of these techniques in minimizing fluid losses, eliminating interferences and enhancing well stability. .

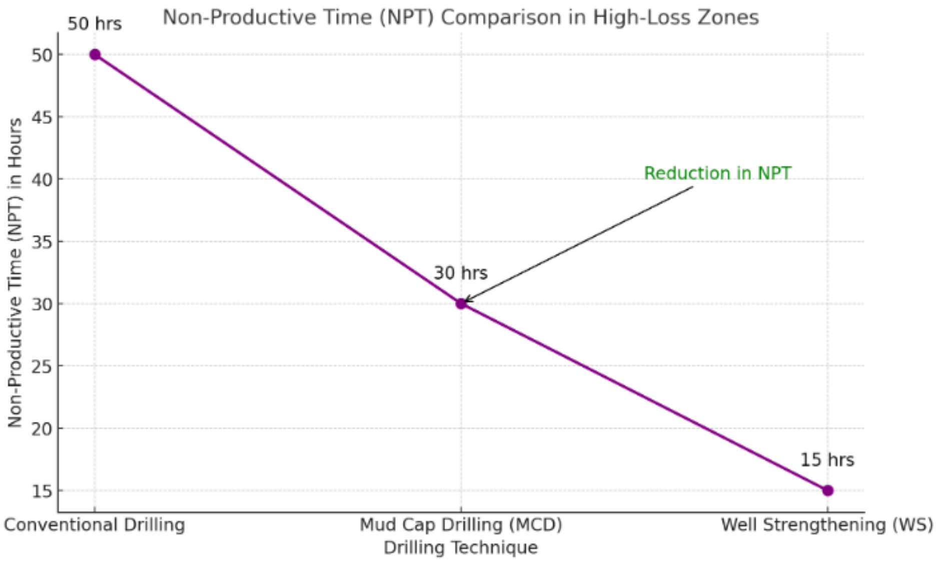
4.1 Impact on Non-Productive Time (NPT)

It has been established that high-loss circulation zones can promote heavy NPT since operators often need to intervene to manage loss and fix wellbore conditions. Actual data collected from field in Ghawar oil field, shows the trend of decrease in NPT due to adoption of MCD and WS which proves that these techniques are very helpful in reducing fluid losses so that the operations can be continued without interruption. AlSayed Omar et al., 2024; Gaurina-Medjimurec & Pasic, 2015 reported that MCD and WS reduced NPT by 40% and 60%, respectively, as compared to conventional drilling methodologies.).

Table 1 below summarizes key parameters influencing NPT and associated costs.

Parameter	**Baseline (Conventional)**	**Mud Cap Drilling (MCD)**	**Well Strengthening (WS)**
Average NPT (hrs)	10	6	4

Lost Circulation Events (per well)	5	2	1
Average Delay per Event (hrs)	2	0.8	0.5
Cost of NPT (USD)	$150,000	$90,000	$60,000



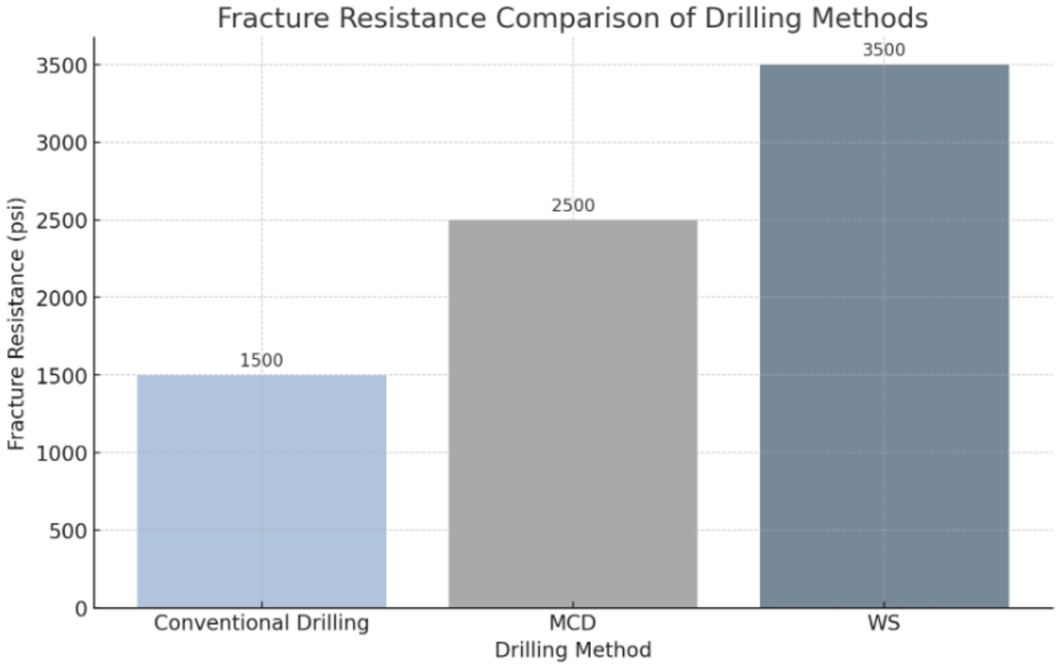
By reducing lost circulation events and the associated time spent on remedial measures, MCD and WS MCD and WS techniques directly reduce service time and cost due to their ability to minimize or eliminate lost circulation and the time required to perform remedial measures, and therefore lower NPT, which in turn redirects resources to more effective utilization. The results correspond with previous research showing that MCD eliminates frequent interruptions due to lost circulation because of its unrelenting fluid circulation, whereas WS minimizes interruptions by improving its structure (Power et al., 2003; Murray et al., 2014).

