sustainability

Review

Development of Reinforced Concrete Piles in the Lower Yellow River, China

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Abstract: Controlling the river regime in the lower wandering reaches of the Yellow River Basin is important for ecological protection and high-quality development. This study reviews the development of pile groynes suitable for wandering rivers. As a widely used form of reinforced concrete pile, pile groynes, including round and sheet piles, have been built in alluvial rivers in large numbers for many years. Currently, research focuses on improving the stability and erosion resistance of these piles. Here, three types of groynes are discussed according to the construction technology: cast-in situ bored pile, vibratory-driven pile, and jetted precast concrete pile. Detailed discussions are provided regarding their respective applicability, improvement processes and characteristics. In contrast to the other two methods, jetting minimizes the damage to the structure and strength of the concrete pile and is characterized as fast-tracking, cost-effective, and environmentally friendly. Enhancing the safety and practicality of concrete piles can be effectively achieved through improvements in construction techniques, modified construction materials, and multi-structure combination pile designs. Furthermore, in the current context of pursuing a resource-saving and environmentally friendly society, energy conservation and emissions reduction have become focal points in engineering technology development, while still maintaining a strong emphasis on construction quality.

Keywords: riverbank avalanche; river control; pile; Yellow River; sustainability

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1. Introduction

Around the world, large quantities of sediment are supplied to channels and deposited at many mid-channel bars, leading to the formation of wandering braided channels. Mass failures of channel riverbanks and collapses of shoal margins and beaches frequently occur due to flow slides and have been documented in estuaries and rivers [1], such as the Brahmaputra River [2], Yangtze River [3] and rivers in the Oklahoma Ozarks [4]. Normally, systematic river-training works are built on wandering rivers to control the river regime. In the Lower Yellow River of China, small-discharge floods frequently occur and have persisted since the Xiaolangdi Reservoirs were implemented in recent decades. At small discharges, the main stream continued to wander within the channel within the planned flood discharging width, resulting in the continuous development of an abnormal river regime in some reaches. Under these circumstances, dangerous situations in the low flow increased, and the main stream was not well controlled; in addition, during large floods, transverse or rolling rivers are more likely, seriously threatening the groyne safety of the lower reaches [5]. Hence, controlling the river regime is an urgent problem for the 1.9 million people living in the Lower Yellow River Basin (Figure 1).

