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Dynamic Behaviors of Gravity Dams in Interaction with Reservoirs and Foundations: A Comprehensive Study

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Abstract

This paper presents a literature review for dynamic analysis of concrete gravity dams. The author of the paper has discussed the different approaches used to analyze the dynamic behavior of dams such as analytical, semi-analytical, and numerical methods. They can be conducted in the time or frequency domain. The author has highlighted various parameters that affect the dynamic behavior of dams, including dam-water interaction, water compressibility, mass and damping of the foundation, sediments at the reservoir bottom, free surface waves, the length of the foundation rock, reservoir, etc. As the analy tical methods of dams have developed, these parameters have been gradually included, enhancing their ability to investigate the behavior of dams more realistically. The author's aim is to illustrate these achievements by briefly reviewing the available published articles and categorizing corresponding researches based on the analysis techniques and considering or neglecting dam-water interaction, sediments, and free surface motions.

Key words: Hydrodynamic forces, Seismic response, Foundation rock, Dam-reservoir interaction,

Introduction

Historically, dams were constructed for a single purpose such as water supply or irrigation. However, as society developed and the demand for various resources increased, dams were built to fulfill multiple purposes including water supply, irrigation, flood control, navigation, water quality, sediment control, and energy production. Multipurpose dams are considered a vital project in developing countries as they offer multiple benefits from a single investment. However, it is important to note that dam failures can result in catastrophic consequences, making the safety of dams a crucial issue. To guarantee the safety of dams, it is imperative to carry out realistic design and analysis. This has attracted significant attention from researchers and has led to advancements in the

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dynamic analysis of dams, particularly gravity, arch, and gravity -arch dams which are typically constructed using concrete. Two- dimensional simulations are commonly used for gravity dams, while three-dimensional simulations are utilized for arch dams.

In classical method, researchers typically neglected the flexibility of dams and analyzed the hydrodynamic pressure acting on rigid dams. Westergaard's work in 1933 was one of the earliest studies in this area and he proposed a formula for calculating the hydrodynamic pressure exerted on a dam due to horizontal ground motion. He assumed an incompressible fluid in the reservoir and named the fluid body confined by a two-dimensional surface on the upstream side of the dam as "added mass". This method was simple and widely used in the analysis and design of dams. However, subsequent researchers have proposed different methods for calculating the pressure acting on rigid dams, considering various conditions [2- 14].

The design and analysis of dams are crucial to ensure their safety and efficiency. In the past, researchers often neglected certain factors such as dam-water, dam-foundation, and reservoir-bedrock interactions, and focused mainly on hydrodynamic pressure on the dam. However, with advancements in technology and research, these interactions and other factors such as water compressibility, foundation mass and damping, sediment, nonlinear effects, and so on, have been gradually included in the analysis methods. This leads to more accurate and reliable results in assessing the dynamic behavior of concrete gravity dams. This paper reviews the available research and studies in this field, presenting their limitations, strengths, and advancements, and outlining future areas for further investigation.

Gravity Dams

The focus of this section is to present the various methods used in the analysis of concrete gravity dams, with a particular emphasis on those studies that take into account the fluid- structure interaction. The diversity of the methods is emphasized, highlighting the differences in the ways the reservoir is modeled and the parameters considered in the solution procedure. The goal is to provide a comprehensive overview of the current state of research in this field.

1 Time-Domain Analysis Methods

This review highlights the different methods and techniques used to analyze the dynamic behavior of concrete gravity dams, taking into account the fluid-structure interaction and other relevant parameters. The aim of this review is to provide a comprehensive overview of the various techniques

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used in the time-domain analysis of gravity dams and to highlight the advantages and limitations of each approach.

1.1 Linear Approaches Where the Reservoir is Not Modeled

In 1967, Chopra (15, 16) considered the effect of water compressibility in his analysis of the dynamic behavior of concrete gravity dams and assumed that the dam deformation was similar to the first mode shape of an empty dam. This approach facilitated the integration of fluid-structure interaction into the solution procedure and highlighted the significance of considering this interaction. Prior to Chopra's work, researchers generally modeled the rigid dam and calculated the hydrodynamic pressure acting on it, which was then applied to the deformable dam for analysis. However, this method resulted in the analysis of two separate systems rather than a coupled fluid-structure system. Nath (17) also investigated the dynamic behavior of gravity dams under horizontal ground motion by utilizing a finite difference method, but with the consideration of fluid compressibility and without considering radiation damping. The dam was modeled as an elastic cantilever beam with a varying cross-sectional area, and a formula was proposed for computing the natural frequencies of the coupled fluid- structure system in terms of the uncoupled fundamental frequencies of the dam and the reservoir.

