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REVIEW

Research on Casing Techniques for Horizontal Drilling in Fractured Strata During Water Conveyance Tunnel Exploration

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ABSTRACT

The most common aspect of water conveyance tunnel construction is the use of horizontal and sub-horizontal exploration drilling of headings of a tunnel to predict geology and groundwater conditions. The instability of boreholes, extreme loss of circulation, and high-head inflow are also common in fractured strata, which often inhibit completion of probe holes and the reliability of coring, packer testing, and grouting tests. Casing, consequently, is a significant enabling technology to stabilize fractured intervals and has a hydraulic isolation under coupled mechanical and hydrogeological disturbances. The review is a synthesis of research and engineering experience on methods of casing to be used in horizontal drilling of fractured rock masses used in the exploration of water conveyance tunnels. The geological and working environment is initially outlined with a focus on fracture-adaptable instability processes and the special goings on of underground drilling, such as the restricted workspace, cuttings difficult to move, and fast movement of the competent and crushed regions. Types of casing systems are then listed, including both standard threaded steel strings and telescopic programs, and more specialized casing system types, including expandable casing, swellable sealing elements, and external casing packers. Special focus is made on the sealing of annulus in horizontal holes, wherein slurry loss, gravity segregation, and non-uniform borehole geometry usually worsen isolation. Lastly, the article suggests adaptive choice of strategy accord-

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ing to real-time drilling reaction, and research priorities, such as tunnel-specific performance measurements, coupled hydro-mechanical modelling, and field trials of sophisticated sealing material and data-driven choice making.

Keywords: Horizontal Exploration Drilling; Fractured Strata; Casing Techniques; Annulus Sealing; Water Conveyance Tunnel

1. Introduction

Water conveyance tunnels are important for hydropower generation, irrigation, inter-basin water transfer, and urban water supply projects, infrastructures[1,2]. The geological and hydrogeological environment that is experienced along the alignment is a strong determinant of the safety and performance of these tunnels in the long term[3]. Unexpected water inflow, instability, and deformation are some of the most important causes of construction risks, especially in complex rock masses such as fractured, faulted, or crushed strata. This has led to the development of further geological investigation of the tunnel headings into becoming a common and essential part of the contemporary practice in tunnel engineering.

Horizontal or sub-horizontal drilling, which is undertaken using tunnel faces, admits, or shafts, is currently a popular exploration and forecasting method[4]. Through such drilling, the mass structure of the rocks, the development of fractures, as well as the conditions of the underground water and the possibility of the existence of undesirable geological conditions in the future of excavation are known directly. Horizontal exploration drilling through tunnels is more advantageous than surface-based boreholes or indirect geophysical techniques with regard to its spatial relevance, resolution, and promptness. The success of such exploration boreholes is, however, limited by the stability of the borehole itself, particularly when the drilling is conducted through fractured strata under high-pressure groundwater.

Fractured rock masses provide a blend of mechanical and hydraulic hindrances to horizontal drilling. Joints, bedding planes, faults, and shear zones are discontinuities that lower the mass integrity of rocks and provide preferential ways through which groundwater moves. In drilling, such characteristics can cause drastic circulation loss, fracture infill erosion, borehole expansion, and local collapse. Water influx may also occur abruptly in fractured areas of water, which are likely to cause additional instability of the borehole and risk the process of tunneling. By comparison with vertical boreholes, horizontal and sub-horizontal holes are highly prone to instability because decomposition of cuttings is not easily facilitated, the maintenance of the drilling fluids is not balanced, and the blockage of the material is more likely to occur along the axis of the borehole[5,6].

In order to overcome these hurdles, casing processes are also commonly used when drilling vertical waterways horizontally during the exploration of water tunnels. Casing in this context means laying down steel or composite tubular components into the borehole to stabilize any fractured part of the borehole, isolate any permeable section, control inflow of groundwater, and even create a solid and dependable medium through which future activities of the borehole, such as coring, packer tests, or grouting, could be carried out[7]. Well-modeled and rigorously fitted casing systems are capable of adding a great deal of success to the outcome of drilling, improving the quality of data, and decreasing the hazards of constructing the tunnel face. On the contrary, poor casing plans can lead to stuck equipment, tests not passing, poor geological interpretation, and wastage.

The practical significance notwithstanding, horizontal drilling casing methods in fractured strata vary significantly from the usual casing methods in vertical boreholes or oil and gas wells[8,9]. Exploration that is tunnel-based is carried out in the narrow underground conditions that may be limited in space and equipment size, and there are stringent safety conditions that are bound to water control and ventilation. Boreholes of short length usually cross over very heterogeneous geological conditions within a short distance. Moreover, casing is commonly placed as a short-term solution, but it should be capable of surviving complicated redistribution of in-situ stress and groundwater pressure, as well as mechanical contact with the fractured rock. The mentioned factors require solid, flexible, and tunnel-specific casing solutions.

An extensive collection of casing systems and installation procedures has been used in fractured rock environments over the last few decades[10,11]. The near-face zones and faulted intervals are usually stabilized using conventional threaded steel casing, telescopic casing programs, liners, and conductor casings. Under even more adverse circumstances, specialized industry technologies have been brought forward, like expandable casing, external casing packers, swellable liners, and chemical or microfine cement sealing. Simultaneously, the installation methods, such as casing advancement methods, annulus sealing methods, and real-time monitoring in the course of drilling, have been developing. Nevertheless, the available literature and reports of the engineers tend to be interspersed in the records of the cases of particular tunnels, the practice of a specific region, or the publications devoted to the concrete project to extract the generalized conclusions or general design principles.

