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REVIEW

Complex-Strata Horizontal Borehole Drilling and Multi-Stage Reaming Technology for Water Conservancy Investigation

Changyou Dai [1,2], *Zijia Ge* [1,2], *Shulei Zhang* [1,2*]

[1] *Yellow River Engineering Consulting Co., Ltd., Zhengzhou 450003, China*

[2] *Shenzhen Xianhe Water Conservancy and Hydropower Engineering Co., Ltd., Shenzhen 518001, China*

ABSTRACT

Horizontal drilling of boreholes using complex-strata drilling and multi-stage reaming technologies has gained greater significance in water investigations, as vertical drilling often fails to fully characterise laterally distributed seepage pathways, weak interlayers, fractures, karst formations, and structurally controlled defects. The review explores the geology, drilling principles, major equipment systems, fluid and cuttings transport systems, borehole stability problems, and multi-stage reaming techniques for constructing horizontal boreholes in complex strata. Close consideration is given to the interplay among lithological heterogeneity, structural discontinuities, groundwater conditions, and operational parameters on drilling performance and borehole quality. The discussion demonstrates that multi-stage reaming is not merely a borehole enlargement process but a formation-adaptive design process to enhance the ultimate usability of the borehole and minimise the risk of instability throughout construction. Common engineering uses in the foundations of dams, reservoir banks, underground hydraulic structures, and post-treatment checking are also covered, along with evaluation criteria that include trajectory control, wall integrity, process stability, and reliability of the investigation. The review also lists existing constraints, such as a lack of standardisation, a lack of integration between geology and drilling control, and excessive reliance on experience-based design in heterogeneous formations. The further development should focus on intelligent drilling, real-time interpretation of responses, process optimisation using digital twins, and integrated investigation systems. The article is systematically presented as a source for the development of horizontal-borehole construction and staged-enlargement technologies in more challenging landscapes in water-conservancy engineering.

*CORRESPONDING AUTHOR:
Shulei Zhang, Yellow River Engineering Consulting Co., Ltd., Zhengzhou 450003, China; Shenzhen Xianhe Water Conservancy and Hydropower Engineering Co., Ltd., Shenzhen 518001, China; Email: zhangshl@yrec.cn

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1. Introduction

The study of water conservation provides the geological, hydrogeological, and structural foundations for planning, designing, building, and long-term safety assessment of dams, reservoirs, diversion tunnels, levees, underground caverns, and related hydraulic infrastructure [1]. Over the last few decades, with the growth in water conservation projects to deeper burial, larger scale, steeper topography, and geologically disrupted areas, the need to characterize the subsurface in high resolution has grown significantly. Traditional investigation techniques such as vertical boreholes, shallow trenches, and minimal geophysical surveys are often unable to fully detect laterally dispersed faults and water-bearing structures, including fracture zones, weak interlayers, karst conduits, seepage channels, fault gouge belts, and heterogeneous weathering interfaces. These are generally long, highly anisotropic targets, and therefore their behaviour in engineering is not always effectively modelled using sparse vertical drilling. In these circumstances, horizontal or near-horizontal borehole drilling has become an even more effective means of direct access to the vital horizons that regulate seepage, stability, and reinforcement efficiency [2–4].

Horizontal boreholes offer several unique benefits in water conservancy studies compared to conventional vertical drilling. They can cut bedding-parallel defects, fault zones, and seepage paths over longer distances, thereby enhancing exposure of lateral stratigraphic variation and providing more representative conditions for in situ testing, pressure water testing, grouting checks, borehole television examination, and long-section geological logging. Horizontal boreholes are particularly applicable in dam abutments, in reservoir banks, in tunnel sidewalls, and in underground hydraulic structures where engineering hazards are not concentrated in distinct planes but are instead spread throughout the structure. Nevertheless, there is a high level of technical difficulty that comes with these benefits. Drilling shall have to proceed under low-inclination or horizontal conditions where cuttings transport is inefficient, borehole cleaning is challenging, and tool-formation interaction is more labile. Moreover, the control of trajectories is more demanding due to the fact that any minor deviations will lead to either hitting the target horizon off-target or undermining the usefulness of the exploration data [5].

The challenge is further compounded by complex strata, which in water conservancy engineering often describe formations with a high degree of heterogeneity, sharp lithological transitions, fractured or disintegrating rock masses, soft-hard interbedding, gravel and boulder layers, karst cavities, swelling or slaking clay-rich units, fault zones, and groundwater-rich intervals. In these environments, borehole walls tend to collapse, shrink, cave in, and lose fluids; drilling equipment is subjected to intense vibration, impact loading, and imbalanced wear; and the interaction between formation behaviour, drilling fluid behaviour, and bottom-hole mechanics becomes highly nonlinear. Practically a horizontal borehole can cut through multiple mechanically contrasting media over a short distance, leading to repeated changes in stable and unstable drilling conditions. These issues not only reduce drilling efficiency but also directly affect borehole quality, data reliability, and the feasibility of further investigation activities, including coring, logging, sampling, permeability testing, and grouting assessment [6].

A large-diameter horizontal borehole is usually necessary in water conservancy exploration to achieve comprehensive detection and treatment. As an example, the larger the borehole diameter, the easier it would be to deploy the instruments, the better the flushing and observation conditions would be, the more frequent the testing, and the greater the space for directional correction, defect treatment, or follow-up engineering operations. However, one-step enlargement in complex strata is not always reliable, especially in long-distance boreholes. Sudden growth of the hole section may drastically increase torque and drag, enhance borehole wall disturbance, diminish cleaning performance, and cause eccentric expansion, local collapse or equipment stalling [7]. For this reason, the multi-stage reaming technology, in which the pilot hole is gradually expanded in controlled diameter steps, has become a promising solution. Multi-stage reaming can enhance the rate of enlargement, minimize operational risk, and improve the quality of the final borehole by sharing the load of the rock-breaking and regulating the geometry development of the borehole. Although of practical significance, research on this topic is fragmented. Available literature tends to focus on petroleum, trenchless crossing or mining applications, whereas the purposes of investigation, geological limitations, and quality demands of water conservancy engineering differ significantly [8].

Currently, the literature on horizontal borehole drilling and reaming for water conservation has several limitations. To start with, most research focuses on drilling or reaming individually, and not enough attention has been paid to their continuity in the process. In practice, the quality of drilling pilot holes is a key determinant of the quality of subsequent reaming, and reaming design is a determinant of drilling parameter selection, borehole arrangement, fluid system, and tool combination. Second, the ability of technologies to operate with complex strata is often described in words. Yet, the mechanisms linking lithological heterogeneity and hydrogeological conditions, borehole instability, and the performance of staged enlargement have not been synthesised. Third, it is evident that engineering practice has evolved rapidly. However, there is still no review work integrating mechanical principles, equipment systems, process design, failure control, and field applications, especially in water conservancy investigation. This disconnect prevents the creation of transferable technical paths and deceleration of experience-oriented construction to mechanism-oriented and intelligent control [9].

It is on this backdrop that this review is devoted to the complex-strata horizontal borehole drilling and multi-stage reaming technology in the investigation of water conservation. The article seeks to develop a logical analytical framework relating geological factors, drilling operations, reaming, and the demands of engineering applications. Instead of treating horizontal drilling and staged enlargement as a single technique, the review treats them as an integrated technical chain for creating high-quality investigation boreholes under challenging formation conditions. Special needs of water conservancy projects are highlighted in the discussion, such as high demands of borehole stability, precise targeting of horizons, identification of long-section defects, compatibility with hydrogeological tests, and the need to accommodate safety, efficiency, and environmental control in some construction sites [2].

What is new in this review is some aspects. To begin with, it makes the investigation of water conservancy the focal point of the analysis, unlike other literature on oil and gas directional drilling or municipal trenchless engineering. The successful completion of holes is not the main goal in water conservation work, but rather the attainment of consistent geologic and hydrogeologic data and support for future engineering validation and remediation. Such a goal alters the standards of judging drilling and reaming technology: the straightness of the borehole, the integrity of the walls, the ability to observe, compatibility with tests, and the minimisation of disturbances take the place of the rate of penetration or the rate of borehole enlargement. The review points out the technical nature of the most useful aspects of hydraulic engineering practice by redefining drilling and reaming technologies through this application-focused lens.

Second, the connection between the complex strata and multi-stage reaming is specifically discussed in this review, and it is a problem which has often been recognised but poorly structured in past literature. Various adverse formations impose different failure modes during drilling and expansion: fractured rock, soft interlayers, gravelly formations, and water-bearing karst or faulted areas increase the risk of circulation loss and abrupt instability. The staged process of enlargement modifies the redistribution of stress around the borehole and the fluid-cuttings transport environment at each diameter level. The synthesis of these interactions leads the review to conclude that multi-stage reaming cannot be considered a larger-hole construction process, but rather a formation-adaptive control mechanism [10].

Third, the review suggests a process-based conceptualisation of the entire technology chain, including the identification of geology and borehole design, pilot drilling, trajectory control, staged enlargement, failure mitigation, and ultimate evaluation. This combined perspective is significant since the effectiveness of complex-strata horizontal investigation does not rely on any one tool or technique, but on the optimization of the parameters. The review is thus focused on the corresponding relationships among formation conditions, drilling mode, bit and reamer selection, drilling fluid system, cleaning efficiency, monitoring technology, and construction sequence. This integration has the potential to offer a more practical foundation for future standardisation and intelligent decision-making.

Lastly, the article identifies the pattern of development of empirical construction into digital, adaptive, and intelligent investigation technology. As real-time monitoring, downhole measurements, data-driven parameter optimisation, and the concept of a digital twin develop, the process of horizontal drilling and multi-stage reaming in water conservancy exploration is reaching a new level. A systematic review is thus opportune not only to provide an overview of current developments but also to expose the remaining gaps in reliability in highly heterogeneous formations [11].