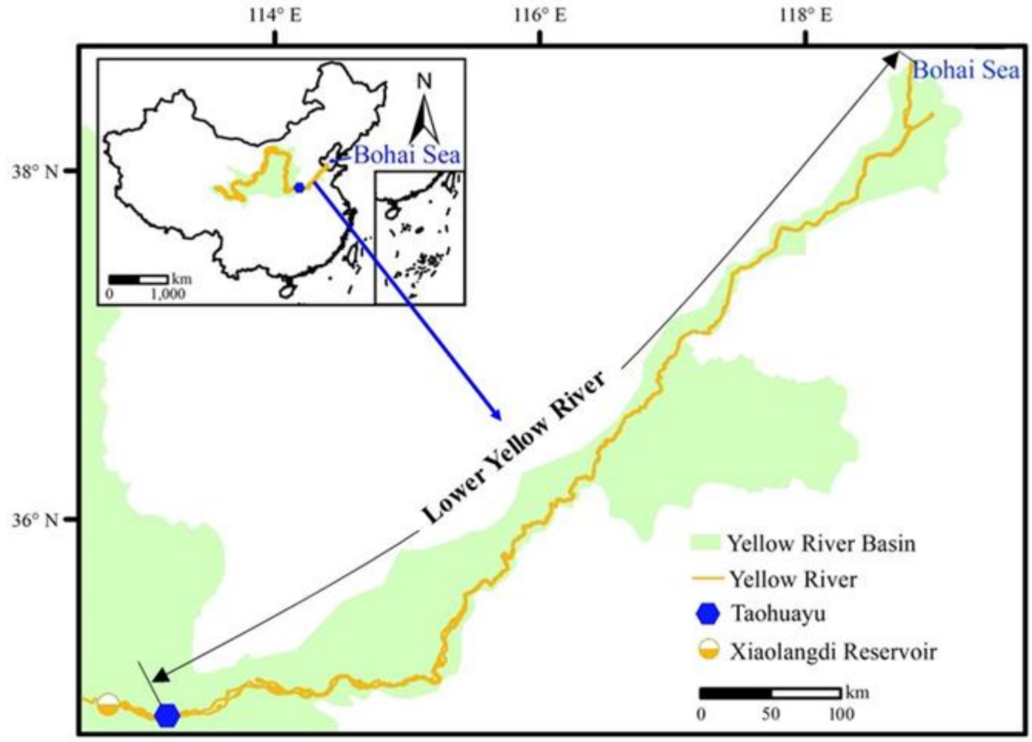

Figure 1. Study area. The Lower Yellow River is defined as the reach between Mengjin in Henan Province and Lijin in Shandong Province, China, with a total length of about 740 km.

Pile groynes can decrease the flow velocity near the riverbank and create rapid sediment deposition, particularly in alluvial rivers with a considerable bed load and high sediment concentration. The pile groyne has been extensively employed along the southern shores of the Baltic Sea for over a century and a half. Successively, over 900 pile groynes have been built along the German part of the coast and about 950 along the Polish coast since 1843. Pile groynes have also been applied to many construction projects on the Rhine River in the Netherlands, the Mississippi River in the USA, and the Baltic Sea in Europe. Since the 1970s, pile groynes have been widely used in many projects on the coast of China, especially in the outlet of the Yellow River. For example, this type of concrete pile has been built in the projects at Dongan, Zhangwangzhuang, Gubaizui, and Weitan in the Henan segment of the Lower Yellow River.

Extensive research has been conducted on reinforced concrete piles. The layout of these piles and the design of individual piles have been tested in Bangladesh. The Netherlands has also accumulated some experience in this field due to the practice of controlling the Rhine River. A large number of permeable pile groynes have been constructed in the Niger Delta and the Yellow River in recent years (Figure 2), and many experimental studies have been undertaken to examine the layout, permeability, orientation, length, and spacing of these permeable groynes. However, due to the special form and complex flow boundary conditions of permeable groynes, systematic studies of the hydraulic conditions, structure types, and construction technologies are still needed. The objectives of this study are to review the development of pile groynes suitable for wandering rivers and propose a way forward for pile groynes in the near future.

Figure 2. Piles along the riverbank of the Yellow River. Photo by Xiangzhou Xu, 15 July 2018.

2. Principles, Classification, and Characteristics of Concrete Piles

Pile groynes can increase beach stability. In wandering rivers, flow velocity greatly impacts the sediment-transport capacity. Pile groynes could reduce the current velocity due to increased hydraulic roughness in the longshore current. Consequently, the decreased current velocity in the pile groyne field reduces turbulence produced at the bed due to wave–current interactions. This, in turn, lowers the erosion potential of shoreline breakers and reduces the amount of suspended sediment. However, under the action of a tidal bore, buckling failures, including head flushing and foot hanging, are often found in traditional rock-filled groynes [6]. Hence, different structures have increasingly been used to meet the multifunctional requirements of river and sea management. Reinforced concrete round and sheet piles have been proposed for purposes such as flood protection, dike construction, and riverbank reinforcement.

As shown in Figure 2, the circular cross-section pile has become a widespread river management technology because of its characteristics, including the regularity of flow around the cylinder, reduced tortuosity of streamlines, strong bearing capacity, and convenient construction. Reinforced concrete round piles are arranged along the diversion lines at a predetermined spacing [7], which can reduce flow velocity and promote sediment deposition through the water resistance and permeable structure of the piles. In practical applications, changing the pile diameter, height, spacing, and number of rows can meet specific flow control and riverbank protection requirements [8]. Reinforced concrete round piles are generally prefabricated in factories and installed using cast-in situ boring, vibratory driving, or water jetting. They are now widely used in river training works in combination with other fundamental approaches, such as geocomposites and riprap [9]. In addition, the structure combining round piles and a triangular vane has become an eco-friendly river restoration method with good performance in outer riverbank protection and meander bend restoration [10]. However, some defects still exist in concrete piles, e.g., material wastage, breakage susceptibility, washout ease, and difficulty controlling construction quality [11]. The Dong'an river-training works in the middle reaches of the Yellow River, a World Bank project financed in 2012, have approximately 81.6 m of reinforced concrete bored piles that eroded and collapsed under the scour of low discharge in 2021 [12]. This case shows that the safety of reinforced concrete bored piles cannot be ignored. Their collapse is caused by main stream scouring with low discharge in the Yellow

