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Casing Collapse Mechanism in Geothermal Drilling in Western Turkey

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ABSTRACT

Casing collapse is a costly drilling and well completion problem that may result in wellbore loss or require very challenging repairs, taking a long time without a guarantee of restoring the well to its original condition. Casing collapse typically occurs just after the well completion process, during the warm-up of the wells for cleaning purposes, or after long-term production from the well. This study comprehensively evaluates well parameters, drilling and completion operations, and measurements taken before and after drilling in western Anatolia, Turkiye. The findings highlight that the most significant factors contributing to casing collapse are annular pressure buildup during the well's heat-up in uncemented sections due to poor cementing, casing deformation caused by corrosive geothermal fluids, and the mobilization of formation particles induced by high fluid extraction rates from the reservoir.

1. INTRODUCTION

Casing collapse is a well integrity issue that occurs when the structure of the well fails due to collapsing and/or buckling. It may potentially result in costly repairs, well abandonment and safety issues. Casing failure is a common problem in geothermal wells due to various reasons including cyclic thermal stress, poor cementing, corrosive fluids, and harsh working downhole conditions (Kardal et al. 2013). Geothermal wells are susceptible to casing collapse due to high external pressures, particularly when formation or overburden pressure exceeds the internal well pressure, creating a crushing force. This risk is amplified by weak points in the casing, such as joints or areas with reduced wall thickness, where collapse is most likely to occur (Southon, 2005).

Operations in geothermal wells, such as flow tests, injection tests, well shut-ins, and cleaning activities, induce temperature fluctuations along the wellbore. These fluctuations result in thermal expansion and contraction of the casing. This repeated thermal cycling creates stress, especially at the connections and joints, which weakens the casing over time. Ingason et al. (2014) reported that IDDP-1 (Iceland Deep Drilling Project well number 1), drilled in the Krafla geothermal field, reached a record wellhead temperature of 450°C and a pressure of 144 bar. However, severe damage to the production casing occurred and the well was abandoned with cement plug. Thorbjornsson et al. (2017) proposed flexible couplings allowing thermal expansion during warm up, control of material stresses below yield and cooling of the well for maintenance.

Poor cementing is one of the most critical reasons of casing failure in geothermal wells. Uncemented sections or gaps between the casing and formation, or between casing strings, can lead to collapse or buckling when exposed to heat during fluid production. Heat causes the trapped fluid within these uncemented sections to expand, resulting in a significant pressure increase that can exceed the casing's collapse strength. If the surrounding formation is impermeable and ductile, such as clay minerals, it cannot crack to release the pressure, ultimately leading to casing failure. The standard cement used in high temperature and pressure wells can degrade over time, weakening the bond between casing and formation. This degradation reduces support and increases the risk of collapse. Suryanarayana et al. (2020) examined the effect of an un-cemented section on the maximum allowable temperature change for a 9 5/8-inch, 47 lb/ft L80 tubular within a 13 3/8-inch casing. Figure 1 demonstrates that when the string is fully cemented, the allowable temperature change is 244°C. As the length of the unsupported section increases from zero, the maximum allowable temperature change decreases sharply, reaching a minimum of 130°C at an unsupported length of 6 meters. As the length of the unsupported section increase, the buckling regime becomes elastic and has a less severe effect compared to shorter lengths.

Lentsch et al. (2015) presented three cases of casing collapse in ultra-deep geothermal wells in Germany. The first casing collapse was attributed to annular pressure buildup (APB) caused by thermal fluid expansion between the casing and liner at a depth of 2300 m during a production rate of 30–50 l/s. The second casing collapse was detected in a well at a depth of 15 m. The analysis revealed that the cement level between the 18 5/8-inch and 13 3/8-inch casings was below the surface, and the collapse was caused by APB when the annulus release valve was closed. The third casing collapse occurred in the 9 5/8-inch casing at a depth of 2500 meters due to a poor cementing job, followed by APB.