Based on the foregoing, this paper presents the geological problem of complex strata, concepts and techniques of horizontal borehole drilling, mechanics and process design of multi-stage reaming, and typical engineering practices in water conservancy exploration. It also addresses performance evaluation techniques, the frequent failure modes, and research directions. In this manner, the review aims to serve as a systematic source of knowledge for researchers and engineers seeking to enhance the accuracy, safety, and effectiveness of subsurface investigations under more challenging hydraulic engineering conditions [12,13].

2. Geological Characteristics and Technical Challenges in Complex-Strata Horizontal Borehole Construction for Water Conservancy Investigation

2.1. Geological Setting and Engineering Demands

The geologically complex environments in which water conservancy studies are typically undertaken include the subsurface with high lithological heterogeneity, active structural deformation, and changing groundwater conditions. The strata in dam foundations, diversion tunnels, underground caverns, and abutment areas are seldom homogeneous engineering media. They are usually fractured rock masses, weathered belts, fault gouges, soft-hard interbedding, gravelly layers, karstified carbonate units, and local water-rich discontinuities. These characteristics are not merely geological accounts; they directly define the practicability, stability and information value of the horizontal borehole development [14].

Horizontal boreholes in water conservation projects are likely to penetrate laterally continuous weak zones, seepage pathways, and structural interfaces more readily than vertical boreholes, at greater distances. This provides them with a distinct advantage in assessing the spatial continuity of defects that govern permeability, deformation, and treatment efficacy. Nonetheless, horizontal drilling is as geologically complex as it is valuable, and thus technically susceptible. A borehole intended to track a target horizon can experience sudden shifts in formation strength, discontinuity density, and hydro-mechanical behaviour over short distances, forcing the drilling system to operate under constantly changing boundary conditions. This makes the engineering requirements in these projects not only to fill the hole, but also to maintain borehole integrity, directional accuracy, and consistency with post-test, logging and verification processes [15–17].

In this respect, complex strata are not to be perceived only as hard-to-form structures, but as the geological-engineering environment that interacts among the structure of the rock mass, the groundwater regime, and the purpose of the investigation. A fractured granitic abutment drilling response, e.g., is fundamentally different to a karstic limestone foundation or a highly weathered interbedded mudstone-sandstone slope. So, a formation-based understanding of such differences should be the starting point for any discussion of drilling and reaming technology in water conservancy investigations.

2.2. Major Geological Features Affecting Horizontal Borehole Construction

Lithological non-uniformity is the first characteristic of complex strata. Many hydraulic engineering locations experience alternating hard and soft formations, partially weathered areas or transitions from intact rock to broken deposits. The result of such changes is significant contrasts in drillability, bit loading, and hole enlargement behaviour. Hard formations are likely to increase tool wear and vibration, whereas soft or plastic periods are more prone to collapse, squeezing, and borehole contraction. In horizontally drilled boreholes, these effects are enhanced by cuttings settlement under gravity and prolonged exposure to the wall, and by the fact that even short, weak periods are less tolerated by the system [18].

The second important characteristic is structural discontinuity. Principal objects of investigation are often faults, joints, shear bands and bedding-parallel fractures which govern seepage and stability. However, these same structures induce anisotropic mechanical behavior surrounding the borehole. In cases where the drilling direction is perpendicular to a fracture set or weak interlayer, the borehole wall may lose confinement quickly leading to sloughing, overbreak or local cavity formation. This is of particular concern during reaming, when stress redistribution in the area of the enlarged hole further stimulates already existing weak areas. The problem is thus not merely that fractured formations are weaker, but that their instability is directional and scale-dependent, making it difficult to predict borehole performance.

Hydrogeological complexity is the third important factor. Fractures with high water content, karst conduits, and high-reactive fault zones can cause circulation loss, pressure disequilibrium, and rapid borehole wall deterioration. This problem is of greater concern in the water conservancy investigation than with many other drilling applications since the borehole frequently crosses the very seepage pathways that the investigation is trying to characterize. Invasion of drilling fluids, washout and hydraulic disturbance can change the original hydrogeological state thus influencing the representativeness of permeability tests or borehole observations. In such a way, groundwater is a cause of technical risk and the reason that limits the extent to which it is possible to implement the stabilization measures aggressively [19].

Fourthly, there are specific problematic materials, including swelling clay, collapsing accumulations, and gravel-boulder layers. Swelling formations may react with drilling fluids and gradually decrease the effective borehole diameter, whilst unconsolidated coarse material tends to result in poor wall definition and unsteady cuttings transport. Mixed strata. The drilling system can undergo several transitions among abrasion-dominated, collapse-dominated, and loss-dominated failure modes [20,21]. This multi-mechanism setting is among the primary factors that explain why a relatively homogeneous formation traditional drilling techniques usually do not work well in water conservation projects (**Table 1**).

Table 1. Representative complex strata in water conservancy investigation and their main effects on horizontal borehole construction.

Strata Type	Typical Geological Characteristics	Main Drilling Risks	Main Reaming Risks	Investigation Implications
Fractured hard rock	Dense joints, broken blocks, variable integrity, strong abrasiveness	Bit vibration, trajectory deviation, local collapse, severe tool wear	Eccentric enlargement, block fall, torque fluctuation	Difficult to maintain borehole smoothness and imaging quality
Soft-hard interbedded strata	Alternating competent and weak layers, mechanical contrast, anisotropy	Uneven penetration, bit walk, wall instability in weak bands	Nonuniform enlargement, local over-reaming, poor borehole regularity	May distort structural interpretation and affect test reliability
Fault and shear zones	Gouge, breccia, crushed rock, weak fillings, high discontinuity density	Hole collapse, sticking, circulation loss, unstable returns	Rapid wall failure, debris accumulation, reaming blockage	Critical for seepage identification but difficult to preserve intact borehole conditions
Water-rich fractured zones	Open fractures, strong permeability, groundwater inflow	Fluid loss, pressure imbalance, cuttings transport deterioration	Borehole washout, unstable cleaning, secondary collapse	Borehole disturbance may affect permeability evaluation
Karstified carbonate formations	Cavities, solution channels, irregular voids, variable rock bridge thickness	Sudden loss of support, drilling fluid leakage, tool dropping	Enlargement instability, uncontrolled overbreak, poor diameter control	Important for seepage pathway detection but difficult to standardize drilling response
Gravel-boulder layers	Coarse unconsolidated particles, weak cementation, poor wall self-support	Hole instability, poor circulation efficiency, irregular borehole geometry	Collapse during enlargement, debris packing, severe friction	Low borehole definition may reduce logging and imaging effectiveness
Swelling clay-bearing strata	Hydration-sensitive minerals, plastic deformation, diameter shrinkage	Borehole squeezing, sticking, reduced annular clearance	Repeated deformation after enlargement, tool drag increase	May compromise long-duration testing and repeated access
Strongly weathered rock mass	Degraded structure, mixed fine and coarse debris, variable strength	Sloughing, unstable cuttings return, low drilling efficiency	Progressive collapse, wall erosion, poor enlargement consistency	Borehole condition may deteriorate rapidly if open-hole exposure is prolonged

2.3. Technical Challenges in Horizontal Drilling under Complex Strata

Trajectory control is the most immediate technical challenge. Investigation boreholes are typically constructed horizontally, and are typically intended to cut a defined geological or structural target with a high degree of positional accuracy. In more complicated strata, though, the deflection of the drill string, bit walk, bias in local formations and the repetitive corrective procedures can slowly move the hole off course. Even though these deviations do not always affect the overall goal of the investigation due to the missed target seepage zone or misrepresentation of the actual geometry of a defect, in contrast to simple completion-oriented drilling. Accuracy of trajectories in this sense is thus not merely a working parameter but a precondition to the geological validity [22].

A second, more long-term challenge is borehole stability. With a horizontal or near horizontal situation, the cuttings are likely to be deposited on the lower side of the borehole and this leads to friction, decreased annular clearance, and rapid local wall damage. In cases where the formation has fractured or weak intervals, this unfavourable transportation geometry is compounded by stress relaxation and fluid disruption, facilitating collapse and sticking. The critical point in this case is that instability can be progressive, not immediate. The local caving or minor enlargement, or repeated drag increase might seem manageable at first, but they might develop into serious blockage when reamed or tested later. It is especially challenging to assess risk due to the slow onset of instability.

The third key challenge is cuttings removal. In vertical drilling, the force of gravity helps to carry the cuttings to a certain degree, but on the horizontal part of the drilling the carrying capacity of the circulation system is the new control factor. The size distribution of particle cuttings in complex strata can undergo sharp changes, ranging from fine slaking material in soft formations to angular fragments in brittle rocks. The presence of these materials may cause the flow regime to be unstable and less efficient in cleaning. The systemic effects of poor hole cleaning include higher torque and drag, obscures the actual formation response, heightens bit wear, and can be erroneously interpreted as nothing more than mechanical tool failure. This is why the hole cleaning can be considered as a core of the formation-adaptation, and not a secondary fluid-management concern [23].

The fourth difficulty is matching of tool and parameter. There is no single type of bit, reamer configuration or drilling fluid system that will work well in all of the complex strata. However in practice, the horizontal water conservatory boreholes may intersect multiple types of formations in a single engineering section. It implies that parameter optimisation cannot be based on a certain design philosophy. A bit weight and an aggressive cutting structure can enhance penetration in competent rock and inhibit vibration and wall damage in fractured intervals. On the other hand, hard rock could have lower efficiency and steering effectiveness due to the conservative parameters that guard weak formations. It is not just a matter of optimising parameters, but of ensuring acceptable performance despite inevitable geological variability [24].