The present studies of the casing methods in the exploration drilling in tunnels also depict a number of limitations. Numerous published materials highlight successful implementations but do not give much quantitative analysis of casing performance or failure modes. The relationship between fractured rock mass properties, groundwater conditions, and casing behavior is one that is not understood fully, especially when conditions are coupled between hydro and mechanical[12]. In addition, the introduction of technologies that are carried out in the oil and gas horizontal wells has been taking place at a much higher rate than the thorough evaluation of the technologies in underground construction, where boundary conditions and operation limitations vary greatly.

In this regard, it is high time that a review of the methods of casing the horizontal drilling technique of the fractured strata in the exploration of the water conveyance tunnel is conducted. This review can serve to solidify the available knowledge, bring out the applicability and limitations of the various casing systems, and offer a step-by-step methodology of choosing and applying casing strategies in different geological and hydrogeological settings. The synthesis of results of field case studies, lab tests, and numerical models can be used to identify typical failure modes, mitigation strategies, and parameters that can control the performance of casing.

This review has threefold goals. To begin with, it will provide a summary of the geological and operational circumstances that require the use of casing in the exploration drilling (horizontal) of water tunnels through fractured strata and the effects on the groundwater. Second, it attempts to categorize the types of casing systems, methods of installation, and methods of sealing, their strengths, weaknesses, and their common uses. Third, it determines research gaps and emergent trends, such as the possibility of adaptive casing strategies, new materials, and data-driven support in further practice of tunnel exploration[10,13,14].

Offering a tunnel-oriented and integrated view, this review is meant to provide service to both researchers and working engineers undertaking underground water conveyance projects. Hopefully, this synthesis can serve to make tunnels safe, predict geological forecasting with more confidence, and further the exploration drilling technology under complicated fracture geology. To explain the exploration environment in the tunnel and the functions that casing should play in fractured, water-bearing environments, a conceptual schematic has been given in **Figure 1**.

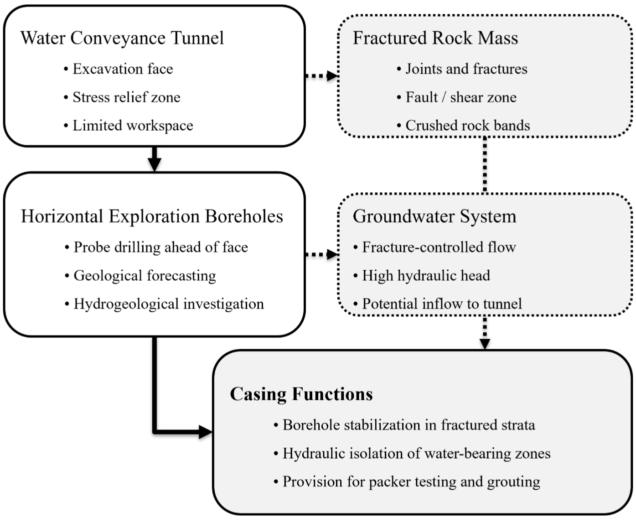

Figure 1. Conceptual schematic of tunnel-based horizontal exploration drilling in fractured strata and the primary functions of casing, including borehole stabilization, hydraulic isolation, and enabling subsequent testing or grouting operations.

2. Geological and Operational Setting for Horizontal Drilling in Fractured Strata

The tunneling exploration in terms of horizontal and sub-horizontal drilling is performed in a geological and functional environment that is fundamentally different from the drilling operations on the surface and the vertical boreholes[15]. Their contact with fractured rock masses, the state of groundwater, and the process of drilling impose a leading control over the stability of boreholes and, to a larger extent, the need, time, and efficiency of casing installation. It is thus necessary to have a clear picture of such conditions to be able to design the casing methods used in the exploration of the water conveyance tunnels rationally.

2.1. Characteristics of Fractured Strata in Water Conveyance Tunnel Alignments

The fractured strata that are usually found along conveyance tunnel alignments are jointed rock masses, fault and shear zones, crushed belts, and locally developed fracture networks in relation to tectonic activity or lithological contrasts[16,17]. The rock masses are defined as having low structural integrity and sharp, short spatial heterogeneity. There can be a large range of fracture spacing, persistence, aperture, and orientation in a single exploration borehole, and so there are alternating intervals of relatively competent rock and seriously weakened material.

Engineering-wise, both mechanical stability and hydraulic behavior are controlled by the level of fracturing. Fractures that are spaced close to each other or are very persistent decrease the self-supporting capacity of the borehole wall, especially when stress relief occurs around the tunnel excavations. The types of fractures that are particularly susceptible to erosion and washout during the drilling process include fractures that may contain clay, gouge, or weathered material, but fractures that are open or partially open may be a source of inflow of groundwater. These fractured areas in water conveyance tunnels are usually accompanied by high hydraulic gradients, since tunnels cross regional groundwater flow systems or confined aquifers with high head[18].