River. Therefore, research into technical improvements, such as the stability and scour resistance of piles, is ongoing.

In contrast, sheet pile is a new type of hydraulic structure system derived from the hydraulic flashboard technique, which integrates many specific techniques from the petroleum industry with the practical needs of hydraulic engineering. Sheet piles are generally installed at their design depth using water jetting [13], and each pile is positioned equidistantly. The water and sediment regulation of the sheet pile is accomplished by the porosity and pore size of the pile foundation. By designing pore sizes and other parameters, sediment in the river can be balanced and deposited at specified locations. Sheet piles have the advantages of fast and low-cost construction processes and can meet the requirements of numerous special environments. Sheet piles have been used for riverbank protection in the Yellow River [13] and the Qiantang River [14] of China with positive results in practical application. Nearly 20 years of practice in the Qiantang River have shown that the sheet pile groyne system can protect riverbanks and seawalls well, avoiding bucking failures and providing a much longer service period with fewer maintenance costs than traditional groynes [6]. Researchers in Hungary have developed prefabricated concrete sheet pile walls, mainly to prevent erosion and provide places for sports activities along the riverbanks, and used them in the rehabilitation of the shores of Lake Velence in 2020 [15]. Various shapes of sheet piles have also been developed for river management applications. A typical example is U-shaped concrete sheet piles, widely used in river dredging to improve urban flood control systems [16]. Inevitably, it is the presence of pores in permeable sheet piles that are highly likely to result in stress concentrations that will lead to cracks at the location of pores [17], weakening the safety performance of the pile. In addition, the turbulent kinetic energy in front of the sheet pile first increases and then decreases with increasing pore size; hence, an inappropriate pore size could increase the scouring intensity at the head of the pile [18]. Not only increasing turbulent kinetic energy but also the high-velocity flow passing through the pores of the commonly used permeable sheet pile (0°) without changing direction may cause riverbank scouring, destruction of aquatic habitats, and high flow thrust on the downstream piles, which ultimately may cause the failure of the spur dike [19].

3. Development of Installation Technology for Reinforced Concrete Piles

Concrete piles can be inserted into the river bed by drilling, vibrating, or water jetting [7]. Concrete piles can also be classified into three different forms using the type of construction technology: (1) Bored pile. This type of pile can be applied to different types of soil and may be firmly connected with the soil. Nevertheless, it is costly, has a slow construction process, and is also prone to various quality problems in complex river conditions. (2) Vibration-driven pile. This pile type is suitable for loose, non-cohesive soils, especially water-bearing sand soils [20]. However, it has the disadvantages of low stiffness and poor quality. This pile type may also adversely affect the environment and aquatic life due to vibration during installation [21]. (3) Jetted pile. Pile jetting is typically recommended when the piles are expected to be driven mostly into sand or loose gravel. It requires very simple equipment, and it is easy to operate. Hence, as one of the major jetting methods, hydrojetting is a very effective and time-saving method for underground structures, but the method disturbs and weakens the soil around the pile, resulting in a lower pile-bearing capacity.