The onset of instability in horizontal boreholes under complex strata is governed by coupled stress–fluid–structure interaction. When a horizontal borehole intersects a fractured interval, the redistribution of tangential and radial stresses reduces the effective confining pressure on structurally controlled blocks. Simultaneously, drilling fluid invasion can elevate pore pressure along discontinuity surfaces, lowering frictional resistance. This hydro-mechanical coupling means that instability is not merely a strength issue but a function of fracture orientation relative to the borehole axis, fluid infiltration rate, and the rate of stress relaxation after drilling. Unlike vertical holes, horizontal sections exhibit asymmetric stress redistribution due to gravitational settlement of cuttings and uneven wall contact, which can localise failure on the low side first and then propagate [25].

2.4. Coupled Challenges during Multi-Stage Reaming

In staged enlargement the complexity of the formation is further enhanced. Multi-stage reaming is typically used since a one-step enlargement is too disturbing and hazardous in horizontal holes that are long. Nonetheless, every reaming step varies the stress condition, wall exposure duration, and hydraulic conditions of the borehole, that is, instability mechanisms transform continuously, and are not fixed. A pilot hole which is sufficiently stable to be drilled in, can become unstable as it is enlarged, as the larger diameter reduces the support of the wall, encourages the production of cuttings, and reveals previously concealed defects.

This brings out a key fact namely, reaming failure is usually passed over to pilot-hole flaws but manifested in the conditions of enlarged holes. Local washout, slight eccentricity or poor cleaning in the pilot stage might be tolerable at first but they tend to increase in subsequent stages. As such, reaming performance can not be assessed outside of the quality of the original borehole. The engineering assumption that reaming is primarily used to increase diameter is a falsehood that deemphasizes the importance of reaming as a diagnostic measure of the overall drilling process [26].

The other challenge is that the optimum diameter increment between stages depends on formation. Small increments enhance control but lower efficiency whilst the large increments enhance mechanical and hydraulic disturbance. In fractured or water-filled strata, excessively violent enlargement can cause collapse which was not encountered during pilot drilling. In the soft squeezing formations, reaming over and over again can be alternatively lengthening wall exposure and increasing deformation. It indicates that no universally optimum staged scheme exists; the reaming sequence needs to demonstrate a compromise between geology, hole length, fluid performance, and acceptable risk.

2.5. Implications for Technology Development in Water Conservancy Investigation

The challenges above point to the fact that the construction of complex-strata horizontal boreholes in water conservancy research is essentially a question of combined adaptation, as opposed to the independent control of processes. The interaction between geological heterogeneity, groundwater influences, the mechanics of drilling, and the goals of investigations occurs during the lifetime of the borehole. Consequently, technologies that have been successful in the oil and gas drilling or trenchless utility crossing cannot be transferable mechanically without alteration. The focus of water conservation investigation is more on the quality of the boreholes, target reliability and post-drilling usability, which demands a new assessment structure.

One of the most important lessons is that the successful construction is determined not as much by optimization of any one of the parameters, including the penetration rate or enlargement rate, but by the stability of the system under varying formation conditions. This changes the technical emphasis to integrated design, which entails geology-based borehole layout, adjustment of adaptive parameters, staged risk control, and real-time interpretation of drilling response. It also shows the necessity of integrating further between investigation geology and drilling engineering. Drilling issues in most projects are dealt with as operational discontinuities, not as a geological indication, but variations in torque, circulation loss, vibration or cuttings morphology can offer useful data on the subsurface structure [26].

In this respect, the technical issues mentioned in this section are not only barriers to construction, but also determine the scientific basis of enhancing the technology of horizontal drilling and multi-stage reaming. Knowledge of the way complicated strata control borehole behavior is the baseline to creating more dependable drilling approaches, more sensible reaming plans, and more education-giving inquiries into water conservation.

3. Complex-Strata Horizontal Borehole Drilling Technologies

3.1. Drilling Principles and Process Systems

The horizontal borehole drilling of water conservation exploration is essentially different to the traditional production-oriented drilling in that its main aim is not merely borehole completion, but the procurement of certain trustworthy subsurface data on strict geological targeting and borehole quality standards. In that respect, drilling process should meet a number of functions at the same time: it should be efficient to penetrate the complex formations, it should be able to ensure the stability of the boreholes, it needs to ensure the representativeness of the geological and hydrogeological observations, and it should furnish a borehole environment in which the subsequent reaming, logging, testing, sampling, or verification of the grouts may be conducted. These composite purposes result in a drilling system that is very sensitive to geological variability and compel the process design to be more integrated than in conventional applications of drilling.

As a principle of drilling, the drilling of horizontal bore holes in complex strata is often based on rotary drilling, rotary-percussive drilling, directional drilling, or a combination of multiple modes. Rotary drilling is the most widely used foundation method due to its continuous operation and integration with borehole quality control, particularly where coring, detailed logging or staged enlargement is expected. But in hard and abrasive rock, pure rotary drilling can be characterized by low penetration efficiency and extreme bit wear. Rotary-percussive techniques can enhance rock-breaking performance under these circumstances, but can also enhance borehole vibration and wall disturbance, which is undesirable in fractured or weak strata. Directional drilling technologies are especially useful in situations where the borehole must trace a narrow target horizon or penetrate a structurally controlled seepage area. However, their use in water conservation exploration is less restrictive than in the petroleum business, since steering accuracy must be compromised to maintain a smooth, testable, and reamable borehole [27].

The drilling process system can therefore be seen as a formation-adaptive workflow rather than a technique. The common system starts with geological targeting and borehole structure design then the pilot hole is drilled, real-time deviation is monitored, parameters are adjusted according to the varying strata and stabilization to suit hole cleaning and wall protection. The pilot hole is not just the initial stage of construction for many complex projects, but also a diagnostic channel that reveals the true reaction of the formation to construction. This reaction subsequently informs subsequent choices regarding bit replacement, fluid reformulation, drilling mode changes, and reaming strategy. It is an iterative process: the geological uncertainty is reduced through drilling and the decisions to drill are being re-optimized with geological information.

A key lesson is that complex strata horizontal drilling cannot be conceptualized as a vertical drilling scaled up. The asymmetry due to gravitation in horizontal sections varies the spatial distribution of cuttings, contact forces, and hydraulic resistance. The bottom of the borehole will be the area of choice as cuttings accumulate and frictional wear occurs and the top might have less support and slower cleaning action. Such asymmetry implies that the drilling parameters that are deemed best in vertical holes can lead to unsteady or erroneous behaviour in horizontal boreholes. Process design should therefore explicitly consider the joint effect of the borehole inclination, annular flow regime, lithological heterogeneity, and the objectives of operation [28].

3.2. Key Equipment and Tool Systems

The adaptability of the equipment system is a powerful determinant of performance of horizontal borehole drilling in complex strata. The rig should be able to offer enough thrust, torque and rotational stability in order to support the long horizontal sections as well as giving fine control during changes in formation in water conservancy investigation. The equipment needed to use the rig, compared to those designed to do a simple shallow geotechnical drill, may require higher structural rigidity, increased feed accuracy, and enhanced compatibility with directional drilling equipment, fluid circulation units, and staged reaming units. Nonetheless, big and aggressive equipment is not necessarily beneficial. High levels of mechanical power may enhance vibration, increase the wear and tear of the wall, as well as decrease the sensitivity of the control of weak or fractured formations. Thus, the choice of rigs cannot be made solely on the nominal capacity but also regarding the possibility to provide the stable and controllable energy input [29].

The drill string is also very important since it serves as the transmission system of energy and mechanical interface to the borehole. Drill string friction, bending and vibration are major considerations in long horizontal sections that affect tool reliability and trajectory control. In complicated strata, these effects are exacerbated by discontinuous borehole geometry, and recurring changes between stable and unstable regions. A string design which works well in hard intact rock can lead to problems as it enters into compressing clay-rich intervals or fractured fault zones. It is due to this that the drill string must be designed keeping in mind the stiffness distribution, fatigue resistance, hydraulic passage capacity, as well as compatibility with steering or measurement tools. The role of the string in these projects is frequently under-estimated, but most failures due to bad formation are in fact due to poor mechanical matching of the geometry of the holes and the drill assembly.

One of the most sensitive formation decisions when it comes to the drilling system is bit selection. Polycrystalline diamond compact bits, impregnated diamond bits, roller cone bits and hybrid cutting structures have their own advantages and disadvantages. In strong and relatively uniform rock, aggressive cutting forms can augment the efficiency of penetration. In interbedded, fractured or abrasive formations, however, very aggressive bits can exacerbate vibration, bit walk and wall breakages. On the other hand, more conservative structures can be more stable, but will have lower rate of penetration, and steering response. The real-life problem is that in practice complex-strata water conservancy projects do not allow a use of a single ideal bit choice across the entire borehole length. Rather, the selection of bit should be considered as a progressive plan whereby the anticipated dominant failure mode, i.e., abrasion, impact, sloughing or deviation, varies with the type of formation [30].

Directional tools and downhole motors are particularly necessary when the object of interest to the investigation is of great geometrical constraint, like narrow fault zones, bedding parallel seepage channels or narrow dam foundation horizons. The tools enhance the control of the path, and when applied in complicated strata, there is a trade-off between steering and smoothness of the borehole. The common directional corrections can cause local doglegs, asymmetrical expansion, or non-uniform wall geometry which can subsequently make reaming and testing difficult. This means that accuracy steering can only work well in combination with a general borehole quality approach. The effectiveness of directional drilling in the study of water conservation must therefore not be evaluated based on whether the target is achieved or not, but also on whether the borehole that is drilled can be used mechanically and functionally.

3.3. Drilling Fluid Systems and Cuttings Transport Control

When the horizontal drilling is made using complex strata, the drilling fluid system is not just a supporting element, but a key element in the borehole stabilization, transporting cuttings and a hydro-mechanical control. The design of the fluid is also limited in water conservancy investigation due to the requirement of not excessively disrupting the natural conditions of seepage and ensuring the validity of the subsequent test. This makes the balance more challenging than in production drilling where extreme stabilization and lubrication can be permissible even though they might be changing the near-borehole environment.