The geological description of fractured strata in the exploration of the tunnel is based on a synchronism of the mapping of tunnel faces, probe drilling feedback, core logging, and hydrogeological observations[15,19]. Nevertheless, the existing geological information is usually incomplete or questionable due to the small diameter and length of horizontal exploration holes, and a high number of circulation losses. Such uncertainty exerts more requirements on casing strategies that need to be flexible enough to deal with the rapidly varying ground conditions. In order to unify the scope of fractured-rock situations pertinent to tunnel exploration, as well as to refer them directly to stability and casing concerns, characteristic situations are summarized in **Table 1**.

2.2. Borehole Instability Mechanisms in Horizontal Drilling through Fractured Rock

Borehole instability in fractured strata has been caused by both the effects of mechanical failure and hydraulic disturbance[19,20]. These mechanisms are enhanced by the effect of gravity and closeness of the tunnel excavation in horizontal and sub-horizontal boreholes, which disturbs the stress field locally. Symptoms of mechanical instability are often blocking detachment along intersection fractures, slabbing of the wall of the borehole, or the gradual widening of the borehole as a result of the controlled breakout along fractures. The borehole can lose all its geometry and become partially or wholly collapsed in highly fractured or crushed areas.

Table 1. Typical geological and hydrogeological conditions encountered in tunnel-based horizontal exploration drilling and their implications for borehole stability and casing needs.

Geological Condition	Fracture Characteristics	Typical Groundwater Behavior	Main Drilling and Stability Issues	Implications for Casing
Moderately jointed rock mass	Discrete joints, limited persistence, small apertures	Low to moderate seepage	Localized sloughing, minor circulation loss	Short casing or liner near tunnel face
Intensely fractured rock	Closely spaced, intersecting fractures, variable aperture	Distributed inflow, pressure-dependent loss	Borehole enlargement, progressive collapse	Early casing installation, staged isolation
Fault or shear zone	Crushed rock, gouge-filled fractures	Concentrated high inflow, high head	Sudden collapse, severe loss of circulation	Telescopic casing, aggressive sealing
Karstified or open-fracture zones	Large apertures, high connectivity	Rapid inflow, unstable pressure response	Washout, loss of borehole geometry	Robust casing with enhanced annulus sealing

Instability is further caused by hydraulic processes[21]. Under conditions of drilling, the circulation fluid can tend to flow more through permeable fractures, which leads to partial or complete circulation loss. The resulting decrease in the fluid support pressure facilitates fracture expansion and relaxation of infill materials. Uncontrolled inflow of groundwater in water-bearing fractured zones can erode thin fillings in the fractures, carry fine particles into the borehole, and cause rapid collapse. The latter are especially troublesome in horizontal boreholes, where collapsed material is likely to be located along the borehole axis and block further drilling or casing.

Fractured strata are characterized by the coupling of mechanical with hydraulic instability[12]. The mechanical collapse usually follows the circulation loss, and the loss and inflow are respectively worsened by the collapse. Once this feedback loop is achieved, it becomes harder to take remedial actions, which is why installing casing in time is essential to segregate unstable or permeable areas. The relationship between mechanical degradation and hydraulic disturbance depends in a systematic way on the fracture architecture and groundwater regime; common cases and the implications of these cases in the stability of boreholes are summarized in **Figure 2**.

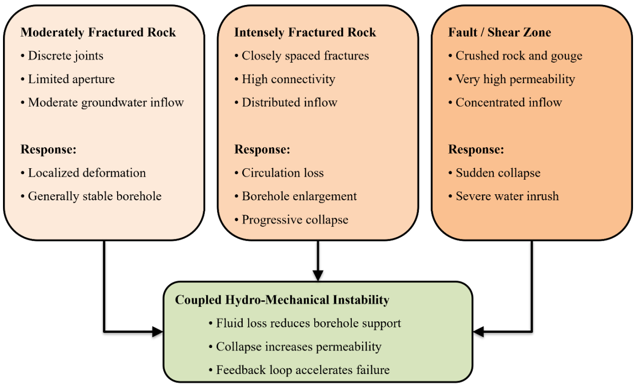

Figure 2. Representative geological and hydrogeological scenarios affecting horizontal borehole stability in fractured strata, illustrating fracture-controlled deformation, circulation loss, and groundwater inflow mechanisms.

2.3. Influence of Drilling Methods and Fluids on Casing Requirements

The type of drilling adopted has a serious impact on the borehole condition and consequently on casing performance[22]. Rotary drilling, wireline coring, or down-the-hole hammer technology is often used in horizontal exploration drilling in tunnels, depending on the strength of the rock, the goals of the investigation, and drilling equipment limitations. Coring techniques offer good geological data, but normally create smaller annular openings and are also more prone to borehole deformation. Non-coring can also progress faster through fractured areas and, in most cases, provide inferior information on fracture features.

Drilling fluids play a total role in borehole stabilization and disturbance. Fluids based on water are often employed in tunnel conditions because they are easy and environmentally friendly, but have low capacity to block cracks or hold cuttings in horizontal sections. They include polymer-enhanced fluids, foams, and systems that are based on bentonite, which can enhance the transport of the cuttings and lessen loss, yet this is strongly dependent on the aperture and connectivity of the fracture. Even the most sophisticated drilling fluids cannot be counted on to hold boreholes intact in an extremely fractured formation, and mechanical stabilization through casing has become inevitable[5,23].

