Geothermal Wells Drilling Risk Matrix

For Geo4All project

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Approvals

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List of Abbreviations

Abbreviations	Expansion
BHA	Bottom Hole Assembly
LWD	Logging While Drilling
MWD	Measurement While Drilling
ESP	Electric Submersible Pump
ECD	Equivalent Circulating Density
SPP	Standpipe Pressure
LCM	Lost Circulation Material
FIT	Formation Integrity Test
QC	Quality Check
RPM	Revolution Per Minute (measurement of rotational speed while drilling)
TD	Total Depth / Target Depth
OH	Open Hole
PPFG	Pore Pressure Fracture Gradient

1. Introduction

This report summarises the development and intended use of a *generic Geothermal Wells Drilling Risk Matrix* prepared for *WP2.2 – Modelling Well Concept Scenarios*. The matrix is intended as a structured reference tool for geothermal well operators, project teams and well engineering stakeholders. It is not a well-specific risk assessment and should not be applied directly to any individual geothermal well without further calibration against the actual well objectives, geological setting, trajectory, offset data, well design, rig capability, contracting model and operational constraints.

The core objective of developing this generic risk matrix is to provide geothermal well operators with a practical example of how drilling risks can be identified, assessed, ranked, prevented and mitigated using a transparent methodology. The methodology presented in this report is a qualitative risk assessment approach based on likelihood and impact ranking scales. The rankings are intended to support consistent engineering judgement and comparison of drilling risks, rather than provide numerical estimates of risk. It is one possible methodology among many. Operators may choose to adapt the structure, ranking criteria, terminology, risk categories and mitigation approach to align with their own internal risk management system, corporate risk matrix, regulatory requirements and project decision-gate process.

The risk matrix has been developed to identify and categorise drilling-related risks in a concise and auditable format. The register captures general geothermal drilling risks and risks associated with more complex well construction strategies, including highly deviated wells and multilateral well concepts. Each risk is assessed using a worst credible ranking (before planned mitigation measures are credited) and a net ranking (after mitigation measures are considered). These terms are explained further in Section 3.1. This distinction allows the user to separate the credible pre-mitigation risk exposure from the expected residual risk after controls are applied.

It is important to recognise that any risk ranking exercise includes a degree of subjectivity. The rankings in this generic matrix reflect the judgment of the assessment team based on the information available at the time of preparation. They should therefore be treated as an indicative starting point, not as a definitive ranking for any specific project. For a real well, the risk ranking should be reviewed and updated by the well-specific project team using the latest subsurface interpretation, offset well evidence, planned well design, execution strategy and available mitigation measures.

The assessment can be supported by offset well experience where relevant and available. Offset information can help the team judge whether certain risk mechanisms have been observed in comparable geological settings or drilling environments. However, offset evidence must also be interpreted carefully because differences in location, formation properties, well trajectory, mud system, drilling practices and equipment can materially change the likelihood and consequence of a risk event. Figure 1 demonstrates an overview of the geothermal drilling risk matrix.