The initial role of the drilling fluid is the protection of the borehole wall. Weak, fractured or highly weathered formations can have an appropriately designed fluid to minimize the invasion of filtrates, create a supporting filter cake, and delay the development of local sloughing or collapse. This stabilizing role however is very formation dependent. Loss of fluids in open fracture or karstic voids can be so high that the normal mechanisms of wall-building are not effective. In clay-bearing strata the chemical activity of the fluid, and the formation can be more significant than viscosity itself. As such, the fluid system has to be adjusted to not only the overall lithology, but also the expected instability mechanism that prevails along the horizontal interval [31].

The second role is cuttings transport that makes the characteristic hydraulic issue in horizontal boreholes. Since the cuttings will settle on the low side of the annulus due to the effect of gravity, the fluid needs to produce sufficient carrying capacity to ensure that the stationary beds are not formed whilst ensuring that the pressure loss and circulation remain acceptable. This task in complex strata is complicated by drastic changes in particle size, density and shape. Hard rock that is brittle can produce coarse and angular fragments and soft rock formations can produce fine and sticky fragments that agglomerate and are stuck to the borehole wall or drill string. The presence of these materials can impair flow efficiency and encourage intermittent transport behavior, where cuttings beds develop, abrasion and regeneration of cuttings beds occur in a cyclic manner. This dynamic instability is a significant contributor to torque variability, drag growth and apparent drilling inefficiency [32].

One of the most important aspects is that dirty hole cleaning can be confused with the issue of mechanical drilling that is purely mechanical. Practically, increasing torque, poor bit performance, or high sticking can be caused by hydraulic mismatch, instead of tool failure. This is especially the case in long horizontal areas where minor decreases in transport efficiency will be accumulated spatially. To successfully handle cuttings, then a combination of circulation rate, fluid rheology, drill string rotation and penetration rate optimization is necessary. These are variables that cannot be considered separately. Very high penetration with no relevant transport capacity merely results in overloading of the annulus, whereas too high viscosity can enhance suspension but leads to higher pumping power requirements and facilitates formation damage. Maximal transport force is not the most robust but rather a stable hydraulic regime that is adjusted to the changing cuttings generation characteristics of the formation.

Other circulation media, such as air, foam or hybrid fluid systems, can have benefits under certain circumstances, particularly where fluid loss is high or the formation sensitivity is critical. However, their use in the study of water conservation is still limited. Air-based systems should be able to reduce formation contamination and enhance penetration in certain hard formations, although they offer less support to the walls and can be hard to control in water-saturated zones. In some unstable formations, foam systems can be used to increase the carrying efficiency, but field control is more susceptible to groundwater inflow and borehole geometry. Therefore, the decision of circulation medium must be controlled by a clear comparison of the stabilization requirements and investigation limitations instead of based on the considerations of penetration-rate only [33].

3.4. Borehole Stability and Trajectory Control Technologies

The two most critical technical aspects of horizontal drilling in complex strata are borehole stability and trajectory control, as they directly determine whether the borehole will serve its investigative purpose. Stability is not only the avoidance of catastrophic collapse but also the maintenance of a geometrically regular, mechanically approachable, and hydraulically controlled borehole throughout the drilling period. The same can be said of trajectory control, which does not necessarily mean arriving at a nominal endpoint, but is also concerned with borehole alignment in such a way that it will be compatible with subsequent reaming, testing, and interpretation.

The interaction of rock mass structure, redistribution of in situ stresses, invasion of fluids and disturbance of operations determine the stability of boreholes in complex strata. The wall of a borehole in fractured formations tends to fail by tearing away structurally confined blocks rather than undergoing uniform plastic deformation. In weak clay-rich periods, the effects of time, of squeezing and hydration may be predominant. Various processes may coexist in short distances in mixed formations. This implies that there is no universal stabilization technique. Mechanical control through parameter selection, hydraulic control through the individual fluid system, and geometric control through smooth borehole construction should work in concert. Among the most significant practical principles, there is the need to reduce unnecessary disturbance. The excessive bit aggressiveness, lack of steadiness in weight transfer, and lengthy open-hole exposure, as well as repetitive corrective reaming, all contribute to the risk of weakening the marginally stable areas [22].

Formation behavior is similarly related to trajectory control. Theoretically, deviation may be corrected using directional tools or steering assemblies, or by adjusting the parameters. Practically, the performance of these measures is based on local drillability contrast, the quality of hole cleaning and smoothness of the boreholes. High lithological heterogeneity may lead to the bit selectively moving into weaker formations and cuttings deposition on the low side can introduce bias in tool movement and decrease predictability in steering. Thus deviation control in complicated strata cannot be reduced merely to a measurement-and-correction problem; it is a system response problem where formation bias, mechanical asymmetry and hydraulic effects all have an effect on the path achieved.

This is greatly enhanced by the use of measurement during drilling and the associated real time monitoring technologies. They can detect drift, torque abnormalities, circulation variations, and vibration trends that could indicate developing instability or improper formation entry earlier. The usefulness of monitoring, however, is dependent on integrating interpretation. Raw measurements, in and of themselves, are not useful for enhancing drilling performance unless they are accompanied by actionable judgments about the state of the formations and the risks associated with the processes. This connection is especially significant in the context of water conservation research, since anomalous responses to drilling can also have geological implications. An abrupt reduction in resistance, extreme loss of circulation or alteration in the texture of the cuttings could be due to the overlap of a faulted seepage zone, not just a working problem. A characteristic of advanced trajectory and stability control in this domain is thus the interconnection between drilling diagnostics and geological interpretation [24,34–36].

3.5. Current Progress, Limitations, and Development Trends

The recent developments in complex-strata horizontal drilling have been characterized by enhancement of rig controllability, directional capability, tool durability and real-time monitoring. Recent developments in complex-strata horizontal drilling have been characterised by advances in rig controllability, directional ability, tool life, and real-time monitoring, whereas the key features of typically used drilling technologies may be systematically compared in **Table 2**. These advancements have made it more practical to drill long horizontal pilot holes in geologically challenging water conservation projects and to keep them more closely aligned with target structures than before. It has also become increasingly realized that the optimization of drilling fluids, the management of borehole cleaning processes and staged process design are equally significant as efficiency in rock-breaking, particularly when the ultimate aim involves multi-stage reaming or finer hydrogeological investigation [15,37].

Table 2. Comparison of main horizontal borehole drilling technologies used in complex-strata water conservancy investigation.

Drilling Technology	Main Principle	Applicable Formations	Main Advantages	Main Limitations	Suitability for Water Conservancy Investigation
Rotary drilling	Continuous rotary rock breaking by bit and drill string	Medium to relatively stable formations; adaptable with suitable bits and fluids	Good borehole controllability, compatible with coring and reaming, relatively mature process	Lower penetration efficiency in very hard rock; may struggle in highly fractured weak zones	High, especially where borehole quality and post-drilling usability are required
Rotary–percussive drilling	Combined rotation and impact loading	Hard, abrasive, and high-strength formations	Higher penetration rate in competent rock, improved rock-breaking efficiency	Increased vibration, greater wall disturbance, reduced stability in fractured or weak formations	Moderate; useful in hard rock but requires careful control when investigation quality is critical
Directional drilling	Controlled trajectory drilling using steering tools and/or downhole motors	Projects with strict target alignment requirements, structurally controlled horizons	Improved trajectory precision, better interception of target zones, useful in laterally extensive defects	May create local doglegs, higher technical complexity, increased demand on borehole smoothness	Very high for target-oriented investigation, but must be integrated with borehole quality control
Composite drilling systems	Combination of drilling modes adjusted to changing strata	Mixed and heterogeneous formations	Better adaptability to formation transitions, flexible process design	Requires higher operational experience, more complicated optimization	High potential in complex strata if real-time adjustment capability is available
Air or foam-assisted drilling	Use of gas or foam-based circulation instead of conventional liquid-dominant fluids	Hard formations or severe fluid-loss zones under selective conditions	Reduced fluid contamination, potentially better penetration, lower liquid invasion	Limited wall support, weaker stability control in water-rich or weak formations	Selective; useful in specific cases but less universal for investigation-oriented borehole construction
Conventional non-directional horizontal drilling	Straightforward horizontal drilling without sophisticated steering	Shorter holes or less demanding target geometry	Simpler operation, lower equipment complexity, easier field deployment	Limited target accuracy, reduced adaptability in structurally controlled investigations	Moderate; suitable for simpler geometries but less effective in precise seepage or defect targeting

Although these advances are made, there are still significant limitations. A major issue is the failure to recalibrate the use of many technologies in practice, they are based on oil and gas or trenchless engineering, without considering the purpose of water conservancy investigation. Consequently, the success of drilling is still too frequently measured by the number of penetrations and completions, rather than by the usability of the borehole, test reliability, and geological representativeness. The second weakness is the ineffective merging of geological forecasting and engineering implementation. The drilling plan is designed in most projects based on incomplete pre-drilling models, and is later changed in a reactive manner, when the problems arise. This causes the repetition of tool changes, unstable parameters, and unnecessary reaming challenges.

Another problem is that there are no standardized criteria of assessing the quality of drilling in complex investigation boreholes. Parameters such as rate of penetration, torque, and deviation are continuously logged, yet their relationship to ultimate investigation performance is not necessarily clear. In the absence of such a connection, process optimization remains an experience-based process that is hard to apply to other projects. This can be especially an issue in complex strata, where what might seem like short-term efficiency at the time can lead to subsequent instability or low-quality data [2].