The relationship between the method of drilling, fluid Type, and the behavior of the fractured rock is connected to casing strategy directly[24]. Steady development without proper stabilization will lead to a possibility of snowballing collapse before casing can be laid in, and over-conservative drilling parameters will decrease efficiency with no certainty of stabilizing the earth. As a result, casing requirements should be considered together with drilling technology and not as a separate consideration of design.

2.4. Functional Requirements of Casing in Tunnel Exploration Drilling

Casing serves a wide variety of purposes, in addition to mere borehole support, in the context of exploring water conveyance tunnels[25]. Its main action is to stabilize fractured intervals and hold a useful borehole geometry throughout the investigation and undertaking activities. This stabilization is necessary when it comes to the reliability of further operations like coring, borehole imaging, permeability testing, and grouting trials.

The hydraulic action of casing is also important. Casing makes it possible to test the conditions of the groundwater in a controlled manner through the isolation of water-bearing fractures or fault zones and to prevent the uncontrolled inflow to the tunnel face. Casing can also serve as a protective measure in a high-head situation, as the chances of sudden water inrush occurrence during drilling are minimized. Moreover, correctly sealed casing systems will offer a set limit on packer testing and grouting, enhancing the test result interpretability and remediation[26].

Casing in exploration drilling is not permanent like permanent tunnel linings or support systems in that case. However, it should be able to resist intricate loading situations, such as when in contact with irregular borehole walls, contact with dissimilar groundwater pressure, and stress redistribution caused by excavation of the tunnels. These functional demands make high demands in the design of casing, the quality of its installation, and the sealing performance, especially in fractured strata, where geological conditions are extremely diverse and unpredictable[25].

Overall, the geological and operational environment of horizontal drilling in fractured strata poses a difficult scenario where the instability of boreholes, the interaction between boreholes and groundwater, as well as equipment constraints, merge. Knowledge of these conditions gives the basis on which the current casing techniques can be assessed and more successful measures can be devised that meet the requirements of the water conveyance tunnel exploration[28].

3. Casing System Types and Strategy Selection

The casing systems implemented in horizontal drilling to explore tunnels in water have developed in line with the complicated mechanical and hydraulic environments in fractured strata[29]. In contrast to standardized casing programmed in vertical wells, tunnel-based exploration drilling normally entails flexible, condition-dependent solutions that can be changed as the drilling goes on. Choosing a suitable casing system is thus a strategic move that incorporates geological knowledge, drilling technique, investigation purpose, and risk tolerance.

3.1. Design Philosophy for Casing in Fractured Strata

The principal design philosophy of the casing in the fractured rock is not remedial but preventive in nature[11]. Since borehole instability in the fractured areas is rather quick and progressive, casing can be used with the best effect when it is installed before the severe collapse or an uncontrolled inflow of water takes place. This necessitates that casing decisions are made based on the perceived problems in drilling as well as the perceived geology ahead of the tunnel face.

The main design factors are the extent of fracturing, the probability of cross-fault or shear zone, anticipated pressure of groundwater, and the functionality needed by the borehole once the casing is installed[30]. Casing must, in many cases, be used in exploration drilling to achieve more than one function at the same time, such as stabilization, hydraulic isolation, and access to test and grouting. Due to this, the casing design has been more inclined towards reliability and flexibility rather than using the minimum possible amount of material. In seriously fractured or water-bearing strata, where the effects of casing failure are extreme, conservative design methods are often used.

The other characteristic property of the casing design in the exploration of tunnels is the fact that once instability occurs, there is minimal margin to improve the situation[31]. Lack of working space and operational limitations in tunnels imply that the complex remedial operations cannot be easily carried out. This fact confirms the need to choose casing systems that are sturdy in times of uncertainty and can be installed quickly.

3.2. Conventional Casing Systems and Their Application

The most common solution currently utilized in the stabilization of horizontal exploration boreholes in fractured strata is conventional steel casing[32]. Standard or flush jointed, threaded steel pipes are widely used because they are available, mechanically strong, and can be used together with the existing drilling equipment. In fractured rock of moderate fracture, casing systems may usually suffice to prevent collapse and isolate localized permeable zones.

Telescopic casing set-ups are commonly used in geological situations where the geological conditions become poor with the depth or distance of the face of the tunnel[33]. In these instances, a bigger-diameter casing is laid close to the collar to stabilize the very disturbed area affected by tunnel excavation, and which is succeeded with smaller-diameter casing strings in deeper fractured ranges. The staged method enables the drilling to continue gradually, as well as keep the boreholes intact, and reduces the chances of total failure.

In exploration holes, where temporary stabilization is the aim as well as the isolation, liner-type casing is sometimes used without being cemented in place throughout its length. Although liners have the benefit of installation with less friction and easy deployment, they have a low sealing capacity unless such is supplemented by other measures. The conventional casing systems, therefore, are most efficient in cases where the geological conditions are moderately fractured, and the groundwater pressures are manageable [25,34].

3.3. Specialized Casing Technologies for Complex Fractured Zones

At the highly permeable or severely fractured strata, the traditional casing solutions might fail to meet expectations [35]. **Table 2** will present a systematic categorization of the types of casing systems and their general areas of use. In order to overcome these circumstances, various specially developed casing technologies have been implemented in the practice of tunnel exploration. First designed to meet the needs of oil and gas services, expandable casing systems have gained growing popularity because they can be used in irregular borehole geometry and minimize annular clearance. These systems are able to enhance hydraulic isolation of fractured areas through expansion into the borehole wall to increase mechanical support.