Geothermal fluids often contain corrosive species that can corrode tubulars, reducing their wall thickness and structural strength. Geothermal waters of meteoric origin often contain significant amounts of sour gases, which may accelerate corrosion when exposed to high temperatures. Additionally, high-salinity and hypersaline geothermal waters are highly corrosive to carbon steel casings. When corrosion is combined with erosion caused by solid particles mobilized by turbulent flow in the reservoir, the casing becomes even more susceptible to collapse.

Geothermal reservoirs are typically found in tectonic active regions. Therefore, manufacturing defects, even microscopic ones, can propagate under stress and create weak points prone to failure. Lentsch et al. (2015) emphasized the effects of high tectonic stresses and overpressure zones on the casing failures. Additionally, using materials that do not meet the required high-strength and corrosion-resistant specifications increases the risk of collapse, especially in the challenging conditions of geothermal wells.

This study focuses on casing collapse cases in western Anatolia, Turkey. Various collapse mechanisms will first be discussed to highlight the issues that need to be addressed in future drilling activities. Subsequently, implemented solutions to prevent the casing collapse will be presented.

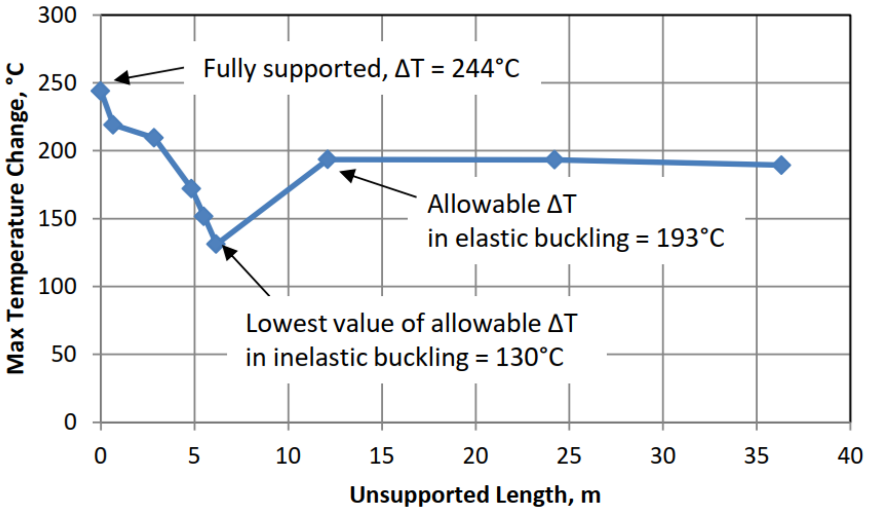

Figure 1: Effect of unsupported section on maximum allowable temperature, 9 5/8 in., 47 lb/ft, L80 (Suryanarayana et al. 2020)

2. COLLAPSE MECHANISM OF GEOTHERMAL WELLS IN WESTERN ANATOLIA, TURKIYE

Geothermal power plants in Turkiye are located in western Anatolia, where horst-graben systems host extensional domain-type geothermal reservoirs. Metamorphic rock is the primary geothermal reservoir, consisting of schist, marble, and quartz. Intersecting normal faults serve as the main preferential paths in Turkish geothermal reservoirs, dominating fluid flow.

Due to the aggressive production programs of various operators producing from the same basin, substantial pressure drops have occurred in the reservoir. Aydın and Akın (2021) reported a pressure decline of 3 bar per year in the Alaşehir field, Turkiye. Similarly, Şentürk et al. (2020) observed a 30-bar decline in reservoir pressure in the Kızıldere field, Turkiye, following the commissioning of the 165 MW power plant's wells. Thus, drilling operations typically experience losses of drilling fluid and cement slurry. Although excess cement is calculated to account for slurry loss during the cementing job, a top job operation is generally conducted to fill the cement level as it falls due to low reservoir pressure. A ½ inch slim tubes are used to perform top job, which typically results in uncemented sections a potential risk of collapse.