3.1. Cast-In Situ Bored Piles

The steps to build a cast-in situ bored pile are as follows: (1) drilling the hole at the pile position, (2) placing the reinforcement cage, (3) pouring concrete into the hole, and (4) fixing the bored pile. Theoretical analysis and practical applications have demonstrated that bored piles can be employed in any ground conditions, including soils and rocks [22]. Due to clayey soils being considered a problematic soil type in building construction, the bearing capacity of bored piles in dense sandy soils [9,23] and deep soft soils [24] has undergone repeated verification. It has been proven that this technology is suitable for these soil types. Table 1 lists the technical characteristics and application evaluations of bored piles built in recent years. The construction process of a bored pile is complex. Furthermore, a bored pile is prone to various quality problems during the construction process, such as deflection or collapse of the drilling hole, breakage or displacement of the piles, blockage of the catheter tube, and floating of the reinforcement cage [25]. Hence, these problems substantially threaten the structure and strength of a bored pile, and an effective solution is critically needed.

Table 1. Cast-in situ bored piles built in recent years.

First Author, (Completion Date), and Affiliation	Overview of the Pile	Evaluation for the Pile	Technology Characteristics of the Pile
Kong [26] (2003), Shanxi Engineering and Research Institute of Metallurgical Industry, China	Squeezed branch pile, a new cast-in situ bored pile technology	High bearing resistance, reliable pile quality, and greatly reduced engineering cost	The plates and branches are penetrated with a hydraulic squeeze tool
Castelli [23] (2004), Parsons Brinckerhoff, USA	Results of an Osterberg load test on high-capacity bored piles at a site susceptible to deep scour	The end bearing resistance and base stiffness significantly increased after base grouting	The piles were constructed with reverse circulation drilling equipment and the base-grouting method
Zhao [27] (2007), Huazhong University of Science and Technology, China	Reinforcing the offset piles using the high-pressure jet-grouting method	Good durability and impermeability of the pile	Injecting high-pressure cement or concrete slurry into the ground to reinforce soil or construct underground structures
Tang [25] (2012), Wuhan University of Science and Technology, China	Analysis of engineering accidents with cast-in situ bored piles	A complex construction process with high technical content requirements and difficult repairs	Various kinds of quality problems during construction: collapsed holes, inclined holes, and catheter tube blockages
Udomchai [9] (2018), Suranaree University of Technology, Thailand	A new riverbank protection structure: the bored pile-bracing system	This structure was stable for both the lowest water level in the river and rapid draw-down conditions	The pile-bracing system consists of long and stiff bored piles, improving the external stability of the riverbank protection structure
Zhou [24] (2020), Zhejiang University, China	The behavior of bored and pre-bored grouted planted (PGP) piles embedded in deep, soft clay	The PGP pile can be considered a type of resource conservation and eco-friendly pile foundation	The PGP pile has superior bearing capacity and ultimate unit skin friction compared to a bored pile

In order to guarantee the quality and durability of the bored piles, Zhao et al. (2007) [27] have proposed a high-pressure jet-grouting method. The jet grouting was successful in the verification tests. An automatic control method has also been shown to improve the drilling quality [28]. With this method, pressure signals from the rotating system are collected and fed back to the controller, and then the force of the feeding system is controlled. Post-grouting is a new technique that improves the stability of a bored-pile foundation [29], which has been successfully applied in the Jamuna Bridge over the Brahmaputra River in Bangladesh. Both the side and tip of the cast-in situ piles were post-grouted, improving skin friction and tip resistance [30]. As a result, this technique has been widely adopted beneath deep foundations.

To increase the bearing capacity of a single pile, the Beijing Huajun Foundation Engineering Technology Development Company has developed a new type of pile, a squeezed branch pile, in which the plates and branches are pressed with a hydraulic squeezing tool [26]. Currently, the squeezed branch pile is considered a universally applicable technology, as it can be applied not only to relatively hard soil layers [31] but also demonstrates excellent performance in highly collapsible loess soils [32]. A pile foundation project in the Eastern Expressway of Ningbo, China, has shown that the squeezed branch piles can save over 30% of the construction materials compared to conventional straight piles while achieving the same compressive bearing capacity [31]. In addition, compared to regular cylindrical piles with the same diameter and length, the concrete bearing capacity per cubic meter volume increases by about 50% for a squeezed branch pile [32]. In addition to improvements in process technology, the constructors may prioritize construction quality while constructing bored piles, e.g., the end bearing resistance, the speed of footage, slurry quality, and pouring concrete velocity [25]. Hence, when dealing with loose and easily slumping soil layers, it is advisable to bury the casing appropriately deep and seal it with clay to prevent issues such as pile collapse [29]. Udomchai et al. (2018) [9] have found that a long and stiff bored pile can improve the external stability of the structure by increasing the embedment length to obtain high passive lateral resistance.