Finn, L. and Varoglu, E. (1973) evaluated the responses of a long gravity dam-reservoir system under the base acceleration normal to the dam axis. In their study, they used the finite element method to investigate the dam motion and expressed the water pressure as a function of the dam's unknown deflections and ground acceleration. However, they neglected several factors such as foundation flexibility, surface waves, water compressibility and viscosity.

In another study, Hall (1986) examined the earthquake response of the Pine Flat dam. This study took into account the effects of water presence, water compressibility, and the vertical component of ground motion. The author also determined the earthquake intensity which triggered nonlinear behavior in both the dam and water. Hall concluded that the presence of water significantly increased the seismic responses of the dam.

Guan et al. (1994) presented a new scheme for the dynamic analysis of a two-dimensional dam-water-soil interaction in the time-domain by assuming that the soil and fluid domain were semi-infinite regions. This study highlights the importance of including these factors in the analysis of gravity dams.

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In their research on crack propagation in gravity dams, Batta and Pekau utilized the linear fracture mechanics principles and plane finite elements [21]. To incorporate fluid effects, they utilized the added mass technique. There are various forms of finite element formulation for dam-reservoir systems, one of which involves considering the pressure and displacement as unknowns of the dam and reservoir, respectively. This formulation leads to an unsymmetric characteristic matrix, which requires solving an unsymmetric eigenproblem. Instead, the decoupled mode shapes can be used. Samii and Lotf compared the decoupled and coupled methods in their analysis of gravity dams [22]. Burman et al. proposed a procedure for analyzing gravity dam-foundation systems using the finite element method, with consideration for soil-structure interaction by a simplified direct method [23]. They used the added mass approach to take into account fluid-structure interaction.

1.2 Linear Approaches Where the Reservoir is Modeled

In their study, Chopra et al. utilized the finite element approach for the dynamic analysis of two-dimensional elastic dam-reservoir systems in 1969 [24]. In the finite element formulation of this work, the water was assumed to be compressible and the nodal unknowns of both fluid and solid domains were the displacements. Antes and Von Estorf employed the boundary element approach to analyze the response of planar gravity dams due to horizontal and vertical ground motions, considering the dam-water interaction and absorption of hydrodynamic pressure waves at the reservoir bottom or the far end into the soil medium [25]. The water was also assumed to be compressible in this study.

Tsai and Lee analyzed gravity dam-reservoir systems by considering the radiation condition in the far-field of the infinite reservoir and applying a time-domain substructure approach [26]. They utilized the finite element scheme for modeling the dam and near-field fluid domain, and took into account the water compressibility in their analysis.

Bayraktar et al. used the Lagrangian formulation for analyzing the dynamic behavior of the dam-reservoir-foundation rock system [27].

Bayraktar and Dumanoglu conducted a study on the effects of asynchronous ground motion on the frequency content and amplitudes of hydrodynamic pressure acting on dams in interaction with water and foundation rock by using the Lagrangian finite element scheme [28]. Their results showed a considerable decrease in the amplitudes of the hydrodynamic pressures when the asynchronous ground motion was considered. Maity and Bhattacharyya used the finite element technique for the dynamic analysis of dam-reservoir systems, with pressure being the unknown parameter in the fluid domain [29]. They also evaluated the effect of dam material and fluid depth on the responses and

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took into account the water compressibility. Lotf utilized the decoupled mode shapes of the dam and reservoir to analyze concrete dams in the time-domain [30]. Kucukarsalan proposed a new method for the time- domain analysis of dam-reservoir-foundation systems, which included the reservoir bottom absorption, by using the dual reciprocity boundary element approach for the infinite reservoir and the finite element method for the dam [31, 32]. The pseudo-symmetric scheme is one of the methods applied for the time-domain analysis of dam-reservoir systems, and Omidi and Lotf verified this strategy by analyzing a concrete gravity dam [33].