The typical casing scheme in Turkish geothermal fields is presented in Figure 2. Poor cementing between the 9 5/8-inch and 13 3/8-inch casing strings is the primary section where most casing failures occur.

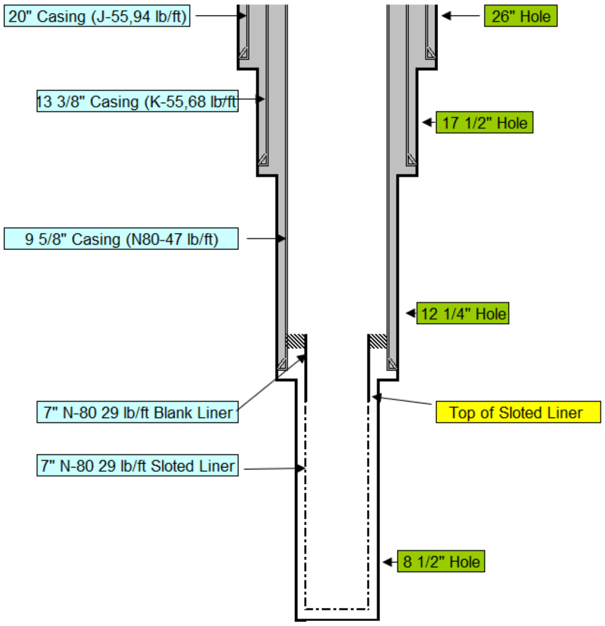

Figure 2: The typical casing scheme in geothermal fields in Western Anatolia, Turkiye

G-class cement with 35% silica, along with additives such as water-loss agents, friction reducers, and retarders, is commonly used. Although G-class cement is suitable for high-temperature conditions, the density of the cement combined with low reservoir pressure often results in slurry loss into the formations. The cement density typically ranges between 14.5 and 15.5 ppg. Poor displacement of the drilling fluid is another critical impact on poor cementing because as the mud is left behind the casing walls that cannot be mobilized in the course of the cementation (Lentsch et al. 2015). Thickening time is also a critical parameter affecting cementing quality. The wait-on-cement time typically ranges from 12 to 16 hours for 9 5/8-inch casing. Extended wait-on-cement times often result in free water segregation due to gravity, with the free water occupying small openings in the cement column and sometimes accumulating at the top of the cement. Top job operations commonly trap the accumulated water near the wellhead sections, typically at depths ranging from 10 to 350 meters. Geothermal wells that experience rapid heat-up during start-up operations may reach their maximum temperature and cause a rapid pressure to increase before the pressure can escape to release trapped pressure, potentially resulting in casing failure. Cement Bond Log (CBL) taken after drilling completion shows that there are free pipe intervals, possibly including free water are potential intervals for casing collapse after heat-up (Figure 3).

Geothermal fluid in Turkish geothermal reservoirs contains significant amounts of non-condensable gases (NCGs), such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S). Aydın and Akın (2023) analyzed the gas composition of NCGs in the Alaşehir field, Turkiye (Table 1), reporting that CO_2 constitutes more than 99% by volume in dry gases. Although recent studies (Aydın et al., 2020; Akın et al., 2020) have documented a sharp decline in NCG content over time, initial production records showed NCG levels ranging between 2% and 4%. These corrosive gases, with a pH value below 6, typically contribute to casing corrosion over the production period.

Table 1: Gas composition of NCG in Alaşehir geothermal field (Aydin and Akin, 2023)

Gas Composition	Volume % in dry gas
Carbon Dioxide (CO_2)	99.38
Nitrogen (N_2)	0.36
Methane (CH_4)	0.21
Hydrogen Sulfide (H_2S)	0.0036
Argon (Ar)	0.003
Hydrogen (H_2)	0.01
Helium (He)	0.00005