Geothermal Well Risk Register

Well:	Geothermal		Risk Register Owner:	Akram Miriyev		View:	Assess Net Ranking			Last Updated:23.06.2026	00-Jan-00	
				Analyzed Offset Wells	BLT-01, KKP-GT-01, ALE-01,							
Step 1. Identify and categorize the Risk Event						Step 2. Assess Risk Ranking		Step 3. Identify Risk Management Measures			Step 3. Assess Net Ranking	
						Worst Credible Assessment					Net Assessment	
Risk No	Risk Event	Consequence	Category	Risk Type / Solution	Owner	Likelihood of Occurrence	Impact	Observed on Specific Offset Wells*	Formation / Lithology	Prevention / Mitigations	Residual Likelihood of Occurrence	Residual Impact
1	Losses while drilling	Unable to drill ahead Unable to trip due to heavy losses	All Types of Wells	Operations		5	C	1. BLT-01 - Observed losses during drilling 8.5" section - partial success achieved multiple LCM pill placement. Eventually losses stopped. Run & cement 7" liner without any losses. 2. ADK-GT-01 : Dynamic losses at 230m were recorded in a rate of 10 m^3/h decreased to 8 m^3/h dynamic losses at 270 m after pumping Lcm. Between 225m-275m total losses was recorded, in total 88 m^3 was lost. In 24" section losses (dynamic) ca. 88 m^3 Static losses at 515 m 0.3 m^3/h was reported when top of marl of Oosterhout formation was drilled.- North Sea formation is naturally more permeable. If the rock formations have high porosity (e.g., sandstone or fractured rock), drilling fluid (mud) can easily flow into these porous zones, causing mud loss. No detailed information were mentioned in the reports about the cause of the losses. 3. ADK-GT-02 : Mud losses were reported between depths of 140m and 280m, with dynamic losses ranging from 15 to 25 m^3/h. At 235m, static losses were recorded at 200 l/h, leading to a total of 65m^3 of losses per day. By the end of the day, the cumulative mud losses amounted to 250m^3.	1. Zechstein Upper Claystone and Z4 2. NUOT 3. NUCT	LCM strategy ready, Optimized filter cake, Mud weight management (differential sticking)	4	D
2	Issues while sliding with motor (oriented drilling)	Deviation from plan, Loss of steerability	Highly-deviated	Operations		2	D			Ensure proper hole cleaning by adequate mud properties, Trained personnel, Optimised trajectory,	1	E
3	High wellbore tortuosity, high local doglegs	High torque and drag levels further down the hole, Issues placing the ESP,	Highly-deviated	Planning		4	E			Watch out for transition zones, Do not exceed a maximum of 3 deg/30m dogleg, Wash and ream high doglegs carefully,	2	F
4	Poor Directional control , inability to follow directional plan for BHA or formation related issues	Additional BHA trips, loss of rig time. Reduced ROP to achieve required steering capabilities Poor hole quality and high well tortuosity if the wrong directions are not corrected on time.	Highly-deviated	Operations		5	D	1. KKP-GT-01 : While drilling 12 1/4" BHA trip was required to establish required build rate. New BHA drilled to section TD. 2. WSP-01 : While drilling the 12 1/4"section some deviation problems were encountered in the Jurassic shales which slowed down penetration rates considerably.-No details on cause of deviation problems were reported. They may be inflicted by layering of shales.	1. NLLFC 2. ATAL	In case of restrictions adjust parameters while reaming, Low RPM and low flow, Avoid reaming down, Trained personnel, Optimised trajectory, Continuously control survey, QC equipment	4	E
5	Hole instability Issues	Tight hole, Loss of hole, Running casing to bottom	All Types of Wells	Planning		5	C	ADK-GT-01 : The geological report and mud logging indicated that the Vlieland claystone appeared unstable while drilling with a 1.30 s.g. mud weight (MW). After increasing the mud weight to 1.35 s.g., fewer overpulls and cavings were observed.-It was observed that the Vlieland claystone	KNNC / Vlieland Claystone Formation	Monitor returns and adjust mud weight as required, Ensure proper hole cleaning and mud inhibition,	4	E
6	Pack offs around BHA while drilling shoetrack or connection	Stuck pipe, Loss of circulation, Loss of equipment	All Types of Wells	Planning		5	E			Monitor string up and down weights carefully, special care when picking up, Monitor trends i.e., torque, ECD, SPP, cuttings,	4	G
7	Losses during cement job	Integrity problems, Cross flow, Ground water pollution	All Types of Wells	Operations		4	D			Optimised cement weight, schedule and pumping, ECD monitoring, Use LC fibres,	3	E
8	Shock & Vibrations While Drilling	Damage to high cost BHA items, lost in hole, BHA twist-off or BHA back-off due to reactive torque. Time consuming fishing operations	All Types of Wells	Operations		4	E	ERM-01 : Drill string broke while drilling the 12 1/4" hole section. Multiple fishing attempts but these did not solve the problem. Sidetrack was required.-Stuck pipe possibly due to swelling clays in sandy claystone.	NM	Monitoring drilling fluid, Set up parameters and ranges by mud engineer, Keep in contact with WSG	3	F
9	Previous section not TD'ed according to plan, shallow set previous casing	Break out of unstable clay or porous sandstone	All Types of Wells	Operations		2	D			Mud properties to adapt to the clay section, Continuous monitoring and control on cavings and formation type, Capability to use casing running system	1	F
10	Kick while drilling / Well Control	Time delay, Break down of 185/8" shoe, Environmental impact, Human injuries	All Types of Wells	Operations		5	A			Use of proper control equipment, Trained personnel, Kick detection, Ensure having enough weighting material on	4	C
11	Leaking liner top packer	Well integrity issues	All Types of Wells	Operations		2	C			Test packer/ liner lap upon installation, Ensure contingency tie-back packer available if liner lap is leaking, Scraping 9-5/8" casing prior to liner run,	1	D