A bored pile possesses several advantages, such as low noise, slight vibration, and solid connection with the surrounding soil, compared to a driven pile. Hence, this method allows for the construction of large-diameter piles [23], and when combined with post-grouting techniques, the advantages become even greater [30]. Nevertheless, the complex construction process and high technical content requirements make it difficult to meet the design requirements. In addition, the bored pile installation process will produce large amounts of slurry, and slurry pollution has become a severe environmental issue in China [25]. Consequently, cast-in situ bored piles have rarely been used in river control engineering. Today, precast concrete piles are used extensively, as they have the advantages of reducing construction noise induced by vibration or compaction, eliminating pollution during concrete mixing on site, providing a reliable and accurate installation, and minimizing transient driving stresses [17]. Additionally, based on the uniform cross-section bored pile, irregular-shaped piles have also undergone development and utilization. For instance, as mentioned earlier, squeezed branch piles have been applied in various foundation applications, including general industrial and residential buildings, high-rise structures, elevated structures, roads, bridges, and docks.

3.2. Vibratory-Driven Piles

As the vibratory pile is being driven, vibrations are caused along with the vertical movement. The continuous pulses of energy transferred from the pile hammer can change the stress-strain behavior of the soil, including displacement, and they can also create excess pore water pressure or even complete fluidization of the soil. Consequently, the frictional resistances are strongly reduced during vibratory driving, enabling the pile to penetrate the ground. Previous studies have demonstrated that when driving piles in non-cohesive soils, such as loose to medium-density soils, vibrated piles exhibit a higher axial pile capacity due to densification, especially at the pile shaft. Conversely, loosening seems to occur in dense to very dense soils, leading to lowered capacity [33]. Specifically, pile driving in soft clay may reduce the soil strength in the disturbed area, bringing it closer to the strength level after remolding, leading to rapid pile failure [34]. Hence, practical applications have shown a noticeable decrease in the bearing capacity of vibrated piles [35]. Table 2 illustrates the complex interaction between the pile and the soil in the driving process.

Table 2. Vibratory-driven piles built in recent years.

First Author, (Completion Date), and Affiliation	Overview of the Pile	Evaluation for the Pile	Technology Characteristics of the Pile
Shen [34] (2005), Shanghai Jiaotong University, China	A case study detailing a riverbank dike damaged by pile driving in very soft clay	Pile driving in soft clay may reduce the soil strength in the disturbed area	The hammer was applied at high frequency to drive the sheet piles into the soft clay

Table 2. *Cont.*

First Author, (Completion Date), and Affiliation	Overview of the Pile	Evaluation for the Pile	Technology Characteristics of the Pile
Xie [20] (2011), Yellow River Institute of Hydraulic Research, China	Construction of pile groynes on a floating construction platform	The construction technology is relatively convenient, and the work arrangements are flexible	A floating construction platform made of multi-purpose steel floating boxes was used in the process of driving a pile
Lamiman [35] (2014), Froehling and Robertson, Inc., USA	A case history where open-ended pipe piles were installed using both impact and vibratory techniques	The bearing capacities of the vibrated piles were reduced by 50% compared with the piles after restrike driving	Restrikes in one or more months were performed on the vibratory-installed piles
Wang [21] (2014), the Chinese Academy of Sciences, China	Characterizing the acoustic properties of a vibratory hammer pile driving and its impact on aquatic life	Loud noise from construction has potentially adverse effects on the environment and aquatic life	Assessing the acoustic characteristics of the largest vibration hammer in the world.
Daryaei [36] (2020), Technische Universität Berlin, Germany	Numerical evaluation of the soil behavior during pipe-pile installation using vibratory driving in sand	The vibratory pile driving has a 20% reduction in momentum compared to impact driving when reaching the required pile depth	The driving frequency affects the displacement, depth, and void ratio of the pile
Staubach [37] (2022), Bauhaus-Universität Weimar, Germany	Long-term response of piles to cyclic lateral loading following vibratory and impact driving in water-saturated sand	Under ideally drained conditions, vibratory-driven piles result in a lower accumulation	Piles will experience significant long-term deformations when subjected to high-cyclic lateral loading after the installation