In 2007, Birk and Ruge developed a symmetric finite element formulation for dam-reservoir systems, in which the far-boundary condition was presented in the time-domain [34]. They emphasized that predicting the behavior of aged dams during earthquakes would enable timely remedial measures to be taken to withstand future earthquakes. Additionally, Gogoi and Maity presented an approach that took into account the time-dependent degradation of concrete due to environmental factors and mechanical loading, as well as the absorption of pressure waves at the bottom of the reservoir due to the p resence of sediments in the hydrodynamic pressure equation [35].

Additionally, Seghir et al. utilized the finite element method for discretizing the dam structure [36]. They proposed a new symmetric formulation for the analysis of an infinite reservoir utilizing the boundary element method, in which the pressure was considered as the unknown parameter in the fluid domain. Later, Gogoi and Maity developed a methodology for conducting seismic analysis of dam-reservoir systems, taking into account the frequency- dependent boundary conditions at the bottom of the reservoir and the truncation surface [37]. This technique accounted for the frequency content of the earthquake excitation and accurately calculated the damping parameters at the bottom of the reservoir and the truncation surface. The dominant frequency at each time step of the non-stationary earthquake signal was extracted by dividing the signal into small time segments, computing the fast Fourier transform of each segment, and applying the dominant frequency as an input in the seismic analysis.

1.3 Techniques Incorporating Nonlinear Effects in Dam-Reservoir Interactions

The influence of cavitation on the dynamic response of dam-reservoir systems has been studied in several studies. In 1983, Zienkiewicz et al. conducted an investigation and found that the effect of cavitation on the dynamic responses of dams was negligible [38]. Similarly, Vargas-Loli and Fenves showed that the cavitation effects on the dynamic responses of gravity dam-reservoir systems were insignificant through a nonlinear dynamic analysis [39]. Fenves and Vargas-Loli developed a

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numerical procedure to calculate the dynamic response of the coupled fluid-structure systems and to investigate the nonlinear behavior of both the structure and the fluid [40]. The fluid was modeled as a bilinear compressible material and the fluid-structure interaction and water compressibility were considered in their analysis. The displacement finite element formulation was used to analyze the structure, and the symmetric coupled equations of motion were expressed in terms of displacements and solved using a fully implicit time integration method. The results of the study showed that cavitation had a slight effect on the responses. El-Aidi and Hall also conducted a nonlinear dynamic analysis and found that cavitation had a negligible effect on the dynamic responses of the dam-reservoir systems when cracks were modeled [41, 42]. Additionally, Vargas-Loli and Fenves evaluated the effect of cracking on seismic responses of gravity dams while considering the fluid-structure interaction and water compressibility [43].

In the study conducted by Hung and Chen [44], the interaction between the nonlinear hydrodynamic pressures and the vibration of a concrete gravity dam was assessed by coupling the Euler's equation with the finite element model of the dam. The horizontal and vertical components of the earthquake force were considered as the force function in the finite difference equations of the fluid motions. Wepf et al. [45] proposed a nonlinear dam- reservoir interaction model for a gravity dam-reservoir system, where a discrete cracking technique based on the finite element model was employed to model the propagation of cracks in unreinforced mass concrete. The reservoir was modeled using the boundary element strategy. Calayir and Dumanoglu [46] utilized the Lagrangian scheme for static and dynamic analysis of the gravity dam-reservoir systems.

In 1995, Cervera et al. proposed a general methodology for evaluating the dynamic behavior of large concrete dam-reservoir systems under seismic excitation [47]. This approach was applied to both 2D representations of gravity dams and 3D representations of arch dams. It incorporated nonlinear material behavior of the dam, transparent fictitious boundaries for handling in-coming and out-going seismic waves, and the interaction between the dam and soil-water. The mechanical behavior of concrete was modeled using an isotropic damage model. This methodology was used to study the degree of unsafety of a gravity and an arch dam. Chavez and Fenves later utilized a novel hybrid frequency -time domain approach to determine the seismic responses of gravity dams, including nonlinear base sliding behavior, frequency-dependent response of the impounded water and flexible foundation rock [48]. These researchers assumed that the reservoir was a boundless continuum and that the water was compressible and inviscid.