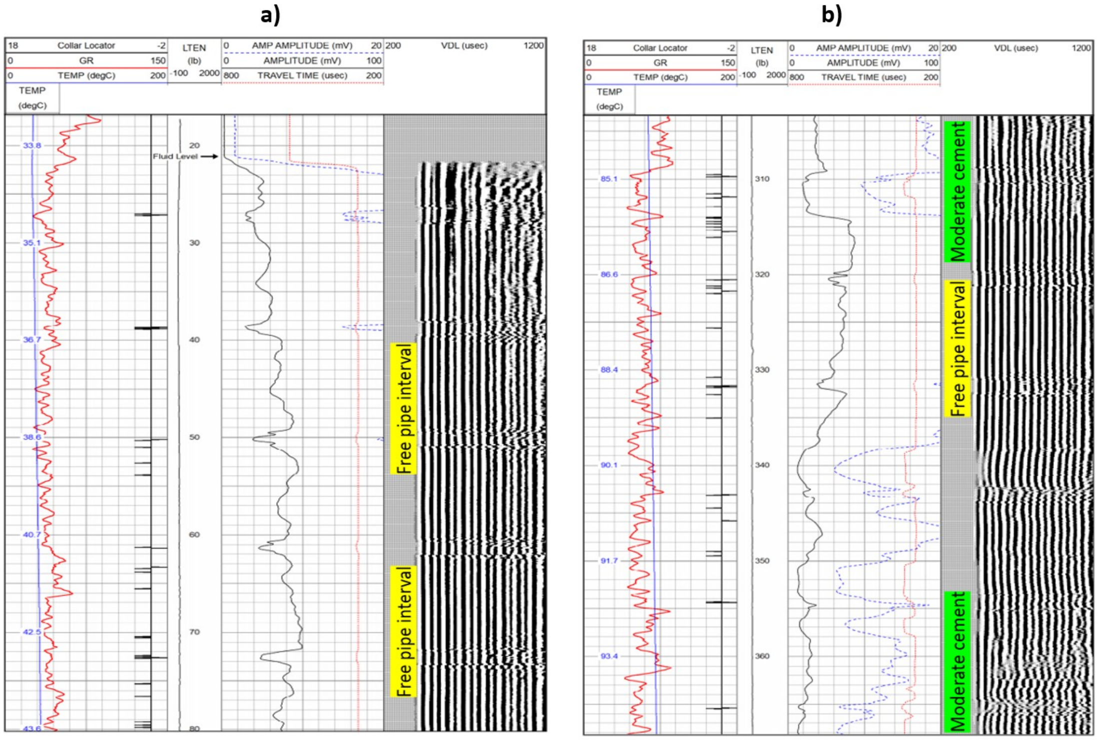

Figure 3: CBL measurement in a geothermal well in Alaşehir field, Turkiye

Additionally, hypersaline brine significantly affects the corrosion behavior of casing materials. Demir et al. (2014) reported sodium chloride (NaCl)-dominated geothermal fluid in the Tuzla field, Çanakkale, Türkiye, located 5 km from the Aegean Coast. The sodium concentration was recorded at an average of 19,000 ppm, while the chloride concentration was noted as 35,000 ppm.

High production rates in geothermal wells create turbulent flow at the sand-face, mobilizing unconsolidated fine particles. As shown in Figure 4, these fine particles are transported with the geothermal brine through the production casing and accumulate in surface infrastructure, such as production lines, separators, and heat exchangers. Over time, these fine particles act as abrasives, causing an erosion effect that reduces the inner diameter of the casings.