Over the past few decades, more and more vibratory-driven piles have been used in practical engineering [20]. Studies have shown that vibratory pile driving was easily performed, but the pile disturbed the surrounding soil and reduced the effective stress in the soil, making the pile foundation unstable [38]. Hence, more research into reducing the ground vibrations generated by pile driving is needed. An analysis of existing research indicates that these problems could be specifically addressed through the following three measures [39]: (1) In the design phase, the use of partly soil-displaced piles or long piles with high bearing capacity could reduce disturbance to the soil around the pile. Particularly prominent among these are pre-stressed hollow piles, which have been widely applied in engineering projects. Due to their hollow structure, hollow piles can reduce disturbance to the surrounding soil and minimize ground vibration and noise transmission while offering advantages such as high bearing capacity, high material efficiency, and a short construction period [40]. (2) In the construction phase, ground vibrations could be reduced by controlling the piling frequency and adopting the corresponding vibration isolation measures. High-frequency vibratory pile driving can avoid soil resonance. Increasing the excitation frequency can significantly reduce the vertical peak particle velocity of the soil at the pile tip depth, reducing the stress disturbance range of the surrounding soil and making the range shrink spatially to the pile shaft. Through a model experiment, it has been found that as the excitation frequency increased from 20 to 60 Hz, the maximum radial range of the influence of the pore water pressure was reduced by 60% [41]. Meanwhile, combining this measure with methods such as reducing the static load of the pile hammer and minimizing the pile diameter can further minimize the effects of pile construction [42]. Additionally, the dissipation of excess pore water pressure by installing a drainage system around the pile may mitigate soil heaving and displacement. Research has also found that the use of expanded polystyrene geofoam in-filled wave barriers can attenuate the effects of vibratory pile driving on ground vibration. When the ratio between the Young's moduli of geofoam and soil is less than 0.1, the attenuation efficiency of the geofoam barrier increases significantly [43]. (3) In the management phase, strengthen monitoring of the surrounding environment and minimize potential environmental hazards that may arise during construction. In addition, a combination of pile driving methods is recommended, specifically employing impact driving in the final phase of the vibratory driving process to increase pile base resistance and resist deformation accumulation in vibratory-driven piles due to cyclic lateral loading [37].

Vibratory driving is the most cost-effective compared to other construction methods, mainly due to its relatively quick installation. It also offers several advantages, including reaching the designated depth with less momentum and work, as well as enhanced soil compaction [38]. However, pile driving can induce ground vibration and produce large amounts of noise, which can harm the environment and aquatic life [21]. Nevertheless, relocating a pile to a different site is inconvenient, requiring large and heavy construction machinery. Vibratory piles have specific soil requirements and are only suitable for loose, non-cohesive soils [33].

3.3. Water-Jetted Piles

In the 1980s, an innovative method, jetted precast concrete piling, was applied in the Yellow River to control the river regime. Jetted piles are suitable for river beds with loose gravel, sand, or soft soil [44]. As the water jet forcefully strikes the soil to produce a hole, the pile can be deeply driven into the river bed by its own weight and the striking of the pile hammer. Many suggestions to improve this technology have been put forward to accelerate the spray speed of the water jet and to ensure the quality of the sinking pile. Construction experience has shown that water jetting and pile driving at the appropriate time are more effective and secure. A jetting pipe with nozzles at its tip may disturb and weaken the ground and then lead the pipe into the soft ground, although the speed of the pile preparation and water jetting are slow [45]. The construction speed has been greatly improved through continuous improvement of the water-jetting device [46].