Future trends of the field thus tend to focus on adaptive and intelligent drilling systems. It is also probable that the future of the field will be focused on adaptive and intelligence-assisted drilling systems as summarized in the integrated workflow in **Figure 1**. These consist of stronger linking of geological forecasting and process design, real-time analysis of drilling response to detect formation, and digital optimization of drilling and cleaning parameters along the borehole pathway. The shift from isolated work to tool improvement to the complete coordination of the process is also important. When it comes to complex-strata water conservancy investigation, the value of a drilling technology cannot be assessed based on any single aspect. Its true meaning is whether it can retain the borehole quality, maintain geological validity, and provide a consistent base for subsequent multi-stage reaming and examination procedures. In this view, the history of drilling technology does not exist independently of the general history of water conservation; it is one of the key facilitating factors [38].

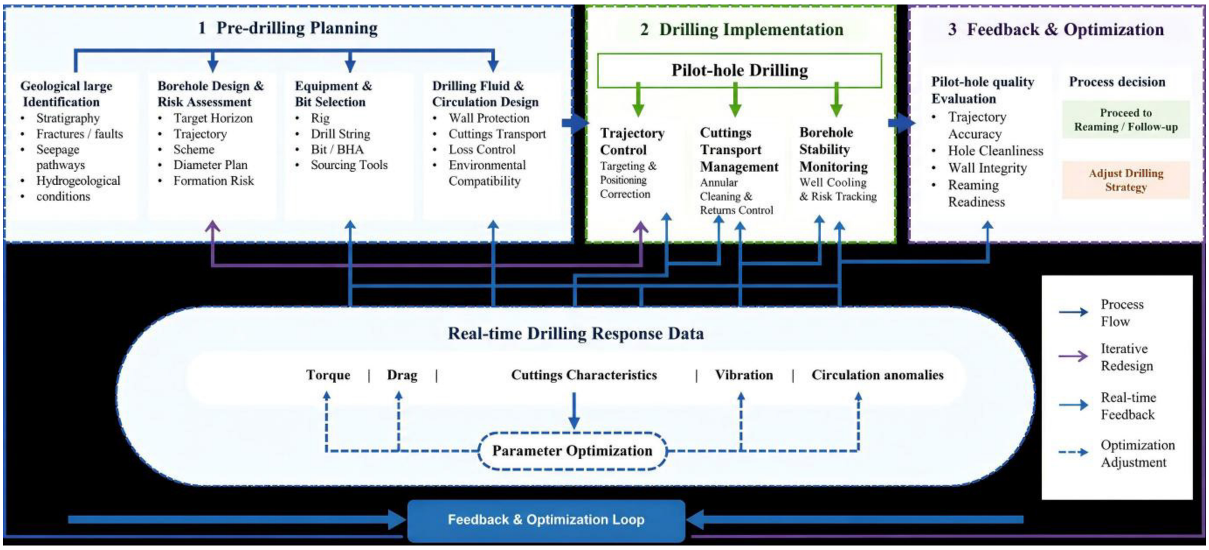

Figure 1. Integrated technical workflow for complex-strata horizontal borehole drilling, showing the coupling among geological prediction, drilling process design, equipment selection, fluid support, trajectory control, and real-time response adjustment.

4. Multi-Stage Reaming Technology: Mechanisms, Methods, and Adaptability

4.1. Concept and Necessity of Multi-Stage Reaming

The useability of a horizontal borehole in water conservation research may well be determined by the capacity of the pilot hole to be drilled successfully as well as the final borehole diameter to allow observation, testing, logging, sampling, grouting verification, or further engineering treatment. On numerous projects, mechanically a small pilot hole is easier to build and manage, but it alone would be incapable of meeting all the demands of hydraulic investigation. Multi-stage reaming has thus turned out to be a critical technical route to converting a small pilot borehole into a wider and more useful engineering conduit and minimizing the hazards of the one-step enlargement.

The fundamental concept of multi-stage reaming is to expand the borehole in steps of two or more controlled diameter steps instead of trying to ream to full diameter following pilot drilling. This simulation process reallocates the rock-breaking efforts through multiple construction cycles and offers the chance to re-evaluate the borehole condition, cuttings transportation efficacy, and shape reaction following any enlargement phase. This is especially significant in complicated layers, where the stability of boreholes is usually extremely low and the effects of excessive aggressive expansion may be devastating. A stabilized formation that is stable under pilot-hole conditions can be unstable when subjected to the increased disturbance of the wall, increased annular volume, and changed hydraulic regime of final-diameter reaming.

Multi-stage reaming is more essential in water conservation exploration than in most production-oriented water drilling applications since the borehole quality criteria are more comprehensive and sensitive. The final borehole should typically be geometrically regular, structurally continuous and of adequate accessibility to support hydrogeological testing or borehole imaging. Local collapse, undue washout, or eccentric enlargement may not deter nominal hole completion, but it may greatly diminish the dependability of the outcome of the investigation. This explains why multi-stage reaming has an engineering importance that goes beyond increasing diameter. Practically, it is an enlargement strategy that maintains quality by balancing the construction feasibility with the necessity of having a stable, interpretable and operationally useful borehole [39,40].

One key lesson to be learned is that multi-stage reaming cannot be considered as a secondary operation that is added to drilling. Instead it is a continuation of the borehole construction rationale that was defined at pilot-hole design. It is interdependent at the start of the pilot diameter, reaming increments, fluid system, tool sequence, and stability control measures. When reaming is only taken into consideration when a pilot-hole has been made, it is likely to be a reactive and inefficient process. The idea of multi-stage reaming in the complex-strata water conservation projects can therefore be regarded as an incorporated enlargement framework as opposed to a mere mechanical follow-up process.

4.2. Reaming Mechanics and Influencing Factors

Multi-stage reaming of horizontal boreholes is a much more complicated business than pilot drilling since the process of enlargement does not only alter the stress distribution around the borehole but also the contact area between tool and formation, and the hydraulic conditions needed to remove cuttings. In reaming, the tool is not only clearing of the side of the borehole; it is also stirring up a mass of rock which has already been re-redistributed through the local stress and fluid interaction in the pilot stage. Consequently, the interval that is reamed tends to have a coupled behavior that pertains to rock breakage, wall loosening, fluid infiltration, and secondary instability.

Each reaming pass modifies three interlinked conditions: (i) the radial stress distribution around the expanded wall, (ii) the hydraulic gradient and flow velocity in the annulus, and (iii) the exposure duration of previously damaged zones. Enlarging the diameter reduces radial confinement, which lowers the effective stress that resists block detachment. At the same time, the increased annular cross-section reduces flow velocity for a given pump rate, potentially allowing cuttings beds to form. If a permeable fractured zone is encountered, the lower effective stress combined with higher fluid invasion can trigger delayed collapse that was not observed during pilot drilling. This coupled behaviour implies that reaming instability cannot be predicted by rock strength alone; it requires evaluating how stress, fluid, and debris transport evolve together across enlargement steps [41].

The resistance that is experienced during reaming is one of the key mechanical characteristics that are not only controlled by the intact strength of rocks but also by the structural integrity of the borehole wall. In competent, and relatively homogeneous formations, reaming is more likely to act as a more predictable process of rock-cutting, and torque and drag are mostly proportional to the diameter increment and tool shape. The reamer can sometimes cut, crush, dislodge or drag pre-broken material in fractured, faulted, or weathered formations, though. This results in very fluctuated load response, and can give false indications of improvement. The momentary loss of torque, say, can be a good sign of efficient cutting in hard rock, but in broken areas can be a bad sign of collapse at the wall, or uncontrolled overbreak. Reaming response interpretation must consequently be geologically contextualized instead of being purely of a mechanical judgment [42,43].

The effect of lithological contrast is particularly pronounced in complicated strata. The reamer experiences an uneven loading and penetration resistance when interbedded hard and soft formations are traversed by the borehole. This condition encourages eccentric enlargement, local vibration and abnormal geometry of walls. The soft layers can be over-reamed or squeezed and the hard layers in between not quite enlarged. The resulting nonuniform profile of the boreholes not only makes the subsequent reaming processes more difficult, but also poses the danger of drag concentration and local blockage. Therefore, not only the preservation of cutting efficacies, but also the geometric consistency between formations that have different deformation and failure properties is one of the essential mechanical challenges of multi-stage reaming.

The conditions of groundwater make the reaming mechanism even more problematic. In fractured rock, karstified formations or permeable fault systems, which are abundant in water, reaming can heighten the exposure of transmissive structures, and enhance fluid loss. This has an impact on cuttings removal and stability of the walls. The increased borehole borehole can also undergo a decrease in the hydraulic carrying capacity at precisely the location where the reamed debris is being generated. Furthermore, the pressure variation in the area encompassing the borehole can either mobilize loose fragments or can lead to soft infill material washed into the annulus. When this happens, a coupled hydro-mechanical instability controls reaming, as opposed to tool performance itself. Such is one of the reasons why reaming plans which seem possible mechanically in laboratory or idealized field environments prove to be untrustworthy in real water conservation projects.

There are also powerful influence parameters of operation. The interaction of the reamer with the borehole wall is calculated in combination with rotation speed, thrust or pullback force, torque capacity and circulation conditions. The excessive mechanical load can be used to advance the enlargement in hard rock, but can cause vibration, instability or tool sticking in mixed formation. On the other hand, inappropriately conservative parameters could minimize disturbance but permit long-term exposure of the wall which is also destructive in weak or time sensitive formations. The effective reaming window is not fixed consequently. It is based on the changing condition of the enlarged borehole and should be dynamically changed according to the behavior of the formation, not only the specifications of the tools [44,45].

4.3. Reaming Tools and Process Design

Multi-stage reaming relies on tool design and borehole characteristics in the compatibility of success. Reaming tools that are involved in enlargement of horizontal boreholes tend to differ in cutting configuration, body geometry, fluid passage design, and stabilizing characteristics. The design question of interest in simple formations can be that of efficiency of enlargement. With more complicated strata, however, the choice of tool also has to take into account the disturbance of the walls, the ability to generate eccentric movement, ability to remove the debris, and the sensitivity of the pilot-hole geometry. A reamer effective in competent rock might become unstable in fractured/squeezing formations when its cutting structure is excessively aggressive, or its body lacks adequate directional stability [10].