Figure 1: Overview of the generic geothermal drilling risk register.

2. Well Construction Strategies

Geothermal developments may consider different well construction strategies depending on reservoir geometry, surface access, target depth, required flow rate, environmental constraints and project economics. The risk matrix has therefore been structured to include both risks that may apply to geothermal wells in general and risks that are more closely linked to specific well construction concepts.

Highly deviated wells are a common development option when the reservoir target is laterally offset from the surface location, when surface access is limited, or when the reservoir contact needs to be increased from a restricted number of surface slots. In geothermal developments, this can be attractive because project economics are sensitive to well cost, flow performance and reservoir contact [1]. However, highly deviated wells can increase exposure to directional drilling complexity, torque and drag, hole cleaning limitations, wellbore tortuosity, logging conveyance difficulty and casing or liner running challenges.

The generic matrix therefore includes a dedicated consideration of risks that may become more relevant for highly deviated geothermal wells. These risks should not automatically be assumed to apply to every deviated well. Their relevance depends on the planned trajectory, inclination profile, dogleg severity, open-hole length, formation stability, mud system, BHA design, casing programme and operating practices. The unique characteristics of geothermal formations—hard, fractured, abrasive rocks with high temperatures and corrosive fluids—can further complicate deviated drilling operations [2].

Multilateral wells may also be considered in some geothermal development concepts, particularly where improved reservoir contact or access to multiple reservoir intervals is required from a single parent wellbore. In principle, multilateral concepts may offer development benefits; however, they also introduce additional complexity in design, drilling execution, junction construction, barrier philosophy, completion integration, intervention access and long-term well integrity assurance[3].

For this reason, multilateral-related risks are treated as a distinct group within the generic matrix. They should be screened carefully during concept selection because their risk profile may be highly project-specific. A multilateral concept that is technically attractive from a reservoir-contact perspective may still be unsuitable if the well integrity, operability, contingency or lifecycle requirements cannot be demonstrated to an acceptable level. The junction completion represents a critical element, as it must withstand wellbore stability challenges, maintain hydraulic isolation when required, and allow for potential future interventions [4]. Studies have shown that multilateral wells can experience borehole instabilities at junction areas, where the geometry changes from circular to elliptical or oval shapes, creating more severe conditions for both fracturing and collapse [4].

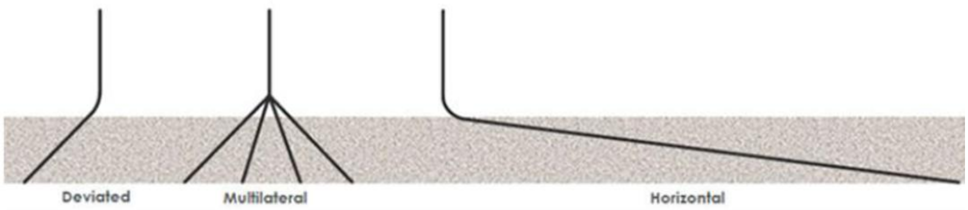

Figure 2: Stick schematics showing typical geothermal well construction strategies.