Table 3 shows research progress on jetted precast concrete piles in recent years, where both advantages and disadvantages are discussed. According to the experimental results, the jetted piles have successfully solved the problems of controlling the river regime at low flow [47]. However, the pile is prone to shifting and shaking because the soil adjacent to a jetted pile has been disturbed by the water jet, and the structure and properties of the surrounding soil have been significantly changed. To increase the soil stress and reduce the erosion displacement, many techniques have been adopted, e.g., digging stress-releasing holes and pre-bored holes [48] and filling the loose zone between the pile and the surrounding soil with boulders, cobbles, and coarse gravels. Nevertheless, the above-mentioned methods are costly and time-consuming. In response, Xu et al. (2006) [44] have developed a low-cost technology, grouted-jetted precast concrete piling, which can firmly connect adjacent piles, improve the shear strength of the disturbed soil zone adjacent to the jetted piles, and enhance the axial and torsional resistances of the precast piles [49]. Initially, this technology has been applied in practical projects, such as a breakwater on the shore of the Bohai Sea and a water discharge control lock at the mouth of the Yellow River, and they have been operating effectively. Meanwhile, after practical engineering analysis, it was found that a jetting system with multiple exit ports equally spaced at the tip instead of a single exit port improved the pile penetration rate, minimized the required quantity of water, and reduced the disturbance zone [50]. Furthermore, the combined action of water jet scouring and vibration fluidization has been identified as an effective measure that can more fully destroy the structures of cohesive sediments and weaken the sediment resistance to the pile [51].

Table 3. Jetted precast concrete piles built in recent years.

First Author, (Completion Date), and Affiliation	Overview of the Pile	Evaluation for the Pile	Technology Characteristics of the Pile
Xu [44] (2006), Ocean University of China, China	Grouted-jetted precast concrete sheet piles: method, experiments, and application	The method might be used in a range of civil engineering projects in coastal regions where the main soil types are sediments and the water is shallow	The technique minimized the disturbance to the surrounding soils and locked the sheet piles together to form a continuous pile group and (or) a diaphragm wall
Thiyyakkandi [46] (2013), University of Florida, USA	The individual and group behavior of jetted and grouted piles and tip grouted-drilled shafts in cohesionless soils	The jetting and grouting operations were suitable for the urban environment, and the jetted and grouted precast piles are promising deep foundation systems for the future	The pile consists of separate grout delivery pipes for side and tip grouting, and the water used for the jetting was recirculated
Yu [45] (2014), Yellow River Zhengzhou Bureau, China	The key technology to drive repeatable assembling piles	The technology was feasible, although the pile preparation and water jetting were slow	Three stages were included in the processes driving the pile: driving the pile with a high-pressure water jet, driving the pile with a low-pressure water jet, and finally stabilizing the pile
Geng [47] (2014), Yellow River Henan Bureau, China	To deal with a flood emergency by assembling flow-guiding piles	The jetted piles can control the river regime in an effective and timely manner, and jetted piling is also a simple, quick, and low-cost technology	A kind of assembled diversion pile plugged or pulled with a crane and a high-pressure water jet perforator
Thiyyakkandi [50] (2017), Indian Institute of Technology, India	Suitability of jetted and grouted precast piles for supporting mast arm structures	Pressurized water jetting is a well-known technique for the installation of precast piles in both offshore and onshore environments	The jetting system with multiple exit ports equally spaced at the tip improved the pile penetration rate and minimized the required quantity of water and the zone of disturbance
Lourenco [52] (2020), Universidade Federal do Rio Grande do Sul, Brazil	Model pile installation by vertical water jetting in clay	Pile target penetration depth can be achieved with lower heights of fall (lower kinematic energy) with water jet systems, minimizing horizontal distance deviations produced by water currents	Controlling the water flow pressure and velocity, jet diameter, and mass of the rods makes it possible to predict the critical installation depth of the pile