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In their study, Bhattacharjee and Leger used the smeared crack finite element model to perform a nonlinear seismic analysis of a 90m tall concrete gravity dam in Canada [49]. They incorporated the effects of reduced frequency-independent added matrices to account for the hydrodynamic and foundation interactions. They also evaluated the impact of initial conditions caused by severe winter temperatures and the influence of hydrodynamic and foundation interaction mechanisms on the nonlinear seismic behavior of the dam. In another investigation, Chen conducted a comprehensive hydrodynamic analysis of a concrete gravity dam, including the effects of free-surface flow and the nonlinearity of convective acceleration [50]. The results indicated that the surface wave effect of water on the dynamic structural analysis of the concrete gravity dam was negligible.

In the context of seismic analysis of gravity dams, Cervera et al. proposed a rate-dependent isotropic damage model which incorporated stiffness degradation and recovery under load reversals, as well as strain-rate sensitivity [51]. To consider fluid-structure interaction, they employed the methodology introduced in their earlier work [47]. Lee and Fenves, on the other hand, developed a plastic damage model for concrete gravity dams subjected to cyclic loading, incorporating fluid effects using the added mass approach [52]. Ghaemian and Ghobarah performed nonlinear fracture analysis of gravity dams by including the water-dam interaction in their formulation, using a staggered approach [53]. In 2001, Vatani Oskouei et al. studied the nonlinear dynamic analysis of dam-reservoir systems while taking into account cavitation, utilizing displacement-based finite elements [54]. Asteris and Tzamtzis also performed nonlinear analysis of a realistic gravity dam-reservoir system, considering fluid- structure interaction through the added mass technique [55].

In recent years, various researchers have continued to study the seismic behavior of gravity dams. Yuchuan et al. compared the behavior of reinforced and unreinforced dams and found that reinforcement improved the seismic resistance of the gravity dam [56]. Akkose and Simsek analyzed a gravity dam-reservoir system under near-field and far-field earthquakes, considering nonlinear effects [57]. ShouYan studied the effect of shear keys on the nonlinear responses of a gravity dam and observed that the presence of shear keys reduced joint opening and sliding displacement [58]. Mirzayee et al. used a combination of discrete and boundary element methods to assess the behavior of cracked gravity dams [59]. These studies have helped to further understand and improve the seismic behavior of gravity dams.

Omidi et al. (60) employed a plastic damage model and different damping mechanisms to examine the seismic behavior of these structures, incorporating fluid-structure interaction with the added mass

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technique. Zhang et al. (61) used the extended finite element method to evaluate the behavior of damaged cracked gravity dams, considering fluid effects through Westergaard's approach. Furthermore, Zhang et al. (62) investigated the impact of strong motion duration on the dynamic response and accumulated damage of concrete gravity dams, while taking fluid-structure interaction into account. These studies demonstrate the importance of considering fluid-structure interaction and various other factors in the seismic analysis of concrete gravity dams.

2 Techniques for Dynamic Analysis in the Frequency Domain

It is important to note that linear dynamic analysis can be performed in the frequency domain. The subsequent sections examine studies that have used frequency -domain techniques to evaluate the behavior of gravity dam-reservoir systems.

2.1 Linear Approaches Where the Reservoir is Not Modeled

Chakrabarti and Chopra (1973) investigated the impact of the vertical earthquake components on the hydrodynamic pressure exerted on gravity dams [63]. They found that the response to this component is significant in the analysis of concrete gravity dams subjected to earthquakes due to the horizontal hydrodynamic forces applied to the vertical upstream face by the vertical component of the ground motion. The authors then proposed a novel "substructure" technique for the frequency-domain analysis of concrete gravity dam- reservoir-foundation systems with the vertical upstream face [64]. The dam was modeled using finite element analysis and the fluid domain was represented as an infinite continuum governed by the wave equation. The structural displacements were expressed as a linear combination of the dam's vibration modes when the reservoir was empty, and the reservoir responses were obtained analytically. The governing equations of the dam and the reservoir were linked by the interaction forces between them. This method achieved excellent results using only a few modes of the dam

Chopra and Chakrabarti proposed a general procedure for linear dynamic analysis of gravity dams subjected to both vertical and horizontal components of earthquakes using the substructure method [65]. The procedure considered the water compressibility, dam, and foundation flexibility, which includes dam-water-foundation rock interaction. The system was composed of three substructures including the dam, the reservoir, and the foundation. The dam was modeled using finite element approach, while the fluid domain and foundation rock were represented as a continuum of infinite length and a viscoelastic half-plane, respectively. The dam displacements were expressed as a linear

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combination of normal modes of an undamped associated dam-rock system. On the other hand, Bouaanani et al. proposed a two-dimensional model using finite element technique to study the influence of ice cover on the dynamic responses of gravity dams [66]. The study showed that the presence of ice cover had an impact on acceleration and frequency response curves, as well as the hydrodynamic pressure distribution in the reservoir.