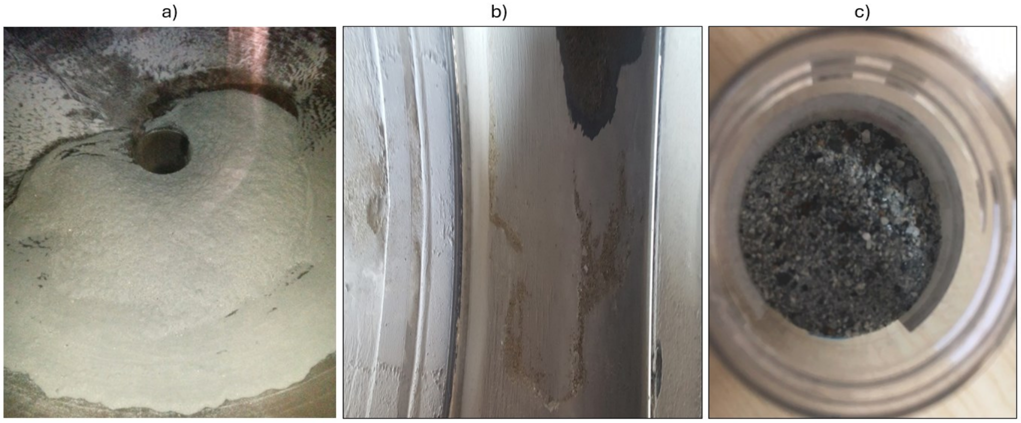

Figure 4: Formation deposition at a) separator, b) valve, and drains (Aydin, 2018).

As a result of corrosion and erosion effects, the caliper log indicated an enlargement of the inner diameter of the 9 5/8-inch casing from 8.59 inches to a maximum of 8.91 inches (Figure 5). This enlargement signifies a reduction in the casing's wall thickness, thereby decreasing its collapse resistance.

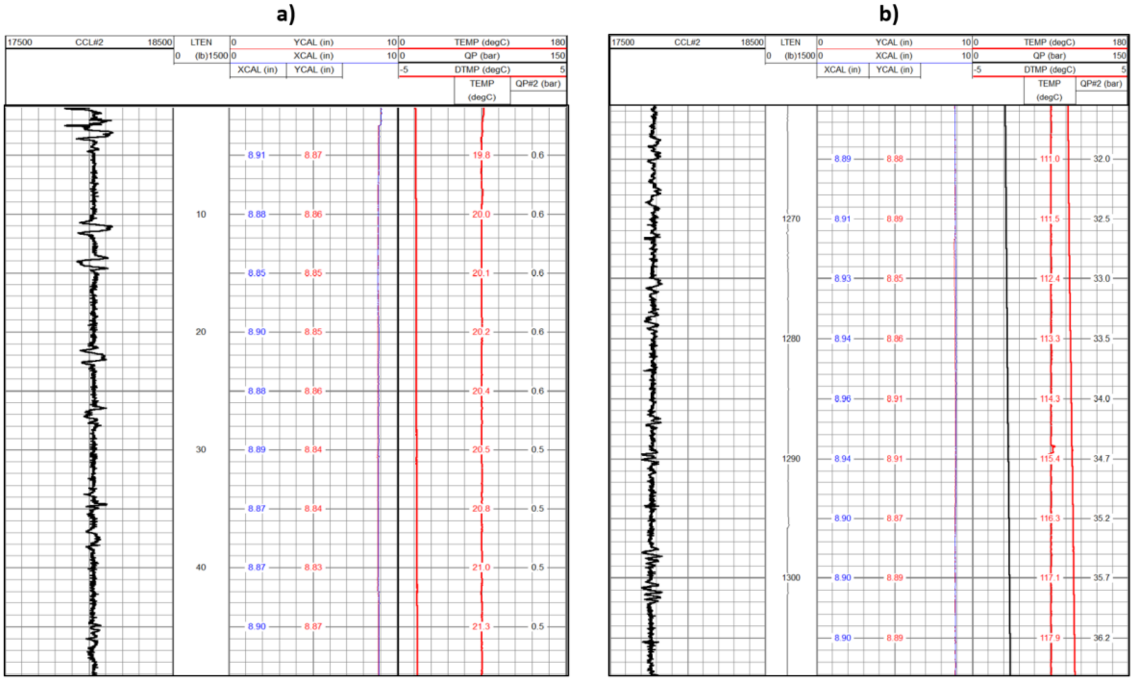

Figure 5: Caliper log measurement in a geothermal well in Kızıldere field, Turkiye

2.1 Experienced Casing Collapse Cases

We present 3 collapse cases in high temperature geothermal wells ranging between 210 and 230 ^{o}C reservoir temperature in western Anatolia, Turkiye.

