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A Critical Review of Embankment Dams in China: From Ancient Origins to 300 m Frontiers

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Abstract- Embankment dams, built with locally available earth and rock materials, are the dominant dam type in China, representing over 90% of the country's approximately 98,000 dams. The review covers the history, technology, design methods, safety concepts, and new frontiers of embankment dam engineering in China in a comprehensive way. The analysis is a development path from ancient earthen embankments (c. 600 BCE) to today's 300 metre class ultra-high earth core rockfill dams. China's engineering accomplishments are placed in a four-phase historical context: arduous initiation (1904–1949), independent entrepreneurship (1950–1979), catch up (1980–1999), and breakthrough development (2000–present). Emphasis is placed on the critical nexus of embankment dam safety and contemporary challenges, such as ageing infrastructure (approximately 90,000 dams from the 1950s–1970s now exceeding or approaching design life), seismic vulnerability in tectonically active western China (PGA up to 0.5 g), increasing extreme hydrological events due to climate change, and unique biological hazards, including termite induced internal erosion. The review embraces recent developments in intelligent construction, deformation control theory, seepage remediation technologies and seismic response analysis. Key knowledge gaps are identified; long term rockfill creep behaviour; scale effects in material testing; climate change implications for spillway adequacy; risk-based decision frameworks for ageing infrastructure and integration of monitoring data into predictive models. China's embankment dam enterprise has been argued to have moved from a technological follower to a global leader. The need remains to consolidate risk informed safety management and remediation investment for the vast inventory of ageing medium and low height dams. Research priorities and policy recommendations are presented in the concluding review.

Keywords- Aging infrastructure, China, dam safety, embankment dam, high earth rockfill dam, intelligent construction; seepage control.

I. Introduction

Embankment dams are structures used to impend water, made of compacted earth, rock or composite materials. They are among the oldest and most widely used engineering solutions by man for water storage, flood control and hydro-power generation. They remained popular worldwide due to some basic advantages: they can be adapted to a wide range of topographic and geologic conditions, they use locally available materials and little steel and cement, their construction is relatively simple and they are inexpensive [1].

In China these characteristics have made embankment dams an important element of the country's hydraulic infrastructure. According to authoritative statistics, China has 98,000 dams [2], more than 90% of which are embankment dams, reflecting the importance of this dam type to the country's water resources management strategy.

The importance of embankment dams in China today goes far beyond their sheer numbers. In the last two decades, China's embankment dam engineering has experienced dramatic increase, with several world record-breaking structures constructed. Successive milestones that have slowly brought China to the forefront of embankment dam technology in the world are Nuozhadu Dam (261.5 m), Lianghekou Dam (295 m, with a maximum section of 303 m in some references) and Shuangjiangkou Dam (314 m under construction).

These mega dams, mainly in China's western river basins that are rich in resources but geologically challenging (e.g., Lancang, Yalong, Dadu rivers), are a demonstration of the nation's ability to overcome extreme technical challenges: deep alluvial overburden (exceeding 100 m in some sites), complex geological structures, severe seismic hazards (peak ground acceleration up to 0.5 g), and high altitude climatic extremities (freezing temperatures during winter construction).

But this impressive technical trajectory exists alongside a less visible but equally consequential reality. A large share of China's embankment dams was constructed in the mid twentieth century and are now nearing or exceeding their design service lives. As noted in the Chinese dam safety literature, most of China's embankment dams were built between the 1950s and 1970s, are close to or have already exceeded their design service lives, show serious deterioration, and some are slowly turning into dangerous dams.

The problem of ageing infrastructure (illustrated by progressive internal erosion, seepage anomalies, structural deformation, spillway deterioration and, in some cases, catastrophic failure) is an urgent problem that needs scholarly and policy attention. This duality (frontiers of technology push, maturity of infrastructure confrontation) frames the core problematic of this review.