2.2 Linear Approaches Where the Reservoir is Modeled

Mei et al. utilized linear acoustic and beam theories to derive expressions for the vibration of simple structures in water [67]. The dam was modeled as a beam for simplification purposes, and both closed-form formulas and numerical solutions using the hybrid element method were obtained. Additionally, Chopra and Gupta employed the substructure technique to evaluate the dynamic behavior of the gravity dam-water-foundation rock system in the frequency domain [68]. On the other hand, Hanna and Humar employed the boundary element method for the analysis of the gravity dam-reservoir systems [69].

In their research, Hall and Chopra used the finite element method to conduct a linear dynamic analysis of concrete gravity and embankment dams in the frequency domain [70, 71]. They considered the effects of water compressibility, fluid-structure interaction, and fluid- foundation interaction. The fluid domain was assumed to be semi-infinite and divided into near-field and far-field regions, with the near-field region discretized with finite elements and the far-field region modeled through a combination of one-dimensional discretization in the vertical direction and continuum representation in the infinite direction.

Fenves and Chopra presented a procedure for analyzing the responses of concrete gravity dams under the horizontal and vertical components of earthquake ground motions [72]. The procedure included the consideration of dam-water interaction and partial absorption of hydrodynamic pressure waves at the reservoir bottom into the foundation medium. They also extended the available substructure system to analyze concrete gravity dams, including alluvium and sediments, while taking water compressibility into account [73].

In 1985, Fenves and Chopra (1974) presented a study on the parameters that play an important role in the dynamic behavior of gravity dams. They introduced simple methods to calculate the fundamental vibration mode response of gravity dams with a reservoir of impounded water supported on a rigid foundation rock and a dam with an empty reservoir supported on a flexible foundation

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rock. In each case, the first vibration mode of the dam monolith was modeled using an equivalent single degree of freedom system. Additionally, they proposed another simple model for the dam-compressible water-flexible foundation systems (1975).

Subsequently, Lotf et al. (1976) introduced a new finite element procedure for linear dynamic analysis of the two-dimensional dam-reservoir-foundation rock system in the frequency domain, considering all interactions rigorously. This method treated layered foundations as easily as homogeneous ones. Humar and Jablonski (1977) analyzed the seismic behavior of gravity dam-infinite reservoir systems using the boundary element method. In 1989, Dominguez and Medina (1978, 1979) performed a dynamic analysis of a two-dimensional dam-reservoir-bedrock system in the frequency domain using the boundary element approach.

In 1991, Bougacha and Tassoulas proposed a finite element method for the two-dimensional dynamic analysis of gravity dam-reservoir systems, taking into account the effects of sediment and underlying foundation [80-82]. The authors used a two-phase medium to model the sediment and their model could be integrated rigorously within the hyper-element formulation, which accounted for the interaction between water, sediment, and foundation. Later, Valliappan and Zhao modeled the gravity dam-water-foundation system using both finite and infinite elements, considering the physical and mechanical properties of the sediment at the reservoir bottom [83]. Their study concluded that the sediment played two significant roles in these systems: energy dissipation in the system and amplification of the incident wave on the water-sediment interface. Additionally, Tsai et al. conducted a modal analysis of the dam-reservoir systems using a combination of substructure, finite element, and boundary element methods [84].

It is noteworthy to mention that the wave radiation towards infinity, wave absorption at the bottom of the reservoir, and cross-coupling between the foundation beneath the dam and the bottom of the reservoir significantly impact the hydrodynamic forces within the reservoir. These effects can be incorporated by using either an approximate one-dimensional wave propagation model or a more rigorous analysis of the interaction between the flexible soil along the base and the water. However, due to the excessive computational demands of the rigorous method, it is commonly simplified by neglecting the cross-coupling and applying the approximate one-dimensional wave propagation model. Chandrashaker and Humar analyzed the effects of these simplifications on the seismic responses of a gravity dam from an accuracy and computational perspective [85]. By utilizing a coupled finite and infinite element method, Zhao et al. studied the impact of the sediment at the bottom of the reservoir on the seismic response of concrete gravity dams [86]. Li et al. also

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investigated the dynamic behavior of a two-dimensional dam-reservoir system by introducing an exact far boundary condition with no spatial discretization for determining the vibration modes [87].