Case-1:

All production tests for Well No. 1 were successfully completed. After nearly one year, the well was reopened for production. During the initial flow startup, the well performed as expected; however, over time, the flow rate declined significantly, eventually dropping to just 20% of its original performance. Consequently, the well was shut in. To investigate the issue, coil tubing was used, but it could not descend beyond a depth of 403 meters. Subsequently, a caliper tool was deployed to check the casing diameter, which confirmed that the casing maintained its full diameter up to 403 meters. To further assess the well, 205 barrels of water were pumped, and an 8 ½-inch impression block was lowered into the well as part of Bottom Hole Assembly (BHA #1). The impression block was placed at a depth of 403.5 meters with a weight of 5 klbs. Upon retrieval and examination of the impression block, no marks were found on it; however, it appeared jammed from the sides. Based on these observations and examinations, casing collapse was identified as the underlying issue. The collapse occurred due to pressure increase in the fluid trapped between the 9 5/8-inch and 13 3/8-inch casings as a result of the top job cement.

The workover operations on Well No. 1 involved extensive milling and investigation to address casing collapse and restore production. Starting at 403.5 meters, multiple taper mills and tools were used across several runs to gradually progress past blockages, with operations extending to a maximum depth of 417.5 meters. Milling parameters were adjusted based on tool performance and observed torque. Several instances of tool wear and blockages were resolved by replacing tools, welding, and implementing gradual back-and-forth milling techniques. Circulation and flow checks were performed to clear debris, assess casing conditions, and manage leaks. The wellhead was dismantled and reassembled, with new perforated casings and tubing installed. Ultimately, the operations restored the well to 80% of its pre-collapse production rate.

Case-2:

The Well no. 2 had produced through artesian flow for 10 years. To enhance its production performance, an ESP (Electric Submersible Pump) was installed. However, 20 minutes after the ESP started operating, the pump was shut down due to an electrical alarm. Despite several attempts, no power could be supplied to the motor, suggesting cable damage within the wellbore. Subsequently, a caliper log inside the 6 5/8-inch ESP production string revealed casing collapse between 230 and 240 meters, reducing the casing diameter from 5.7 inches to 3.8 inches (Figure 6). The collapse occurred due to pressure increase in the fluid trapped between the 9 5/8-inch and 13 3/8-inch casings as a result of the top job cement. A workover rig attempted to pull out the ESP with an overpull force of 90 tons, but no movement was observed, and the ESP remained stuck in the well. As a result, the well was converted into a reinjection well.