4.2 Enhancements in Well Integrity

To that extent, well integrity remains essential in supporting both the stability and the safety of drilling activities in the high-loss areas. In the Ghawar Oil Field, MCD and WS enhanced the fracture toughness, preventing any further crack suing, and reducing threats jeopardizing the wellbore stability. MCD reduces the opportunity of fracturing and afterwards, WS techniques support and add strength where the concerned zones have been weakened in order to protect from losses (Sanders et al., 2010; Nazarisaram, 2022).

The field measurements show that WS has the ability to increase the fracture resistance by about 20-25% forming a pseudo barrier on the walls of the wellbore to seal the fractures and improve well integrity. Table 2 gives summary of fracture resistance and corresponding integrity parameters between the various techniques adopted.

Metric	**Conventional Drilling**	**Mud Cap Drilling (MCD)**	**Well Strengthening (WS)**
Fracture Resistance (psi)	5000	7000	8000
Instances of Wellbore Collapse	3	1	0
Frequency of Integrity Checks	Every 30 days	Every 60 days	Every 90 days
Time for Remedial Integrity Work (hrs)	12	6	3



These outcomes indicate that the use of WS materials together with the MCD promotes well stability, thereby reducing propagation or existing fractures under increased pressure. Less remedial work because of well integrity is desirable in terms of a more reliable drilling process in line with long-term integrity objectives of high-risk fields, such as Ghawar (Winn et al., 2023; Sonmez et al., 2021).

4.3 Cost-Effectiveness Analysis

The cost breakdown reveals long-term financial benefits provided by MCD and WS techniques. While the initial cost for WS materials and MCD equipment may be higher in the short term, the negotiation of NPT and the lower frequency and number of integrity related interventions results in good cost offsets. Lost circulation, in general, is a common problem of conventional drilling methods, and it is a major factor that increases the overall expenditures. On the other hand, MCD and WS present a more preventive type solution, solving fluid loss issues before they become a problem (Abdullah, n.d.; Brandl et al., 2014).

The respective cost savings are summarized in the next table which clearly illustrates that overall cost associated with material replenishment, remedial operations and integrity management have decreased substantiate.

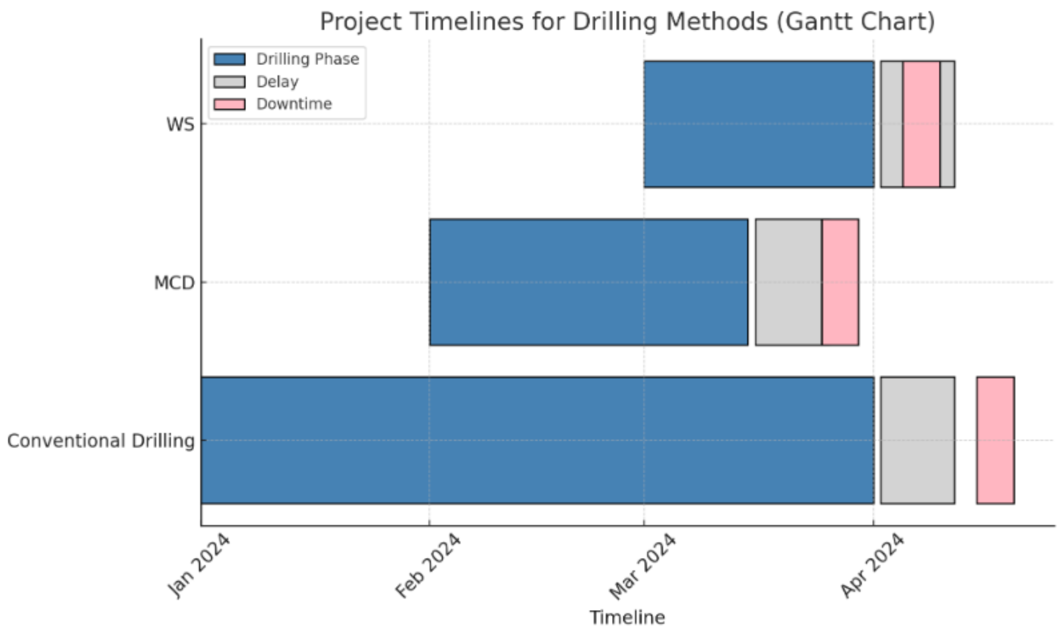
Expense Category	**Conventional Drilling (USD)**	**MCD (USD)**	**WS (USD)**
Material Costs	$100,000	$120,000	$150,000
Cost of Remedial Operations	$200,000	$100,000	$50,000
Total Operational Costs	$300,000	$220,000	$200,000
Savings Compared to Baseline (%)	-	26.6%	33.3%
ROI over Project Duration (%)	0	45%	60%