Of special importance is the correlation between the quality of pilot-holes and the choice of reamers. A pilot hole that is well aligned, frequently geometric and well cleaned allows a greater variety of tool aggressiveness and diameter development. In comparison, in case the pilot hole has local washouts, local collapses or deviation anomalies, the reamer should have the capability to tolerate these anomalies whilst minimizing the amplification. This implies that the design of reaming tool cannot be assessed independently of the borehole it is required to increase in size. Practically, however, the reaming strategies that are most successful are usually those with the greatest nominal cutting capacity, but which can withstand geological heterogeneity and inherited pilot-hole defects without leading to unstable enlargement behavior.

Process design is also very important. The staged diameter scheme identifies the mechanical load on each pass of enlarge and has a highly significant impact on the stability of the wall. Small steps tend to enhance controllability and decrease immediate disturbance, but raise the overall time of construction, and expose the formation to repetitions. Big increments can enhance efficiency, but in fractured or defective strata it can tend to generate too much torque, ineffective cleaning and unsteadiness. The best order is thus project specific and should consider not just the ultimate target diameter, but also borehole length, formation sensitivity, anticipated groundwater conditions and the quality of pilot-hole that is likely to be achieved.

The alternative of forward reaming and back reaming is also worthy of consideration. Forward reaming can be more easily combined with the normal progress of drilling, but can provide less desirable transport of debris in certain horizontal sections. In some configurations, back reaming can enhance the mechanical control of the enlargement process, particularly where the pilot hole is well established, but also presents some independent challenges with regard to pullback load, hole cleaning and tool guidance. No universal method is better in complex-strata water conservancy investigation. Their applicability varies with the interaction with the local formation, fluid regime and construction aim [22].

The other important issue is the reaming and circulation design coordination. With addition of borehole diameter, the annular space, volume of debris and the hydraulic demand vary. In case the circulation system is not modified at every step, reaming process might fail not due to the lack of cutting capacity but due to the inability to remove the created debris. This is an example of a more general rule: reaming design cannot be a mere tool selection and a diameter progression. It is a coupled system that entails tool structure, hydraulic support, time of operation and stability control. This depicts a more general rule; reaming design does not consist merely of selecting a tool and a diameter sequence, but rather a coupled system encompassing tool structure, hydraulic support, timing of operation and stability control as illustrated schematically in **Figure 2**. The extent of these components integration tends to make staged enlargement manageable or increasingly destabilized the borehole [46].

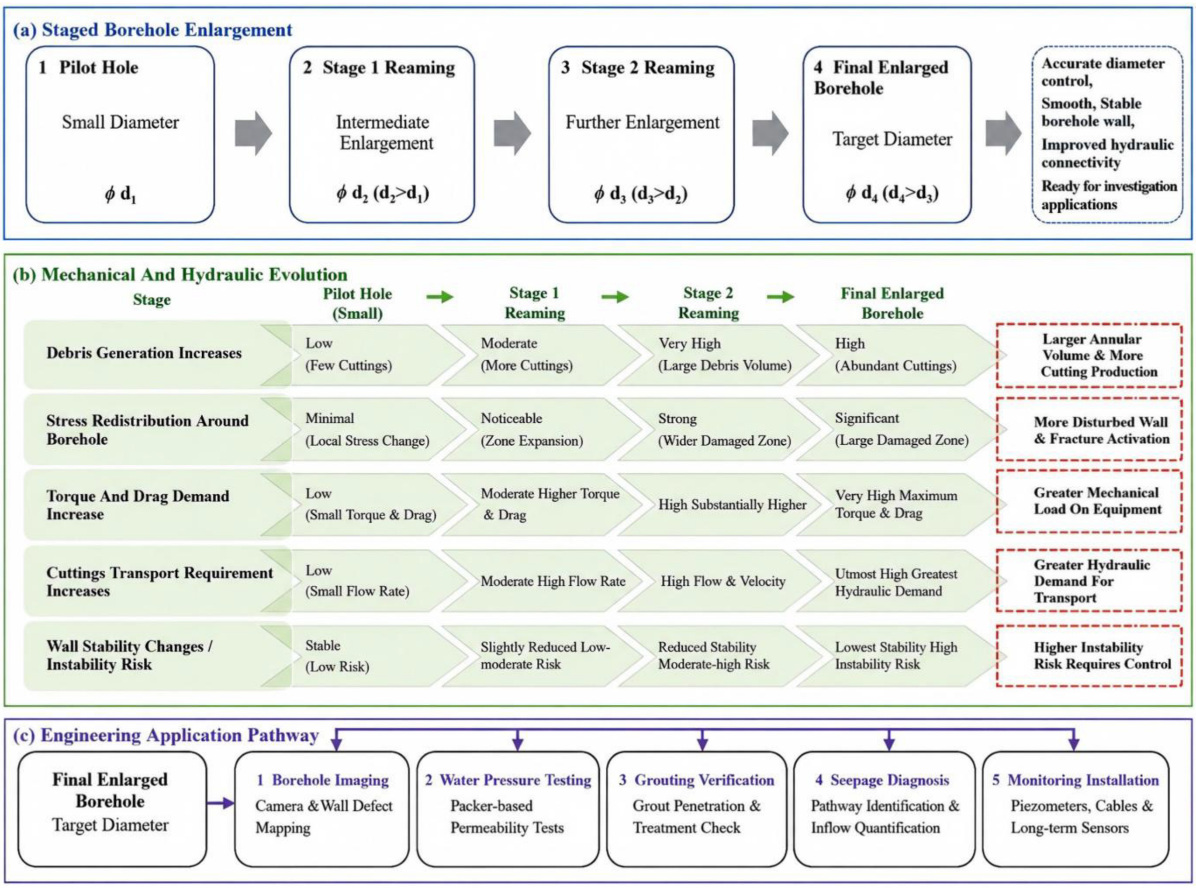

Figure 2. Schematic of pilot-hole enlargement by multi-stage reaming, highlighting the evolution of mechanical and hydraulic conditions during staged diameter increase and the final engineering functions of the enlarged borehole in water conservancy investigation.

4.4. Failure Modes and Mitigation Strategies

Multi-stage reaming in complex strata has various failure modes, which are not often random. Multi-stage reaming failure modes in complex strata are heterogeneous and occur infrequently, though not randomly; their common forms, effects, and management measures have been summarised in **Table 3**. The majority of them can be attributed to a combination of geological weakness, pilot-hole defects, and a lack of process adjustment. One of the most frequent and the most significant types of failure is borehole collapse. It can either be immediate on enlargement where the reamer uncovers unstable structural planes or weak infill materials or it may be gradual as a stage has been made and the conditions of wall support become weaker. In both, collapse during reaming tends to be more destructive than during pilot drilling due to increased debris production and reduced confinement to oppose further collapse [47].

The other issue is eccentric reaming that is mostly experienced in interbedded formations or boreholes with asymmetric pilot-hole geometry. A lop-sided profile created by preferential expansion on one side of the borehole, enhances drag, lowers tool stability and diminishes the dimensional integrity needed in subsequent operations. Eccentricity is not merely a question of poor alignment; it is an imbalance of forces that is created by geological contrast, tool design or accumulation of cuttings. It is usually harder to detect in the early stages and once it has developed, it is likely to escalate to higher levels in later stages, hence the importance of early detection and correction.

Table 3. Main characteristics, failure modes, and mitigation strategies of multi-stage reaming in complex strata.

Reaming Aspect	Typical Manifestation	Main Risk Mechanism	Engineering Consequence	Recommended Control Strategy
Small diameter increment reaming	Multiple closely spaced enlargement stages	Repeated tool passes and longer exposure time	Better controllability but lower efficiency and possible time-dependent instability	Use in weak or highly broken strata where stability control is more important than speed
Large diameter increment reaming	Fewer enlargement stages with greater diameter increase per pass	High torque, large debris generation, strong wall disturbance	Faster enlargement but higher risk of collapse, blockage, or eccentricity	Limit use to relatively competent formations with good pilot-hole quality and reliable cleaning
Forward reaming	Enlargement in the direction of drilling advance	Debris transport may become difficult in some horizontal intervals	Efficient process continuity, but sensitive to hole cleaning limitations	Combine with an adequate circulation rate and frequent response assessment
Back reaming	Enlargement during pullback	High pullback load and sensitivity to local irregularities	Can improve control in selected configurations, but may intensify drag concentration	Preferably, when the pilot hole is stable and alignment is reliable, monitor torque and drag continuously
Aggressive cutting structure	High cutting efficiency and rapid wall removal	Excessive disturbance in weak or mixed formations	Faster enlargement but higher probability of wall damage and irregular profile	Use selectively in competent rock and reduce aggressiveness in fractured or soft intervals
Conservative/stabilised reamer design	Lower aggressiveness with stronger geometric guidance	Reduced instantaneous cutting efficiency	Better borehole regularity and lower disturbance	Appropriate for faulted, interbedded, or instability-prone formations
Poor pilot-hole quality inheritance	Local washout, collapse, deviation, or inadequate cleaning from the pilot stage	Reaming amplifies inherited defects	Eccentric enlargement, sticking, and final borehole unusability	Prioritise pilot-hole conditioning before enlargement and avoid forcing reaming through unstable sections
Inadequate hole cleaning during reaming	Cutting bed formation, return flow instability, and debris accumulation	Annular transport failure	Torque increase, blockage, sticking, secondary collapse	Match the circulation system to each diameter stage and adjust the penetration/reaming rate dynamically

Sticking and excessive torque often occur when hole cleaning falls behind garbage production or when debris is deposited in locally enlarged or collapsed areas left by reamed fragments. This is especially problematic in horizontal boreholes since gravitational settlement encourages the development of cuttings beds. These beds add mechanical resistance, obscure the actual state of the wall, and can initiate secondary collapse by blocking circulation. Notably, sticking can be the last manifestation of an instability that is developing in advance and not a standalone phenomenon. When the tool gets stuck, it might be due to some distance. That is why it is better to be monitored over slow increment of drag, uneven torque variation, or alteration of return flow rather than wait until acute symptoms of failure appear [48].