In 1997, Dominguez et al. conducted a boundary element dynamic analysis to investigate the dynamic behavior of a concrete gravity dam that was subjected to ground motions and interacted with the water, foundation, and bottom sediment [88]. This method was versatile and could be applied to continuous systems consisting of water viscoelastic and fluid-filled poroelastic zones of arbitrary shape. The researchers evaluated the influence of the bottom sediment on the seismic response of gravity dams for both rigid and half-space viscoelastic foundation, and also assessed the effects of the degree of saturation and thickness of the bottom sediment. It was concluded that the sediment compressibility had a significant effect on the dam response, and the influence of the foundation flexibility and sediment thickness was also considered. In a separate study, Lotf and Sharghi utilized the finite element approach to analyze the dynamic behavior of gravity dams [89]. They employed semi-infinite and quadratic boundary elements for the reservoir and foundation, respectively.

Bayraktar and Akkose (90) evaluated the impact of foundation rock properties on the stochastic dynamic behavior of gravity dam-reservoir systems. A common approach in modeling the interaction between the reservoir and foundation is through the utilization of a one-dimensional model, however, as highlighted by Lotf (91), this method can lead to significant errors when considering both horizontal and vertical ground motions. Despite the frequent assumption of the water domain being a semi-infinite fluid region, there are scenarios where the reservoir cannot be considered as such. This has been shown by Lotf and Fathi (92), who demonstrated that the length of the reservoir can greatly impact the response and should not be modeled as an infinite domain. Miquel and Bouaanani (93) proposed a simple method for estimating the first mode shape of gravity dam-reservoir systems, which accounts for both the water compressibility and dam flexibility.

In 2012, Keivani and Lotf made advancements in the unsymmetric Lanczos approach, which they utilized to efficiently solve the eigenvalue problem in the context of the dam-reservoir interaction system [94]. The traditional approach to modeling the dam-reservoir system involves the use of fluid and solid finite elements and hyper-elements. However, this process is known to be time-consuming due to the formulation of hyper-elements in the frequency domain. In order to address this issue, Lotf and Samii proposed a more efficient and rapid method as an alternative to the traditional approach [95].

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Conclusion

In conclusion, the dynamic behavior of a concrete gravity dam and its interaction with the surrounding environment, including the water, foundation, and bottom sediment, has been extensively studied by various researchers. The efects of these interactions on the seismic responses of the dam are significant and have been analyzed using different approaches such as the boundary element dynamic analysis procedure, finite element analysis, and Lanczos eigenvalue approach.

The impact of the foundation rock characteristics on the stochastic dynamic responses of the dam-reservoir system has also been explored. Most engineers assume the water domain to be a semi-infinite fluid region, but researchers have found that the length of the reservoir can significantly affect the response and should not be modeled as an infinite domain. To address these issues, researchers have proposed alternative methods such as the first mode shape estimation technique and a fast and efficient method using hyper-elements in the frequency domain.

Overall, the studies conducted in this area have found that the dam-reservoir system is a complex system, and its response is influenced by various factors such as the compressibility of the bottom sediment, the degree of saturation, the foundation rock characteristics, and the length of the reservoir. In light of these findings, it is crucial to consider the fluid-foundation interaction effects when designing and analyzing concrete gravity dams.

It is worth noting that the computational efforts of rigorous analysis methods are often high and may be simplified by neglecting certain interactions, such as cross-coupling. While this simplification may have an impact on the accuracy of the results, researchers have investigated the trade-off between accuracy and computational effort.

In conclusion, the studies in this field have advanced our understanding of the dynamic behavior of concrete gravity dams and their interactions with their environment. These studies have also highlighted the importance of considering fluid-foundation interaction effects in the design and analysis of concrete gravity dams. Further research in this area could further enhance our

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understanding of this complex system and help to improve the safety and reliability of these critical structures.

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