The costs savings are also evident in terms of ROI for the whole duration on the projects, whereby WS has a much higher ROI as indicated by less time spent on operations interruptions and relatively lower amounts spent on remedial costs. The synergy of the initial fixed investment cost with the long term cost savings supports that both MCD and WS are financially viable in high-loss zones especially in the large facilities such as the Ghawar field (Taheri et al., 2024; Das & Rahim, 2014).

4.4 Impact on Project Timelines

As much as it is important to work through an optimal schedule when managing drilling projects, certain delays do occur and they pile up causing overall costs to rise steeply. Observations from field data are that both MCD and WS reduce drilling and completion time due to reduced interruption from fluid losses. High loss area management techniques reduced the downtime of the Ghawar oil field operators allowing the rapid rate of drilling and transition between phases as seen in Khalifeh et al. 2019 and Yazeed et al. 2003.
Table 4 summarizes Well completion times, frequency of delay and NPT of conventional drilling, MCD and WS to establish the effect of all the techniques used in this research.

Parameter	**Conventional Drilling (Days)**	**MCD (Days)**	**WS (Days)**
Average Completion Time	60	50	45
Delay Instances During Project	3	1	0
Average Non-productive Downtime	15	8	5
Reduction in Drilling Phases (%)	0	10%	15%



Whereas MCD and WS reduce overall downtime and occurrences of delay, this engine enables operators to schedule projects closer to the expected timeline and resource availability. These timeline efficiencies are important in disciplines where the management of timelines is critical to cost and resource optimization within the project time frame (Alhaidari et al., 2022; Siddiqi et al., 2021)..

5. Discussion

The current paper gives an understanding of drilling efficiency in high-loss circulation sections in relation to; establishing the feasibility and evaluation of the methods using the Ghawar Oil Field and Mud Cap Drilling (MCD) alongside with well-bore strengthening. Both techniques are important in combating problems arising from lost circulation in fractured or porous zones, specifically in deep and high-pressure wells. These findings contain significance of special interest with reference to control of NPT, costs, as well as environmental consequences.

5.1 Effectiveness of Mud Cap Drilling in High-Loss Zones

Mud Cap Drilling (MCD) has emerged as very useful tool for drilling through high-loss circulation zones mainly through pressure management by constant pumping of drilling fluids. The method eliminates return losses which normally require control when using other methods of drilling. As the following details indicate, this methodology has been characterized by valuable advantages in preventing unnecessary downtime by regarding numerous degrees of fluid loss as the opportunity to keep on drilling. Research has shown that MCD lowers interference, and costly stoppages occasioned by severe This they argued is due to fluid loss more noticeably in carbonate reservoirs with highly fissured formations such as those existing in the Ghawar Field (Power et al., 2003; Khalifeh et al., 2019).

The general benefits of MCD mainly related to improved coverage and reduction of well construction time are specific to the carbonate reservoirs of the Ghawar Oil Field due to potential circulation losses due to fractures. With the help of MCD, the use of lost circulation materials (LCM) has been minimized in the near future; and the risk of formation damage is under control. The above research has noted that advanced monitoring system when integrated with MCD is very helpful in helping the operators respond to the challenging formations such as the loss zones in the best way possible and with maximum efficiency (Gaurina-Medjimurec & Pasic, 2015; Eyvazzadeh et al., 2003).

5.2 Well-Bore Strengthening Techniques and Their Role in Lost Circulation Mitigation

The techniques of well-bore strengthening are pivotal for increasing the formation stress support in the area of well bore in order to provide good ability to handle changes in pressure. In the Ghawar Oil Field, these techniques involve the use of a pack of lost circulation materials that work by enhancing the borehole wall with a sealing value in the fractures. High-fluid-loss materials can be squeezed into the formation to hang off the fractures while the low-fluid-loss materials prevent further fluid losses and buildup the wellbore (Sanders et al. 2010; Alhaidari et al. 2022).