Critical attention should also be paid to the damage to the walls as a result of over-aggressive reaming. In certain projects, the need to be efficient in construction results in large diameter jumps or high load reaming that causes rapid enlargement of the hole but destroys the near-borehole structure. This damage might not preclude completion, but it reduces the borehole's viability for hydraulic testing, imaging, or structural interpretation. This type of successful failure is especially problematic in water conservancy research where the usefulness of a borehole can be much more important than its rate of enlargement. It is possible to fill a borehole in a geometrical manner and make it scientifically useless through over-disturbance.

Prevention and mitigation strategies should be founded on prevention and not rescue. Good pilot-hole construction (first line of control) is high-quality, as many reaming failures are carried forward due to unresolved defects in the original borehole. The second one is parameter adjustment based on stages and close matching between diameter increment, reamer aggressiveness and circulation capacity is done. The third one is real-time diagnosis of abnormal response, not just torque and drag variations, but also cutting character, fluid-loss behaviour, and deviation irregularity. These indicators can be an earlier indicator of instability in complex strata than actual visual confirmation.

The more general lesson of these failure modes is that multi-stage reaming is not a stable transition but merely a sequence of mechanical enlargement. Each change in diameter alters the borehole environment; each reaming step establishes a new equilibrium among wall support, debris production, and fluid transport. The best mitigation measures are those that regard reaming as a gradual risk-management process based on geological knowledge [49–52].

4.5. Adaptability and Technological Implications

Multi-stage reaming technology can accommodate geological heterogeneity without compromising borehole functionality, thereby enhancing its adaptability. The adaptability in water conservancy investigation is assessed not only by the feasibility of the enlargement, but also by the stability of the final borehole, its interpretation, and compatibility with the planned engineering work. This criterion separates the field from most traditional drilling applications and justifies considering multi-stage reaming from a more technical perspective.

One key implication is that staged enlargement must be formulation-based, not based on standard diameter progression. The same reaming sequence can also have a very different outcome in fractured granite, karstified limestone, or soft-hard interbedded strata of the sedimentary. Adaptive design involves identifying the intervals that are controlled by abrasion, structural instability, and hydro-mechanical sensitivity. Only at that point can the enlargement strategy be reconciled with the predominant site risk mechanisms [47].

This is also an indication of where this technology is heading. Closer integration of geological prediction, pilot-hole response analysis, reaming tool design, and real-time process control will be important for achieving more reliable multi-stage reaming in complex strata. The discipline is shifting, however, towards a more diagnostic and adaptive model in which each reaming stage is viewed as both an operation and a source of geological information. This development is of particular significance to water conservancy investigation since the borehole is not only a construction item, but also an open route into the subsurface.

Multi-stage reaming, in this sense, goes beyond simply increasing the borehole diameter. It is a pivotal connection between the feasibility of drilling and the quality of investigation. Its real merit is that it enables the drilling of large-diameter horizontal boreholes at geologically challenging sites without compromising the stability, continuity, and interpretability required for water conservancy engineering [10].

5. Engineering Applications, Evaluation Methods, and Future Development

5.1. Typical Applications in Water Conservancy Investigation

Complex-strata horizontal borehole drilling and multi-stage reaming engineering value proves best in water conservancy work, where important geological information is not dispersed vertically but laterally. At dam foundations and abutments, e.g., the continuity, aperture and hydraulic connectivity of weak interlayers, weathered belts, fault damage zones and seepage conduits are usually of greater importance than the mere depth of the bedrock. In such environments, horizontal boreholes are especially useful, as they can cut across these features in the direction of their distinctive extension, enhancing the interpretation of the structure and enabling a more continuous evaluation of permeability and grouting conditions. This method offers a superior foundation for locating the lateral continuity of concealed defects, which may govern leakage or local instability, compared with vertical drilling.

The importance of horizontal boreholes is equally evident in high-slope and reservoir investigations. The bedding-parallel slip surfaces, highly weathered contact zones, or local groundwater-saturated fracture networks tend to be controlled by bank deformations and seepage hazards, which occur along the slope direction instead of normal to it. Traditional borehole designs can identify isolated weak regions but, with high probability, cannot confidently characterise their continuity or connection. Horizontal drilling can enhance this by providing access routes that align with the slope's structural reasoning. Such boreholes with multi-stage reaming can be used to enable repeated borehole television inspection, water pressure testing, deformation monitoring, or targeted treatment verification. In this sense, reaming is not merely an enlargement procedure but a process of converting an informative geological pilot hole into an engineering investigation channel with multiple functions [2].

Another significant area of application is underground hydraulic structures, such as diversion tunnels, outlet tunnels, culverts and powerhouse caverns. The rock that encloses these structures is usually influenced by stress redistribution from excavations over existing geological weaknesses. Inflows of water, instability of the linings, and concealed fracture zones could occur along sidewalls, crowns or foundation contacts that cannot be detected solely by surface-based vertical drilling. These areas can be accessed directly by horizontal or subhorizontal boreholes, excavated out of galleries, adits, or tunnel faces, and it is feasible to survey concealed defects in advance of excavation or behind support structures. The capability to safely enlarge the borehole is of particular concern in these settings because final holes are usually required to accommodate integrated services such as geophysical logging, permeability testing, remedial grouting, or visual inspection [53].

Complex-strata horizontal boreholes are also becoming increasingly important in verification-oriented investigations. Whether there is a defect or not is not always the important engineering question in most water conservancy projects, but whether the treatment has changed the defect zone. The use of grouting curtains, seepage control systems, and local reinforcement measures is often subject to post-treatment assessment in situations where the access is restricted and the target structure is laterally extensive. Staged, reamed horizontal boreholes may be used as high-quality channels for secondary inspection, secondary evaluation of residual permeability, and direct observation of treatment influence zones. The change in the role of drilling technology is emphasised in this application: it is not just for exploration in the pre-construction stage, but also a tool for complete-cycle engineering diagnosis, feedback, and validation.

A key point of these applications is that the effectiveness of the technology is not so much dependent on the nominal drilling reach as the extent to which borehole construction is tuned to the geological and hydraulic characteristics of the target zone. Horizontally drilled projects that treat horizontal drilling solely as a longer borehole often have limited interpretive value. In comparison, projects that combine target-oriented borehole design, stepwise expansion, and a testing plan are better placed to obtain information of direct engineering value. This supports the role of horizontal drilling and reaming in water conservation research, as it provides a form of subsurface access that can be utilised where traditional methodologies are ineffective due to geometric or geological constraints [54].

5.2. Performance Evaluation and Comparison

The assessment of complex-strata horizontal drilling and multi-stage reaming technology for water conservation exploration should extend beyond traditional construction measurements. Many drilling fields consider performance to be measured by the rate of penetration, the final diameter or the efficiency of completion. These signs remain applicable, though not sufficient in the current scenario, since a mechanically finished borehole may still not provide reliable geological information or a reliable test of hydraulicity. It should thus be evaluated within a more comprehensive framework that incorporates construction feasibility, borehole quality, the investigation's functionality, and engineering interpretability.

One of the most significant dimensions of assessment is the quality of boreholes. Practically, this involves the accuracy of the trajectory, regularity of diameter, integrity of the wall, continuity of the enlarged interval, and absence of collapse, extreme eccentricity or continuous accumulation of the cuttings. These parameters dictate the borehole's capacity to support further operations such as imaging, coring, pressure testing or grouting verification. An efficient drilling process that creates irregular geometry or unstable walls might seem successful in the short run, but will prove ineffective as soon as investigation work is undertaken. This discrepancy is one of the key reasons why performance assessment of water conservancy initiatives should be tied to post-drilling utilisation rather than halting after holes [55].

The second dimension is the trustworthiness of the borehole's geological and hydrogeological data. The intended target horizon or defect zone should be intersected by a high-quality investigation borehole with adequate positional control and limited disturbance of the intended target horizon or defect to maintain the interpretive value of cuttings, core, imaging, and permeability observations. This is particularly required in water-bearing or weak formations where aggressive drilling fluids, unsteady reaming, or frequent corrective treatments can modify the initial near-borehole state. When this happens, the borehole loses its descriptive quality as the natural structure on which it was intended to represent. So, investigation reliability is not a passive result; it is a measure of the preservation of the geological meaning of the interval accessed by drilling and reaming.

Process stability is a third evaluation aspect. A drilling technique in complex strata cannot be judged based on average performance values, due to the frequent occurrence of unstable operations that produce misleadingly acceptable results and hide a very serious local risk. The frequency of torque variation, the intermittency of loss of circulation, the cumulative increase in drag, local sticking, or repetitive instability treatment are all indicators of low process robustness, even if the borehole is ultimately completed. In the case of water conservancy investigations, process stability is important, as it influences the quality of the boreholes and the level of confidence in the interpretation. A technology that only works with a large-scale response to reactive intervention might not be easily ported or generalised to other projects with varying geological environments.

Relative assessment of approaches also needs to be considered. Pure rotary drilling, rotary-percussion systems, directional drilling, and various staged reaming sequences offer different benefits depending on the formation and the project objective. No generally better method is applicable throughout the whole range of complex strata. An example would be that a drilling mode with greater aggressiveness can be superior to others in hard, intact rock but unsuccessful in fractured and water-sensitive formations, where borehole usability is the key factor of interest. Equally, the high reaming diameter step can lead to seemingly high efficiency in competent mechanically stratified zones but result in unacceptable instability in interbedded or faulted zones. As such, the contextual comparison should be meaningful and not abstract. Techniques must be evaluated in relation to the prevailing geological hazards, the planned post-drilling activities, and the capacity to withstand disturbance within the target water conservation project [56].