Another example of a specialized solution can be swellable casing and liner systems [25]. These systems have materials that grow when in contact with water, thus closing any fractures and annular voids without the actions of complicated cementing processes. The swellable elements may also be used in fractured strata where there is active groundwater flow, where they may be the quickest and most efficient method to offer isolation, though their durability under different pressure conditions is a subject of research.

Isolating discrete intervals in a borehole is also done by external casing packers and mechanically forced sealing devices [36]. The technologies are especially useful in cases where selective testing or stage grouting must be applied. The issue with successful application, however, is their effective placement and consistent activation, which may be difficult in long horizontal holes due to varying borehole conditions.

Table 2. Classification of casing system types used for horizontal exploration drilling in fractured strata, including structural principles, advantages, limitations, and typical application conditions.

Casing System Type	Structural Principle	Main Advantages	Limitations	Typical Application Scenarios
Conventional threaded steel casing	Rigid mechanical support	High strength, availability, simplicity	Limited sealing without cement	Moderately fractured strata
Telescopic casing program	Staged diameter reduction	Adaptable to variable geology	Reduced final borehole diameter	Long probe holes with worsening ground
Liner casing	Partial support without full cementing	Easier installation, reduced drag	Poor hydraulic isolation	Temporary stabilization
Expandable casing	Radial expansion against borehole wall	Conforms to irregular holes	Cost, limited tunnel experience	Highly fractured, irregular boreholes
Swellable liner/packer systems	Water-activated expansion	Rapid sealing, no cement	Performance uncertainty	Water-bearing fractured zones

3.4. Annulus Sealing and Casing–Rock Interaction

The efficiency of a casing system is highly determined by the way the annulus between the casing and the borehole wall is treated, regardless of the type of casing [37]. This annular space is not usually homogeneous in specimen fractured strata, and it commonly contains enlarged cavities, open fractures, and areas of weak infill. The features can weaken the mechanical stability and hydraulic isolation when untreated.

The cementing is the most popular form of annulus sealing, which, however, in a horizontal exploration hole, is not an easy task [38,39]. Segregation due to gravity, slurry being lost prematurely in fractures, and not being displaced entirely by the drilling fluid is a persistent problem. In order to counter the problems, lightweight, thixotropic, or microfine cement formulations are frequently used, occasionally with staged injection methods. Chemical grouts or resin materials can also be employed in highly permeable areas in order to get rapid setting and minimize washout.

The three factors that control the overall performance of the system are the interaction between casing, sealing material, and fractured rock mass[40]. A high stiffness contrast between the casing and the rock surrounding might cause a localization of stress and a deformation of the casing, but on the other hand, inadequate bonding might create a leakage pathway along the casing. This interaction is therefore the key to successful casing strategy selection.

3.5. Strategy Selection under Geological Uncertainty

Among the characteristic issues faced in the exploration drilling of a tunnel is the fact that the geological uncertainty levels are very high in front of the excavation face. Consequently, casing strategies should be dynamic, as opposed to being fixed. Early casing schedules are normally based on the available geological models and past exploration data, and such schedules are often updated in accordance with the real-time drilling conditions, including penetration rates, torque variations, and circulation losses[11].

The choice of adaptive strategy can frequently be the trade-off between the risks associated with installing casing beforehand and the implications of the delay[41]. Premature casing can lead to a decrease in the efficiency of exploration and the inability to collect data, and delaying casing can lead to an irreversible borehole collapse or uncontrolled influx of water. Practiced professionals, then, use already established decision thresholds, based on both the geological indicators and operational parameters, to make decisions on casing deployment.

Conservative and flexural casing approaches are typically preferred in fractured strata in relation to water conveyance tunnels. The strategies focus on the initial stabilization of high-risk areas, employment of staged systems or telescopic systems, and the combination of casing decisions with drilling and testing goals. Working to ensure that the choice of the casing system is consistent with the current developing knowledge of the ground conditions, the engineers can make the process of horizontal exploration drilling in the complicated fractured areas safer and more efficient[37].

3.6. Hydro-Mechanical Coupling in Casing Performance

The long-term integrity of a casing system in fractured strata is governed by the coupled hydro-mechanical (HM) interaction between the tubular string, the annular sealant, and the surrounding rock mass. As drilling progresses, the redistribution of in-situ stresses and changes in pore water pressure within the fracture network can lead to non-uniform loading on the casing. Numerical modeling studies, particularly those employing the Discrete Element Method (DEM) or Finite Element Analysis (FEA), have shown that high-head groundwater inflow can erode fracture infills, leading to localized loss of support and subsequent casing deformation or “buckling”. Conversely, the casing provides a mechanical boundary that resists fracture dilation and maintains hydraulic isolation. Understanding these interactions is critical for selecting sealant materials that can accommodate mechanical strain while maintaining a low-permeability barrier against high-pressure seepage.

4. Installation Techniques, Performance Evaluation, and Failure Mitigation

The success of a casing system in fractured strata does not depend only on the type and design of a casing system, but also on how it is installed, verified, and the future risk management[42]. The installation activity in horizontal drilling to explore the water conveyance tunnels is performed under difficult conditions in the underground and in most cases on unstable ground. Casing deployment is a risk-sensitive and technical procedure. Performance appraisal and mitigation of failure are thus part and parcel of casing practice and not a consideration of post-installation.