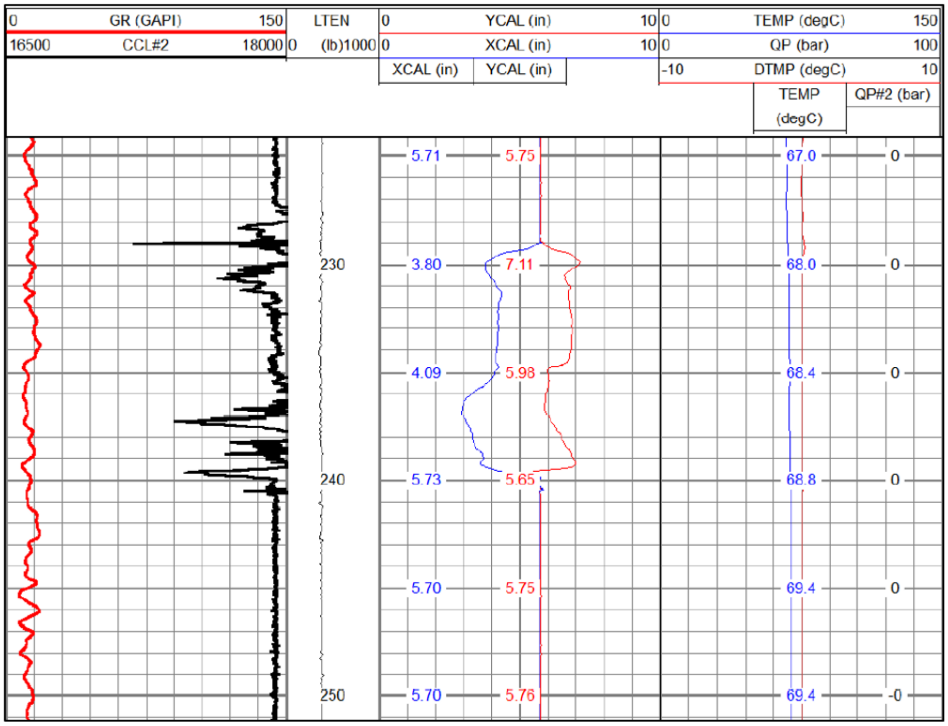

Figure 6: Caliper log measurement in a geothermal well in Kızıldere field, Turkiye (Aydin et al. 2021)

Case 3:

Well No. 3 was completed with an 8 ½-inch drill bit at a depth of 3425 meters, experiencing total drilling mud loss. The casing scheme of the well is similar to the standard design used in western Turkiye. A 20-inch surface casing, 13 3/8-inch intermediate casing, and 9 5/8-inch production casing were lowered and cemented, followed by a 7-inch liner hung inside the 9 5/8-inch casing without cementing (Figure 2). During the 9 5/8-inch casing cement job, the cement level dropped to 350 meters from the surface. A top job cement operation was subsequently performed using ½-inch slim tubes through the annulus.

Nitrogen lifting was conducted using a coiled tubing unit to initiate flow during cleaning and completion testing operations. However, during deployment, the coiled tubing encountered a stuck at a depth of 2158 meters. This resulted in a complete inability to mobilize the string, with no movement achievable in either the upward or downward direction.

To perform fishing operations, a workover rig with a 150-ton pulling capacity was employed. The coiled tubing was captured at the wellhead and severed at 823 meters, where the collapse occurred. Using a taper mill assembly, the string was run into the well, contacted the top of the fish at 823 meters, and the stuck tubing was released but subsequently fell deeper into the well. The section between 825 and 835 meters was milled using the taper mill assembly.

The collapse zone was repeatedly cleared using milling tools and overshot assemblies, with a total of 11 casing correction operations and 17 fishing maneuvers performed. In total, 831 meters of coiled tubing were recovered. It was determined that the remaining coiled tubing, with its top end at 2120 meters, was more tightly stuck than anticipated. Consequently, the well was abandoned.

3. SOLUTIONS TO PREVENT COLLAPSE OCCURRENCES

Geothermal reservoirs in western Turkiye have experienced significant pressure declines due to aggressive exploitation over the past two decades. In low-pressure fields, the weight of drilling mud and the density of cement slurry must be carefully adjusted to suit the specific field conditions. High-density cement slurry (14.5 to 15.5 ppg), in particular, often leads to slurry losses into the formation, causing the cement level behind the casing to drop. This necessitates a top job cementing operation, which can result in poor cementing quality and uncemented sections. Therefore, a lower density cement is essential to prevent top job cement.

The cement thickening time is a critical parameter influencing cement quality. Extended thickening time often leads to free water accumulation in small openings and at the top of the cement column. Therefore, a well-specific cement slurry composition must be designed to account for the depth and temperature of the well. By optimizing the thickening time to meet the minimum necessary requirements, free water accumulation during the cementation process can be minimized, ensuring better cementing quality.

In the Turkish geothermal industry, CBL is generally not conducted, although they should be a standard procedure after each cementing operation to assess the quality of the cementing job. For existing wells, it is recommended to perform a CBL measurement prior to running an ESP or coiled tubing to identify any potential risks of APB. Identified risks are typically mitigated by creating small perforations in these intervals, a process known as punching, to release pressure as the well heats up. While punching introduces a potential risk of fluid flow into the perforated zone and penetration into the cement over time, no such issues have been observed to date. Additionally, it is worth noting that no casing collapses have been reported in wells where punching has been performed.