2.1. Economic Comparison: Sidetrack, New Well and Well Intervention Options

When an existing geothermal well exhibits declining performance or fails to meet production targets, operators typically evaluate three principal remediation strategies with distinct cost profiles and technical risk implications. Well intervention represents the lowest-cost option (€0.5–3 million), encompassing stimulation treatments, perforation campaigns, scale removal, liner repairs and pump optimisation, offering rapid performance improvement without drilling a new hole; however, effectiveness is highly dependent on the root cause of underperformance, and intervention may deliver only temporary gains if fundamental well placement or structural integrity issues exist. Sidetrack wells eliminate the cost of surface facilities, conductor installation and upper hole sections (representing 20–40% of total well costs), with typical costs ranging from 50–80% of a new well depending on kick-off depth (depth at where the sidetrack begins) and trajectory complexity, though they introduce operational constraints including whipstock operations, hole size restrictions imposed by parent wellbore casing diameter, dependence on parent well integrity, and uncertainty regarding older wellbore cement condition and accessibility. New wells provide maximum design flexibility and the most predictable drilling and well construction outcome, allowing optimal surface location selection, modern drilling practices, updated mud systems and advanced completion technologies, but carry the highest capital burden due to full drilling costs, site preparation, environmental permitting, rig mobilisation and surface casing installation. The selection between these options should be guided by a multi-criteria decision process that evaluates expected incremental production capacity, well lifespan post-remediation, technical risk profile, offset well data availability, capital budget constraints and opportunity cost of capital compared to alternative field development investments. A staged approach is often prudent: initial low-cost intervention to diagnose well performance limitations and gather data, followed by a sidetrack if the intervention proves insufficient, with new well development retained as a contingency option, thereby managing capital exposure while progressively reducing decision uncertainty.

3. Geothermal Wells Drilling Risk Matrix

The Geothermal Wells Drilling Risk Matrix provides a visual summary of the generic risk register. It allows the user to compare risk events by likelihood and impact and to distinguish between the initial worst credible assessment and the expected net assessment after prevention and mitigation measures are applied.

The matrix should always be read together with the full risk register. The matrix provides a high-level visual overview, while the register contains the details of the risk event, consequence, category, applicability, potential offset evidence and proposed prevention or mitigation measures. The matrix alone should not be used to make design or operational decisions.

Because this matrix is generic, its primary value is methodological. It demonstrates how geothermal well drilling risks can be structured, compared and communicated. For an actual well, the matrix should be converted into a well-specific risk assessment by updating the risk list, ranking assumptions and mitigation measures to reflect the real project conditions.

3.1. Methodology

The assessment uses an **8 x 8 risk matrix**. The vertical axis represents impact, ranked from A to H, where A represents the highest impact, and H represents the lowest impact. The horizontal axis represents the likelihood of occurrence, ranked from 1 to 8, where likelihood increases from left to right.

Each risk is assigned two rankings:

1. **Worst Credible Assessment -** the credible risk level before relying on the full effectiveness of the planned prevention and mitigation measures.

2. **Net Assessment** - the expected residual risk level after prevention and mitigation measures are applied.

The worst credible assessment is not intended to describe the worst imaginable scenario. It is intended to describe a realistic but adverse scenario that could credibly occur for the type of well concept being considered. The net assessment then reflects the expected residual exposure after controls have been defined and credited.

For this generic matrix, the rankings should be understood as illustrative. They reflect the assessment team's judgement and the assumed context used during preparation. Different operators or project teams may reasonably rank the same risk differently if their geological setting, well design, available offset data, operational capability or risk tolerance differs.

The methodology is therefore best used as a structured discussion framework. Risk assessment matrices are widely used in the drilling industry to classify risks according to their probability of occurrence and severity of impact, with qualitative assessments using likelihood and consequence scales to support decision-making [5]. Its purpose is to make risk assumptions visible, encourage consistent comparison between risk events, and support clear documentation of prevention and mitigation measures. It should not replace well-specific engineering analysis, peer review, operational readiness assessment or formal risk workshops.