4.1. Installation Techniques for Horizontal Casing in Tunnel Environments

Modern casing strategies increasingly rely on real-time data acquisition systems that monitor drilling parameters such as torque, rate of penetration (ROP), and circulation loss to identify instability precursors. Sensor technologies, including high-frequency surface measurements and downhole “Measurement While Drilling” (MWD) tools, provide the granular data necessary for adaptive decision-making. Recent research has demonstrated the potential of machine learning (ML) algorithms, such as random forests and neural networks, to predict "stuck pipe" events or severe circulation loss by analyzing these parameter trends. For instance, case studies in complex strata have shown that ML-based predictive models can improve casing success rates by triggering early deployment before irreversible collapse occurs. However, a significant gap remains in miniaturizing these technologies for the small-diameter, short-range horizontal holes typical of tunnel exploration, where space and cost constraints often limit high-end sensor deployment. Borehole irregularities and localized collapse are common in fractured strata and greatly increase drag, increasing the chances of poor installation or casing deformation[43].

Boreholes are frequently reamed to a diameter size in excess of the outer diameter of the casing in order to allow installation with a reasonable margin of allowable deviation and debris. Nevertheless, over-reaming can widen broken areas and destabilize the rock, especially in weak or water-bearing rock. Consequently, the art of reaming has to be weighed against an installation clearance requirement. In other applications, casing is installed as the drilling goes on to minimize the unsupported borehole and exposure to collapse.

Tunnels create operational constraints that make installation more difficult[44]. The casing is limited by the working space, which curtails casing handling and makes-up work, and the casing alignment is important to avoid buckling in the long horizontal setting. Such difficulties require a high level of control of drilling path and casing orientation, and the close interaction of drilling and installation teams. Since the isolation performance is usually governed by annulus treating instead of the casing strength itself, the main sealing methods and their capabilities in the fractured formations can be compared in **Table 3**.

Table 3. Annulus sealing methods for casing in horizontal boreholes intersecting fractured rock, comparing material characteristics, operational advantages, typical challenges, and suitability across permeability regimes.

Sealing Method	Material Characteristics	Advantages	Main Challenges	Suitability for Fractured Strata
Ordinary cement grout	High strength, low cost	Structural bonding	Loss into fractures, segregation	Low to moderate permeability
Microfine cement	Fine particle size	Improved penetration	Longer setting time	Fine-fractured zones
Thixotropic/ lightweight cement	Controlled rheology	Reduced segregation	Mix sensitivity	Horizontal holes
Chemical/resin grout	Rapid setting, low viscosity	Effective in high-flow fractures	Cost, environmental constraints	Fault zones, high inflow
Mechanical packers/seals	Physical isolation	Precise zonal control	Installation complexity	Selective testing and grouting

4.2. Annulus Sealing and Completion Practices

The leading factor of hydraulic isolation and long-term stability once casing is installed is annulus sealing[45]. In fractured strata, sealing operations have to deal with irregular annular geometries, non-uniform fracture apertures, and active groundwater flow. The most common one is cementing, although the technique of its successful implementation in horizontal exploration holes is not an ordinary phenomenon.

The position of the horizontal cement depends on the status of the segregation of the heavy particles, where the ones with a greater mass will be layered at the bottom of the borehole and may form a channel along the upper section[46]. Besides, the cement slurry flowing into open fractures may result in partial sealing and bond weakness. In order to overcome these challenges, modified formulations of cement of low density, high thixotropy, or small particle size are typically utilized. Several methods are also applied to enhance control on placements in highly fractured areas; these include staged cementing techniques, where sealing is actually done in several stages.

Situations where cementing has become impractical or ineffective are dealt with by the use of other sealing materials, such as chemical grouts or resin systems. These materials are able to fill small fractures and cure in a short time, which means they are applicable in high-flow conditions. Their application should, however, be done with consideration of compatibility with groundwater chemistry, environmental constraints, and tunnel safety requirements.

4.3. Performance Evaluation and Quality Control

The assessment of casing systems in the exploration drilling of tunnels has its own challenges[47]. Vertical wells typically use direct inspection techniques that are impractical, and the transitory nature of exploration casing constrains the extent of post-installation testing. However, performance assessment is necessary to ensure that casing goals have been attained as well as to guide further drilling and testing.

Qualitative data is collected by looking at operational indicators realized during and after installation. The presence of abnormal torque or resistance during drilling outside the casing shoe can be an indication of bad stabilization or non-sealing of the casing. Equally, changes in the rate of inflow or pressure response of the packer during packer tests that are not expected can indicate leakage along the casing or via poorly closed fractures. Isolation effectiveness is determined through pressure tests that are performed on the top and bottom of the casing shoe, where possible.

Borehole imaging equipment is used in certain projects to determine casing placement, deformation, or the condition of the annulus[48,49]. Though a few can be used in horizontal holes, they can be valuable in understanding the mechanisms of failures and inform remedial actions. The process of systematically determining which parameters to install and which indicators to show is becoming a significant part of the quality control and project-to-project knowledge transfer.

4.4. Common Failure Modes in Fractured Strata

Casing systems in fractured beds are sensitive to multiple modes of failure, despite careful design and installation[50]. Casing buckling, opalization, or connection damage based on too much installation forces or on contact with irregular borehole walls are examples of mechanical failures. Cumulative friction can cause localized stress concentrations and deformation, especially of thin-walled casing in long horizontal holes.