Jetted piles are gaining preference over traditional deep foundation methods as construction techniques continue to advance, including driven piles and drilled shafts. Jetting operations produce less noise and vibration than dynamic driving operations [50], making them comparatively environmentally friendly. Achieving the target penetration depth requires less drop height (lower kinematic energy) when water jet systems are used [49], resulting in significant time savings. Additionally, this method also minimizes damage to piles in hard clay or dense sand, in contrast to other pile installation techniques [48]. In offshore operations, traditional methods of pile installation struggle to adapt to deep water environmental conditions, while water jet technology seems to be the perfect solution to overcome the issues of conventional anchoring systems [51]. Furthermore, aside from the aforementioned advantages, jetting can be used for round piles and sheet piles, such as wide flange, T-shaped, or similar concrete sheet piles. However, under different flow conditions, round reinforced concrete piles are preferred for engineering applications. Hence, jetted piling is recognized as a robust, fast, cost-effective, and environmentally friendly method in construction [44]. Jetted piling has been applied in several river control projects in China, including those on the Yellow and Qiantang Rivers. This method may play a more important role in a wider area in the future.

4. The Way Forward

Nowadays, the quality of the piles and their effectiveness in controlling flow have been significantly improved with the development of the design and construction technology. However, the instability of the pile foundation induced by wave erosion still has not been completely solved. Innovative design methods and new engineering materials are anticipated to improve the safety and practicability of the concrete piles [53]. Thus, in the near future, research on new jetted-piling technology may intensify to avoid the squeezing effect caused by vibration. However, the bearing capacity of these concrete piles may be radically improved with new methods, such as increasing the friction between the pile and soil. Combination piles of multiple structures are currently found to have good applicability in simulations and will, therefore, become a trend in future management systems.

The construction of riverbank revetments and bridges has more urgent requirements during the development of a resource-saving and environmentally friendly society [54]. Optimizing concrete formulations [55], employing environmentally friendly concrete materials, and exploring replaceable construction materials have become crucial to achieving sustainability. Existing research indicates that the use of construction materials, such as cement and steel, should be minimized [54], as these materials boost energy consumption and CO_2 emissions, posing challenges to environmental sustainability [56]. Consequently, steel and polymers are emerging as potential replacements for concrete reinforcement for several structures and building components due to their attractive cost–structural efficiency ratio, high durability, and minimal construction risks, making them more sustainable alternatives [57]. Furthermore, the sustainability of pile installation is currently an important concern. The largest source of carbon emissions during pile construction is construction equipment. The development of machines powered by novel energies can improve the environmental impact of the installation process. Hence, reducing carbon emissions during pile construction, i.e., minimizing fuel and material consumption and reducing waste generation during installation, can be achieved by implementing sustainable construction practices and improving the quality of construction processes [58].

5. Conclusions

Based on the analysis of the present state and future trends in concrete piles for river regulation, the following conclusions can be drawn: (1) concrete pile, as an innovative form of groyne, is an effective practice for controlling meandering rivers with a considerable fine bed load and high sediment concentration. The concrete pile provides hydraulic roughness to the longshore current, which leads to a reduced littoral current velocity in the pile-groyne field and a thinner layer of suspended sediment. Compared with nonpermeable groynes, pile groynes are cheaper and save more time. (2) Multi-structure combination piles are becoming a trend in shoreline management. The shapes of the piles can be changed to suit the site conditions and meet the requirements of many special environments. Compared to round piles, sheet piles have the advantages of fast and low-cost construction processes, making them the primary structural component in river control projects. (3) The water-jetting method for pile installation has the favorable characteristics of fast track, cost-effectiveness, and environmental friendliness. Unlike cast-in situ bored and vibratory-driven methods, jetting minimizes damage to the structure and strength of the concrete pile and can be applied to the construction of various pile types and shapes. The jetted pile is a great prospect for controlling wandering rivers in the future. However, the jetted pile is difficult to stabilize during water jetting, which needs further study. (4) In the current context of pursuing a resource-saving and environmentally friendly society, it is essential to comprehensively enhance the quality of pile foundations and reduce their environmental impact. This includes improvements in construction materials, construction processes, and, particularly, advancements in energy efficiency and emissions reduction.

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