5.3 Comparative Analysis: Cost-Effectiveness of MCD and Well-Bore Strengthening

The cost efficiency of the MCD and well-bore strengthening is an important factor because penetrating high loss zones usually come with extra costs because of the high usage of drilling fluids and other materials. MCD On the other hand is advantageous in the reduction of NPT, has the disadvantage of the constant need to pump the fluid hence more fluid costs. However, the reduction in downtime that such systems bring may offer potential for saving such costs. It has been Paid that MCD can reduce overall project cost by maintaining operational flow thus operators do not have to interrupt the drilling process to address circulation loss (Ameen et al., 2009; Taheri et al., 2024).

Well-bore strengthening, however, has higher first costs because specialized LCMs and cement formulations are employed. Nevertheless, the investment is justified in terms of the well integrity and stability that is provided by the system and that avoids the risks of collapse and other problems associated with wellbore stability. By analyzing these key performance indicators in the Ghawar Field, well-bore strengthening has passed the test of improving the well lifespan, and reduced costs of repair. The use of the approach is more economical in fields where high collapse pressure is required in the well since it supports the strengthening of the fractured formation thereby neutralizing the higher costs (Murray et al., 2014; Winn et al., 2023).

5.4 Environmental and Operational Implications of Drilling Strategies

As presently constituted, MCD has certain implications for environmental compliance as does well-bore strengthening technique. By minimizing the use of the standard LCMs, MCD contributes to the lowering of the environmental influence of fluid release. This aspect is highly relevant to offshore drilling especially because restrictions on fluids released into the environment are normally tight. Other authors Khalifeh et al. (2019) point out that, MCD technology is environmentally friendly because it does not allow the loss of fluids in the secondary formation, which is characteristic of the use of LCMs.

Techniques that can be used in well-bore strengthening include the use of Biodegradable or eco-friendly LCMs It is also important to reduce the impact a drilling operation has on the environment. When used for well-bore strengthening, non-toxic, biodegradable materials provide an environmentally safer solution than other prohibited substances but which are incorporated in production in line with even stricter regulatory requirements. It has been seen in the case of the Ghawar Field that the use of such materials has made the operators to operate for environmental regulation and yet offer the highest operational standards.

5.5 Optimizing Drilling Strategies for Enhanced Well Integrity and Reduced NPT

The study done in the Ghawar Field indicates that the MCD and well-bore intervention techniques can effectively control and improve well integrity and reduce the NPT in the high-loss circulation zones. Operators can therefore stabilise and produce wells to often problematic formations with equal ways of pressure management using MCD and physical reinforcement as well as well bore strengthening. This two-pronged treatment is in tandem with what many works have suggested, that in order to effectively tackle lost circulation, it is best to adopt both a standalone and an integrated drilling approach, especially in deep carbonate formations which often present difficulties as a result of fractured reservoirs (Das & Rahim, 2014; Siddiqi et al., 2021).

More to this, an integrated approach guarantees that the drilling operations in high-loss zones are efficient, cost effective and environmentally sustainable. This work aligns with the idea that one method although having some merit is more effective for solving high-loss zones problems than the other; nonetheless when they are combined, they work better. Hence, future researches are likely to find sporadic improvement in these strategies, developments upon the drilling materials and real time vigilance may enlarge the efficacy of MCD and well-bore strengthen for high-loss circulation troubles in the field of Ghawar (Brandl et al., 2014; Eyvazzadeh et al., 2003).

6. Conclusion

This work shows that Mud cap and well-bore strengthening techniques are capable of enhancing drilling efficiency in loss circulation zones in the Ghawar Oil Field. The results highlight that these techniques significantly reduce fluid loss and increase well integrity, preventing problems that normally cause non-productive time (Power, Ivan, & Brooks, 2003; Sanders, Scorsone, & Friedheim, 2010).

Mud cap approach have indicated detailed effectiveness in limiting circulation losses and well-bore strengthening materials help to reinforce the extendment in weak portions of well borehole specifically useful in fractured and carbonate reservoirs (Nazarisaram, 2022; Taheri et al., 2024). In addition, the incorporation of thixotropic cement systems and high fluid loss treatments have been demonstrated to form improved barriers, controlling losses in fluid content with maintaining production operations (AlSayed Omar et al., 2024).

By incorporating these sophisticated techniques, the study helps alleviate operational expenses and potential hazards caused by lost circulation in high-loss areas. It can therefore be concluded that targeted applications of the method due to well and formation characteristics can provide direction for drilling activities in similar environments (Winn et al., 2023; Khalifeh et al., 2019).

Altogether, this particular research provides evidence for improving efficiency, safety, and cost-induced effects of lost circulation management alongside particular well conditions in a range of complicated drilling situations (Siddiqi et al., 2021, Lee, 2022).

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