Hydraulic failures are also very common and, in most cases, they are harder to notice[51]. Poor sealing of the annulus can lead to leakage systems along the casing, and this can lead to bypass of isolation zones by groundwater. Fracture reactivation of fracture seals may occur in highly fragmented rock when it experiences the drilling or testing pressure. In extreme situations, water inflow cannot be controlled, and as such, it can undermine both the borehole and the tunnel face.

The next critical scenario of failure is when the casing becomes trapped during the installation process, and it is either by the borehole collapsing or by over-friction[37]. Stuck casing not only inhibits completion of the exploration hole, but it can also block the future drilling or testing, requiring abandonment or expensive clean-up efforts. In order to connect the observed failure modes to real-life response and to assist in risk-based casing planning, the mitigation measures and failure modes representative of these are summarized in **Table 4**.

Table 4. Common casing failure modes in fractured strata during tunnel-based horizontal exploration drilling, diagnostic indicators, consequences for investigation quality and safety, and representative mitigation measures.

Failure Mode	Primary Causes	Typical Indicators	Consequences	Mitigation Measures
Borehole collapse before casing	Intense fracturing, fluid loss	Sudden torque increase, stuck tools	Abandoned hole	Early casing, reduced open-hole length
Stuck casing during installation	Excessive friction, debris	Incomplete run-in	Loss of borehole function	Reaming control, staged installation
Poor annulus sealing	Slurry loss, irregular geometry	Leakage during testing	Invalid test results	Staged grouting, alternative sealants
Casing deformation	High thrust, uneven contact	Increased drag post-installation	Restricted access	Stronger casing, alignment control
Seal degradation	Fracture reactivation, pressure cycling	Delayed inflow	Reduced isolation	Adaptive pressure management

4.5. Mitigation Strategies and Adaptive Management

A successful management of casing-related risks in fractured strata depends on the proactive and responsive management during the drilling operation[52]. The possibility of sudden instability before the installation of the casing can be mitigated by pre-stabilization (use of controlled drilling parameters and purposeful usage of loss control materials). In high-risk zones, pre-grouting before the borehole face may be used to enhance the integrity of the mass of rocks and to make them less permeable.

In the course of installation, real-time control of the torque, thrust, and circulation behavior allows identifying the appearance of issues early and making a timely intervention. Casing plans commonly include contingency plans such as stepwise installation, partial withdrawal, or changes in sealing materials, which are necessary to adapt to unforeseen circumstances[25].

In a wider context, improvement policies have the advantage of a combined mechanism that connects geological forecasts, drilling monitoring, and casing effectiveness[53]. The experience gained from casing failures, where these experiences are systematically collected and examined, can be very useful in the correction of design requirements and installation procedures. Fractured strata around water conveyance tunnels necessitate such adaptive management in sustaining borehole functionality, data reliability, and security of tunnel construction operations in the conditions of high uncertainty of the ground. **Figure 3** offers an adaptive workflow based on this review, and it links the drilling observations with casing decision thresholds and their verification steps.

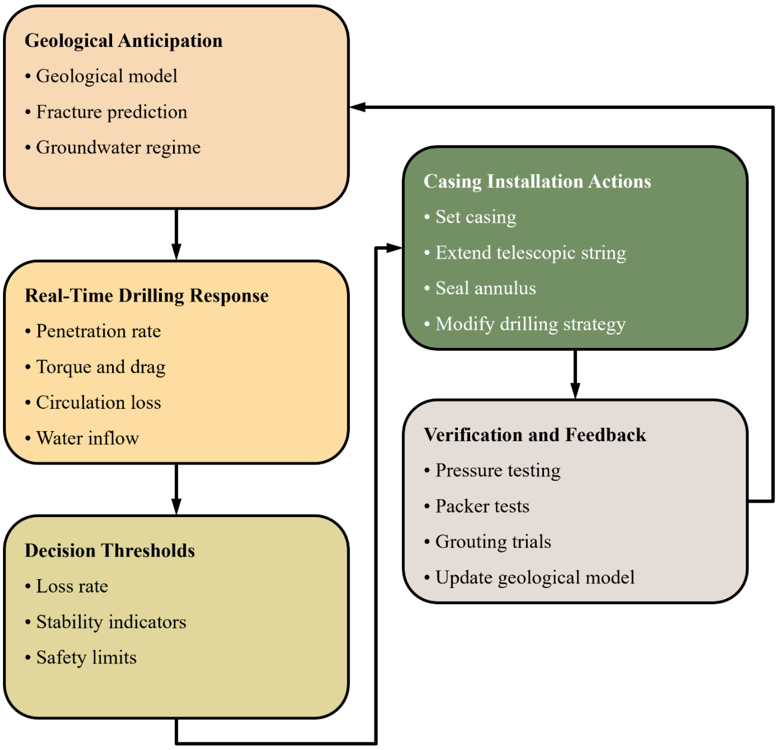

Figure 3. Integrated workflow for adaptive casing strategy selection in tunnel exploration drilling, linking geological anticipation, real-time drilling response, intervention thresholds, installation actions, and verification feedback.