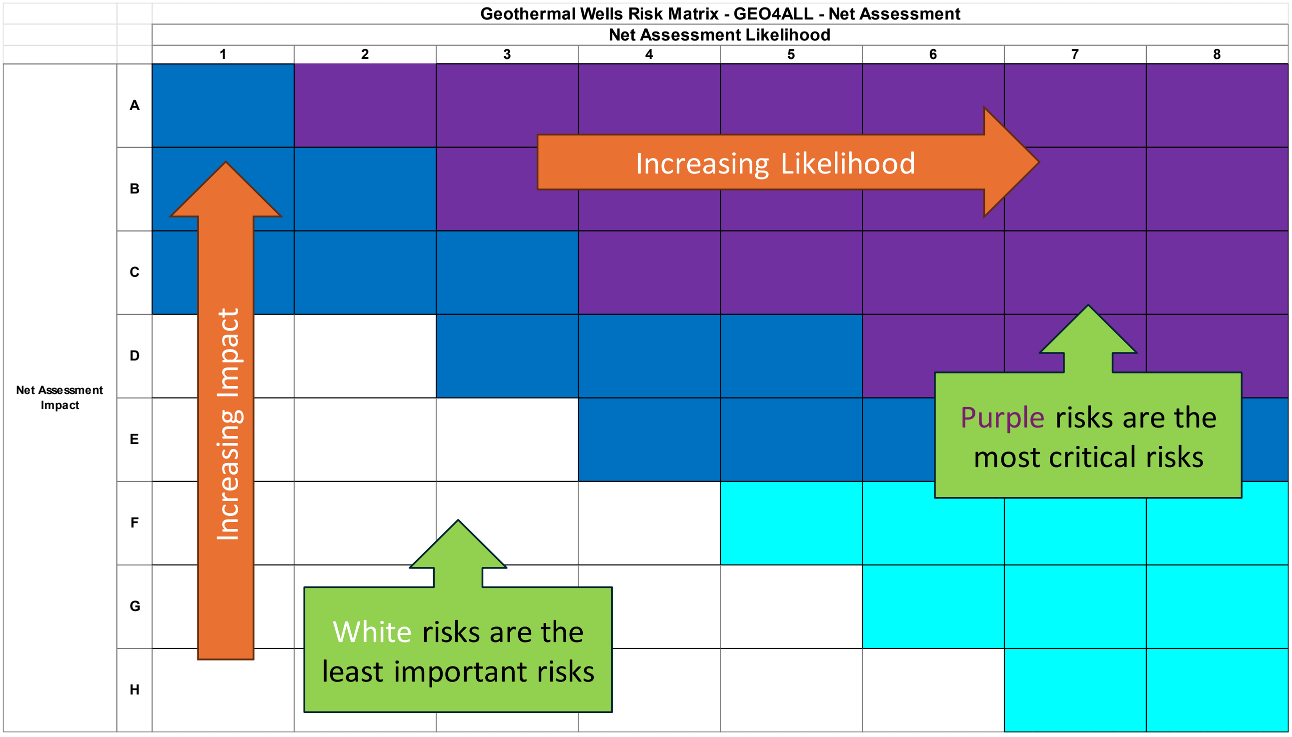

Figure 3: Explanation of the 8 x 8 matrix scale, including likelihood and impact axes.

3.2. Workflow for Well-Specific Drilling Risk Matrix

To apply this generic methodology to a specific geothermal well, the following stepwise process is recommended:

1. **Define the well context.** Confirm the well objective, target reservoir, planned trajectory, hole sizes, casing design, completion concept, rig type, operating envelope and key project constraints.
2. **Compile relevant input data.** Gather offset well data, geological prognosis, pore pressure and fracture gradient assumptions, formation strength data, drilling performance records, losses history, mud system lessons, cementing experience, well control considerations and any known local

operational constraints. The larger the data pool from geological surveys and offset wells, the better the engineering assumptions and drilling program can be refined.