When initiating well production, flow rates should be maintained at low levels, or pumping should be periodically halted until the well reaches its full production temperature. Gradually heating the casing allows more time for any trapped water in the casing annuli to escape through available flow paths into the surrounding formation.

Geothermal wells with high flow rates often lead to the mobilization of fine particles within the reservoir. These particles act as abrasives, creating an erosion effect that gradually reduces the inner diameter of the casings. Thus, the casings become less resistance to collapse. To mitigate this issue, optimizing the flow rate can be an effective approach. Additionally, the use of optimized slotted liners at the sand face can help filter out solid particles, further reducing the impact of erosion.

Aydin and Merey (2021) proposed using a 9 5/8-inch casing as a liner suspended within the 13 3/8-inch casing, as illustrated in Figure 7. This casing design will help prevent casing collapse caused by uncemented sections between the 9 5/8-inch and 13 3/8-inch casings. In this configuration, APB will result in formation fracturing, allowing the pressure to be safely released.

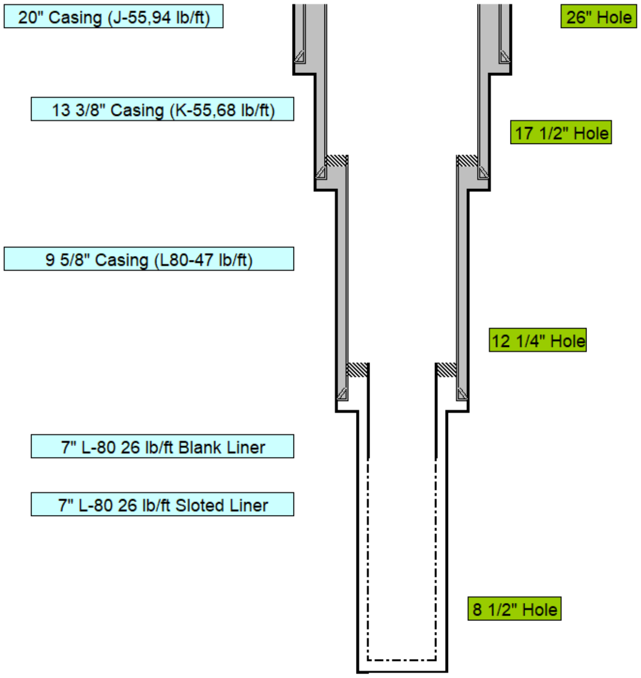

Figure 7: Proposed casing design for geothermal wells in western Anatolia, Turkiye to prevent casing collapse

4. CONCLUSION

This study investigates casing failure mechanisms in geothermal wells located in western Anatolia, Turkiye. It presents three cases of casing collapse, primarily attributed to annular pressure buildup between the 9 5/8-inch and 13 3/8-inch casings. The analysis identified poor cementing practices, particularly those associated with top job cementing, as a critical factor contributing to these collapse issues. Following practices are suggested to prevent casing collapses:

- The density of the cement slurry must be carefully optimized to match the specific field conditions, minimizing the need for top job cementing, which often leads to uncemented sections.
- By optimizing the thickening time to meet the minimum necessary requirements, free water accumulation during the cementation process can be minimized, ensuring better cementing quality.
- Well production should begin at low flow rates or with intermittent pumping to allow gradual casing heating, enabling trapped water in the annuli to escape into the surrounding formation.
- In the Turkish geothermal industry, while CBL is rarely conducted, it should be standard after cementing to assess quality and recommended before running ESP or coiled tubing to identify and mitigate APB risks through punching.
- High flow rates in geothermal wells can mobilize fine particles in the reservoir, causing abrasive erosion that reduces casing thickness and resistance to collapse. This can be mitigated by optimizing flow rates and slotted liners at the sand face to filter out solid particles and minimize erosion.
- Using a 9 5/8-inch casing as a liner in new wells can prevent casing collapse caused by uncemented sections between the 9 5/8-inch and 13 3/8-inch casings.

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