5. Conclusions

Horizontal and sub-horizontal exploration drilling constitutes a vital part of geological prediction and risk management during the construction of water conveyance tunnels, although its performance in the fractured formations is often hampered by borehole unsteadiness, drill age severity, and inflow of the groundwater. In such a context, casing is not only a key protective device but a fundamental facilitating technology that makes or breaks the completion of drilling, interpretation of hydrogeological tests, and the control and safety of unfavorable zones immediately before the tunnel route. The literature sources reviewed in this paper all point to the fact that effective casing practice in fractured rock relies on the coordination of casing design, the timing of installation, and the sealing of the annulus upon the mechanical-hydraulic behavior of the rock mass, not making casing a standardized, one-size-fits-all intervention.

One of the key lessons learned during the course of previous research and during the commission of the project is that fractured strata can place extremely nonuniform boundary conditions on horizontal boreholes. The fracture intensity, aperture, and infill properties and connectivity change at short distances and respond strongly to the regimes of groundwater pressure. These are the factors that determine the likelihood as well as the rate at which instability will develop. In line with this, the best casing strategies are both preventive and adaptive. The preventive measures are applied by focusing on constraining open-hole exposure during high-jurisdictional intervals, stabilizing the near-face disturbed zone at its initial stage, and isolating permeable features before the increase of the circulation loss into progressive collapse. Adaptive strategies acknowledge that pre-drill geological models are hardly adequate on a tunnel scale and thus incorporate real-time drilling feedback, including loss behaviour, torque evaluation, penetration-rate anomalies, and water-inflow indicators, into the decision-making rule on when to set casing, whether to extend telescopic strings, and what sealing control to use.

In general, in casing systems, threaded steel casing that is conventional and staged/telescopic programs are the most popular due to their mechanical stability, accessibility, and familiarity in terms of operation in underground construction. Nevertheless, the review also notes that in specific circumstances, application of specialized technologies, i.e., expandable casing, swellable sealing elements, and external casing packers, provides significant benefits, in particular, in the case of irregular borehole geometry, highly conductive fractures, or the necessity to isolate intervals selectively to conduct tests and grout. Their wider use in the exploration of tunnels, though, is limited by their inadequate field validation, poor performance under the cycling of groundwater chemistry and pressure, and practical limitations of their operation in constrained underground conditions. This is the reason why technology selection must be viewed as a risk-related decision that considers both the extent of the fractured zone and the aftermath of failure in operation, as opposed to a change in technology to a conventional casing.

The hydraulic integrity of most casing systems in fractured strata turns out to be determined by annulus sealing. The successful installation of casing may still allow leakage to occur through incomplete sealing because of loss of slurry to fractures, gravity division in the horizontal positioning, or inadequate displacement, which can lead to leakage pathways that disrupt the aims of isolation and invalidate the dependability of the packer tests, inflow testing, and grouting tests. The analyzed evidence indicates that enhanced sealing performances relate to the customization of grout and cement formulations to fracture conditions, embracing the staged sealing activities when the permeability is excessive and including some activities that surpass the installation finishes. Practically, the casing performance would be evaluated by the ability to provide functional isolation and serviceable access to the desired investigation work, and not just by the ability of the casing string to reach its target depth.

Modes of failure reported in fractured strata, such as stuck casing, long run deformation or buckling, shoe leakage, micro-annulus flow, and seal degradation due to fracture reactivation, support the necessity of integrated planning and contingency design. The mitigation is effective, as defined by early stabilization; the thresholds of intervention in high-head areas are conservative, and recovery pathways under the conditions of tunnel constraints. Notably, most failures can be explained by interrelated series: loss of circulation decreases the borehole support, instability encourages drag and hinders installation, and lack of full sealing permits continued inflow that continues to worsen conditions of the borehole and adjacent tunnel. The control of such coupled sequences involves the need to incorporate casing decisions into a more general observational scheme involving geology, drilling response, and water control.

There are various gaps and development priorities in research. To begin with, the field does not have coherent and tunnel-specific measures of casing performance and isolation quality sufficient to compare across projects and make evidence-based choices. Second, coupled hydro-mechanical models explicitly modelling the fractured rock, groundwater head, development of borehole enlargements, and casing-seal interaction are not yet developed for tunnel exploration geometries and severely restrict predictive ability. Third, the long-term action of sealing systems in response to variations in pressure, chemical assault, and repeated testing/grouting intervals is not adequately recorded despite the fact that such actions are prevalent in water conveyance endeavors. Lastly, new strategies, including real-time decision support streams via drilling data streams, enhanced borehole imaging of horizontal holes, and new sealant materials with thixotropic, microfine, or self-healing capabilities, need to be methodically verified with a well-designed field experiment and published.

In the future, innovation in the casing of horizontal drilling in fractured strata will probably be led by a move to a less experience-based approach to practice, to a more data-driven, performance-proven design. This involves coming up with standard reporting procedures that will record geological characteristics, drill age parameters, loss and inflow behavior, casing setup, covering material, and positioning techniques, and after installation confirmations. It also involves factoring in casing planning with tunnel geological forecasting and water control measures, such that, rather than casing being an isolated operational process, casing is implemented as a constituent of a consistent risk management procedure. This review will contribute to the safer, more reliable, and more efficient exploration drilling of water conveyance tunneling in fractured ground applications by consolidating existing information and the relationship between fractured ground behavior, casing technology, and the practice of installation.

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Conflicts of Interest

The authors declare no conflict of interest.

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