3. **Screen the generic risk register.** Review each generic risk and decide whether it is applicable, not applicable, or requires modification for the specific well. Add missing well-specific risks where required.
4. **Define consequences clearly.** For each applicable risk, describe the credible consequence in terms of safety, environment, well integrity, cost, schedule, data acquisition (loss of the ability to acquire planned subsurface and operational data), reservoir access and long-term well performance. Risk is defined as the combination of the likelihood of occurrence of a hazardous event and the severity of its impacts.
5. **Assign the worst credible ranking.** Rank each risk using the agreed likelihood and impact scales before crediting all mitigation measures. The ranking should be based on evidence where available and expert judgement where uncertainty remains.
6. **Define prevention and mitigation measures**. Document the planned controls, including design changes, equipment selection, operating limits, procedures, monitoring requirements, contingency plans, decision points and responsible owners. Where appropriate, a bow-tie approach [6] may be used to systematically identify potential causes, consequences and the associated preventive and mitigative barriers. The bow-tie complements the risk matrix by providing a structured visual representation of the pathways between causes, the hazardous event and its preventive and mitigative barriers, rather than replacing the risk ranking process.
7. **Assign the net ranking.** Re-rank each risk after considering the expected effectiveness of the prevention and mitigation measures. The net ranking should only credit controls that are realistic, resourced and likely to be implemented.
8. **Review risk distribution.** Examine the matrix to identify clusters of material residual risk, high-consequence items, risks requiring management attention and areas where additional engineering work is required. Risk matrices typically distil rankings into three categories: acceptable, tolerable, and intolerable.
9. **Link risks to project controls.** Carry material risks into the basis of design, well programme, decision-gate documentation, tender specifications, operational procedures and readiness reviews.
10. **Maintain the matrix as a live document.** The risk matrix should be owned by the project team and updated as the well design matures, new offset information becomes available, vendor input is received, uncertainties are reduced or operational assumptions change. While consultants may support its development and periodic review, responsibility for maintaining the risk matrix should remain with the operator throughout the project lifecycle.

3.3. Worst Credible Risk Assessment

The worst credible assessment provides a view of the credible risk exposure before the full benefit of prevention and mitigation measures is credited. In a well-specific application, this view is useful for identifying which risk areas require early engineering attention, additional data gathering, concept changes, contingency planning or management visibility.

In the generic matrix, the worst credible view should be interpreted as an indicative screening output. It does not mean that the same risk distribution will apply to a particular geothermal well. A project with strong offset control, a simple trajectory, proven formations and mature operational practices may rank several risks lower. Conversely, a project with limited offset data, challenging formations, complex trajectory or novel well architecture may rank some risks higher.

The value of the worst credible assessment is that it encourages the team to consider the exposure that exists before controls are assumed to work. This is particularly important for geothermal wells because project teams may face uncertainty in subsurface conditions, formation behaviour, temperature effects, drilling performance, loss mechanisms and well productivity requirements. The worst credible view helps avoid underestimating risks simply because mitigation measures have been listed.

For a well-specific risk workshop, the worst credible assessment should be supported by clear evidence and assumptions. Where offset evidence is limited, the uncertainty should be documented in the risk register together with the assumptions used for the ranking. Where additional information cannot reasonably be obtained, the ranking should be reviewed by the project team and decisions made based on the best available evidence, supported by appropriate contingencies where required.