There is a need to evaluate economic and environmental aspects as well, but this should not be reduced to guiding only construction costs. Multi-stage reaming, real-time monitoring, or adaptive fluid systems can add to upfront costs but can minimise the chances of borehole failure, misinterpretation, or the need to conduct a remedial investigation again. In water conservancy engineering, where poor characterisation of the subsurface can result in ineffective treatment or an improper estimate of seepage risk, the indirect cost of poor investigation may outweigh the apparent benefits of a lower-cost drilling method. The compatibility with the environment is also crucial. The loss of drilling fluids, contamination of formations, and unjustified disruption of seepage channels can not only affect the outcomes of investigations but also pose broader ecological and operational issues. An all-inclusive evaluation system must thus take into consideration lifecycle technical value, not short-term construction efficiency [57].

A key learning point from the current practice is that the lack of standardised evaluation criteria is a significant shortcoming. Most projects document extensive operational information, yet there is no continuous way to correlate it with the investigation's ultimate effectiveness. The further development requires a more specific performance scheme in which the indicators of construction, the geometry of the boreholes, the usability of the investigation, and the geological validity are jointly evaluated. In the absence of such integration, technical comparison will continue to be experience-based and hard to generalize [56].

5.3. Emerging Trends and Research Frontiers

Further progress in complex-strata horizontal borehole drilling and multi-stage reaming of water conservancy survey is likely to be influenced by a shift in empirically built construction to adaptive, data-driven, and technology systems based on geology integration. The growing complexity of the project sites, the need to have a more dependable characterisation of the subsurface, and the realisation that traditional drilling measures are not sufficient to reflect the performance of the investigation are driving this transition [58].

The increasing adoption of real-time monitoring and smart control is one trend. On-site measurements during drilling, torque, drag, return flow, and vibration measurements, as well as dynamic trajectory tracking, are already enhancing the capability to detect abnormal activities in the borehole during construction. The second process will be to convert these data streams into practical geological and engineering decisions. Alterations in drilling reactions in complex strata usually provide valuable information regarding transitions in lithology, concealed fracture zones, or seepage structures. The introduction of intelligent drilling into the field of water conservancy research thus rests not only on automation but also on the joint interpretation of drilling mechanics and geological cues. This would enable the operational adjustments to be made earlier and more specifically.

The second frontier concerns digital modelling and digital twins for borehole construction. Conventional design methods tend to treat the geological model as set in stone before drilling, with minimal modification during drilling. As a matter of fact, there is continuous discovery of new information about the subsurface as horizontal drilling in complex strata continues. Borehole construction process, geological interpretation, and risk prediction model could be developed simultaneously in near real time through digital twin frameworks. This would allow the trajectory decisions, remaining increments, and stabilisation strategies to be upgraded dynamically as more evidence on the formation becomes available. In the case of water conservancy research, this is particularly useful, since the engineering value of a borehole is largely determined by whether it remains on the actual geological target rather than the pre-drilling hypothesis [59].

Another significant direction is innovation in tools and materials. Formation-adaptive, more robust bit and reamer designs would be required for use in conditions where hard abrasive rock, weak interlayers, and water-sensitive materials are present within the same borehole. Simultaneously, the drilling and reaming fluid systems should be made more selective and eco-friendly, particularly in the case of natural seepage conditions, which need to be maintained to test or ecologically justify. It is not merely a question of developing stronger tools or more stable fluids, but rather of devising systems which can be run in a changing geological regime without creating undue disturbance. This suggests a shift towards modular and adaptive tool systems instead of one-mode systems.

Combining drilling with multi-source investigation methodology is also bound to gain significance. Horizontal boreholes that are expanded by staged reaming provide a useful platform for integrating direct-drilling data with borehole imaging, geophysical logging, hydrogeological testing, distributed sensing, and localized treatment monitoring. The borehole could be used in the future as less of a solitary exploration tool and more of a conduit for integrated subsurface diagnosis. This change will necessitate better liaison among drilling engineers, hydrogeologists, engineering geologists, and monitoring experts, but would potentially add considerable interpretive richness to a water conservancy investigation [60].

Standardisation is another priority in research. Despite the rapid development of the field in engineering practice, standardised approaches to borehole design, the choice of staged reaming, quality evaluation, and performance evaluation based on investigations remain scarce. The lack of these standards makes comparison across projects difficult and slows the transfer of successful experience into widely applicable technical guidance. Further studies should thus not just focus on individual technical advances but also seek to define assessment systems and design concepts that are robust across representative groups of complex strata.

The last and more general tendency is the one from construction-centred thinking to investigation-centred thinking. In the old practice, the success of drilling was usually determined by the ability to complete and enlarge the holes. That standard is no longer adequate in contemporary water conservancy endeavours. The real test of success is whether the technology can provide a stable, interpretable access route to the most important subsurface structures that govern seepage, deformation, and treatment performance. Such a view will probably lead to more continuing innovation than any single increase in penetration rate or equipment power [61,62].

Collectively, these trends imply that the following phase of development will be a more strongly coupled geology, mechanics, hydraulics, and data analysis. Taken together, these trends portend that the following phase of development will be more closely coupled with geology, mechanics, and hydraulics, as well as data analysis, and that the relevant assessment dimensions and development priorities will be summarised in **Table 4**. Complex-strata horizontal drilling and multi-stage reaming are unlikely to be developed through the isolated optimisation of specific tools. Their true future lies in integrated systems that can respond to geologic uncertainty while maintaining borehole quality and maximising the engineering value of the inquiry. **Table 4**. Assessment parameters and subsequent development directions of complex-strata horizontal borehole drilling and multi-stage reaming in the investigation of water conservation [2,63,64].

6. Conclusion

Complex-strata horizontal borehole drilling and multi-stage reaming technology have become a significant technical method in modern water conservancy exploration, especially for projects where key geological and hydrogeological targets are laterally distributed, structurally controlled, and complexly described by traditional vertical drilling methods. With the expanding scope of water conservancy engineering to include deep abutments, karstified foundations, steep reservoir banks, and highly intricate underground hydraulic structures, there has been a significant increase in the need to access the subsurface on a more precise, continuous, and operationally useful scale. Horizontal boreholes are useful here not only for accessing hard-to-reach targets but also for directly investigating seepage pathways, weak interlayers, fault damage zones, and intervals of treatment effects in a geometrically significant manner.

This review demonstrates that the key issue with such technology is that geology, drilling mechanics, and engineering goals are coupled. Complex strata are not merely challenging formations in a generic sense; they are a dynamic environment where lithological contrast, structural discontinuity, groundwater activity, and time-dependent instability interact during the construction of a borehole. Such interactions render horizontal drilling quite different from merely extending vertical drilling practice. The stability of the borehole, the direction of the borehole, cutting conveyance, as well as the flexibility of the tools, is more sensitive under horizontal conditions, especially when the structure is composed of hard abrasive rock, fractured weak tissue, soft interlayers, and water-bearing structures within the same interval of the borehole.

In this context, multi-stage reaming is not just a diameter-enlargement process but a formation-adaptive mechanism for maintaining borehole functionality and minimising the risks of direct construction of large diameters. Its real value in the study of water conservation is that the pilot holes may be converted into larger, more useful channels for borehole studies, hydrogeological tests, grouting checks, and combined engineering diagnosis. Simultaneously, the review highlights that the quality of the pilot hole, staged-diameter design, fluid support, tool compatibility, and real-time feedback on formation changes highly regulate reaming performance. Process integration is the key to the success of staged enlargement, not reaming force alone.

One of the significant lessons from this article is that drilling and reaming methods in water conservation research must be considered based on the usefulness of the boreholes and their geological soundness, rather than on penetration efficiency or nominal completion. A borehole that has reached its intended depth but has lost its structural integrity, target accuracy or testing compatibility cannot be considered a complete success in an investigation-oriented engineering scenario. This opinion distinguishes water conservancy applications from most traditional drilling fields. It explains why a broader performance structure is required, encompassing trajectory precision, wall stability, hydraulic cleanliness, post-drilling functionality, and the representativeness of the acquired geological data.

Some of the unresolved issues are also pointed out in the review. The technologies used nowadays are still dependent on experience-based adaptation to highly heterogeneous formations, and the transfer of methods from oil and gas or trenchless construction is still imperfect due to differences in the goals of water conservancy investigation. There are still no standardised evaluation criteria for the quality of complex-strata horizontal boreholes, and the integration of geological interpretation and drilling control is not as strong as required in numerous projects. These lapses suggest a future development towards geology-oriented design, adaptive process control, enhanced real-time diagnostics, and complete process integration of drilling, reaming, monitoring, and testing.

In the future, the most likely trend is a shift toward intelligent, investigation-based technical systems and away from empirical borehole construction. It involves real-time monitoring, dynamic parameter optimisation, the concept of a digital twin, and the coexistence of interpreting drilling response as a geological signal. It also involves the production of more flexible bits, reamers, and circulation systems applicable to mixed formations and environmentally sensitive hydrogeological settings. Finally, the development of complex-strata horizontal drilling and multi-stage reamings will require more concerted efforts among engineering geologists, drilling engineers, hydrogeologists, and monitoring experts.

In short, drilling complex-strata horizontals and boreholes with multi-stage reaming technology provides an important basis for enhancing the accuracy, safety and interpretability of water conservation studies. It is not only about drilling deeper or faster, but about building stable, accurate, and information-intensive boreholes that can meet the entire lifecycle needs of hydraulic engineering.

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The authors declare no conflict of interest.

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