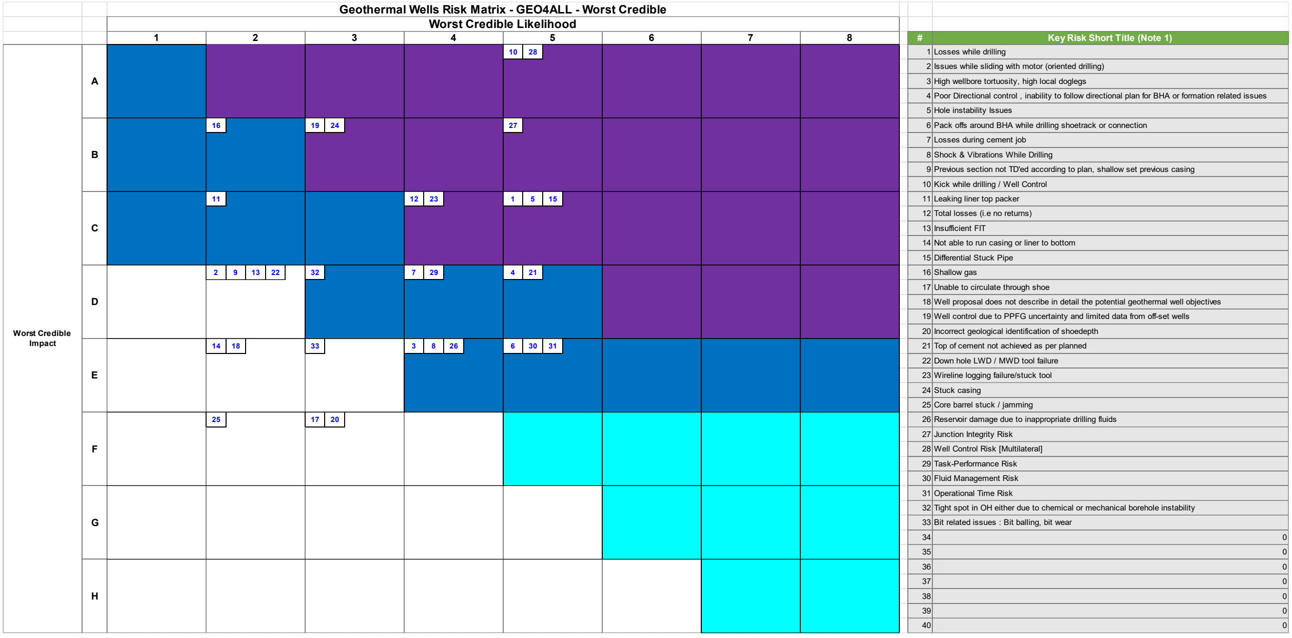

Figure 4: Snapshot of the generic worst credible risk matrix.

3.4. Net Risk Assessment

The net assessment represents the residual risk after prevention and mitigation measures are applied. It is useful for checking whether the planned controls reduce the residual risk to an acceptable level in accordance with the project's risk acceptance criteria.

In the context of this generic matrix, the net assessment should also be treated as illustrative. The effectiveness of any mitigation measure depends on the actual well design, operational discipline, rig capability, contractor performance, equipment availability, monitoring quality and decision-making process. Therefore, the net ranking should always be revalidated for the specific well.

A net ranking should only credit mitigation measures that are practical and implementable. For example, a control should not be credited unless it has a clear owner, is technically feasible, can be incorporated into the well programme or operational plan, and can be verified before or during execution. This prevents the matrix from giving a false impression of risk reduction.

The comparison between the worst credible and net assessment is one of the most useful outputs of the methodology. It shows where prevention and mitigation measures are expected to reduce either the likelihood, the impact, or both. It also highlights where residual risk remains material and should be carried forward into decision gates, operational readiness reviews, contingency planning and management discussions.

For a well-specific project, the net assessment should be reviewed at each key design or planning milestone. It should also be updated after major changes in trajectory, casing design, mud strategy, well control assumptions, completion concept, rig selection, contractor input or subsurface interpretation.

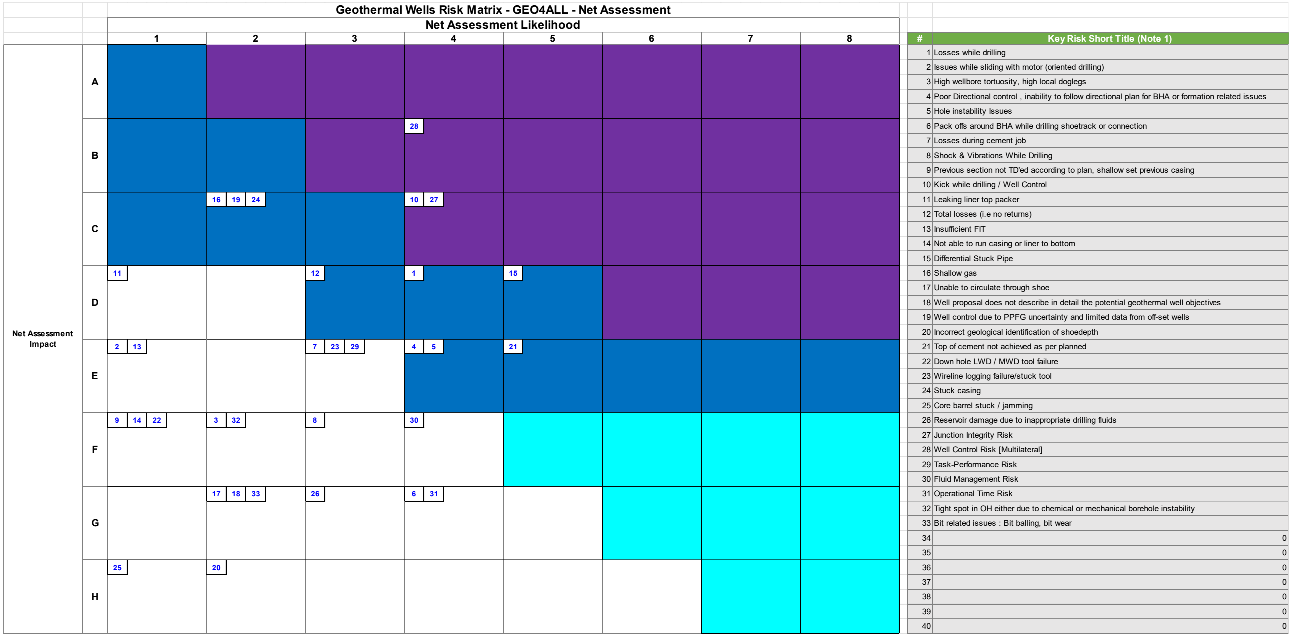

Figure 5: Snapshot of the generic net assessment risk matrix.

4. Conclusion

The Geothermal Wells Drilling Risk Matrix provides a structured and practical framework for discussing geothermal drilling risks. In its current form, it is a generic risk matrix and should not be interpreted as a directly applicable assessment for any specific well. Its main purposes are to show geothermal well operators typical drilling risks for geothermal well and one possible method for identifying, categorising, ranking, preventing and mitigating drilling risks in a transparent and systematic way.

The matrix can support early-stage discussion between geothermal operators, well engineers, subsurface specialists, drilling contractors, service providers and project decision makers. It helps make assumptions visible and encourages the team to distinguish between pre-mitigation exposure and residual risk after controls are applied.

However, the rankings in the generic matrix are inherently subjective. They reflect the judgement of the assessment team and the assumed context at the time of preparation. A different project team, operating in a different geological setting or using a different well design, may reasonably reach different rankings. For this reason, the generic matrix should be used as a starting template rather than a final answer.

Before being used for a real geothermal well, the matrix should be converted into a well-specific risk register through a dedicated risk workshop. The team should update the risk list, likelihood rankings, impact rankings, consequences, mitigation measures, residual rankings and ownership based on the actual well objectives, offset data, subsurface uncertainty, operational constraints and execution strategy.

Overall, the recommended use of the matrix is as a live engineering tool. It should be updated as the project matures and as new information becomes available. When used in this way, the matrix can support better risk communication, more disciplined mitigation planning and clearer decision making throughout geothermal well design and execution.

The methodology provides a structured basis for geothermal drilling risk assessment. Future work should focus on validating the risk rankings using additional geothermal well data and integrating the methodology into digital well planning workflows.

5. References

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6. Appendix

Attachment: Geothermal Wells Drilling Risk Register & Matrix – Excel File