The aim of this paper is to review critically the state of the art of embankment dams in China. The specific objectives are:

1. To map the historic evolution of embankment dam engineering in China, to place current accomplishments in the context of long-term patterns of development and to recognise the socio-technical catalysts of each phase.
2. To describe the principal technical characteristics, classification systems and representative projects characterising the portfolio of embankment dams in China, pointing out the strengths and limitations of each type of design.
3. To discuss important design methodologies and safety assessment frameworks (seepage control, seismic analysis, deformation control) while acknowledging the existing epistemic uncertainties and incomplete knowledge.
4. To analyse the new safety challenges including seismic risks, extreme hydrological events in the context of climate change, biological hazards (termites) and specific problems of ageing infrastructure.
5. To critically review recent innovations in intelligent construction, deformation monitoring and seepage remediation technologies, and evaluate their proven effectiveness and remaining limitations.
6. To inform academic inquiry and policy formulation, through identification of critical knowledge gaps and informing directions for future research.

The review is based on a synthetic and critical methodology, using peer reviewed journal articles (indexed in Web of Science, Scopus and CNKI), technical reports from major dam owners (e.g. China Three Gorges Corporation, State Power Investment Corporation), government documents (Ministry of Water Resources, National Energy Administration) and detailed engineering case studies of representative projects.

Where the evidence is sparse, mixed or ambiguous, these gaps are openly acknowledged and not hidden by assumption or extrapolation. Where the original language contains technical nuances that cannot be safely paraphrased, direct quotations from authoritative sources are used.

II. Historical Evolution Of Embankment Dams In China

A. Ancient Origins and Pre Modern Developments (c. 600 BCE – 1900 CE)

Embankment dams have been constructed in China for about 2600 years. The earliest recorded examples are from the Spring and Autumn period (c. 600 BCE), when earthen levees were constructed to protect against floods and store water. The Shao Bei in Anhui Province (an early reservoir created by earthen dikes) is an example of this ancient hydraulic tradition. Earthen embankments continued to play a vital role in China's water management paradigm during the imperial period, especially for flood control of the Yellow River and Yangtze River systems.

However, these historic structures were mostly low height levees and dikes (typically less than 10 m) rather than the high storage dams that characterise modern embankment dam engineering. The crucial transition from empirical earthen embankments to systematically engineered embankment dams (with controlled selection of materials, graded filter layers, mechanical compaction and intentional impervious elements) would have to await the twentieth century. This historical gap is significant in that it means that China, despite its ancient hydraulic tradition, had no native high embankment dam technology prior to the modern era; the technology was entirely imported and adapted from Western and Japanese practice starting in the early 1900s.

B. Four Phase Developmental Trajectory (1904–Present)

Chinese hydropower development scholars, notably Yang Zeyan and colleagues, have usefully divided the country's dam engineering history into four distinct phases, characterised as "arduous initiation, independent entrepreneurship, catch up, and breakthrough development". Each phase has different technological characteristics, institutional arrangements, sources of funding, and engineering outcomes.

Phase I: The Arduous Initiation (1904–1949)

In the early years of modern embankment dam construction in China, foreign (mainly from the United States, Germany and Japan) technical assistance, limited domestic engineering expertise and severely constrained industrial capacity were available. The heights of the dams were modest (mostly less than 30 m), the construction equipment was rudimentary (manual compaction or animal drawn rollers), and there were virtually no formal design standards. However, this period provided the foundation for the first generation of designed embankment dams (e.g. the first modern reservoir dam at Shimen, Beijing, built in 1937) and nurtured the first cohorts of Chinese hydraulic engineers who would become the leaders in the post 1949 era. A major drawback of this period was the absence of systematic quality control. Many dams of this period, where they survive, exhibit heterogenous compaction and undocumented material properties.

Phase II: Autonomous Entrepreneurship (1950–1979)

After the founding of the People's Republic of China in 1949 the country launched an ambitious water infrastructure development program, spurred by the needs of flood control, irrigation expansion and rural electrification. Tens of thousands of embankment dams were constructed in the 1950s through 1970s, many through mass mobilisation of rural labour under the "indigenous methods" policy that emphasised rapid construction and use of local materials at the expense of formal engineering design. This period greatly increased China's reservoir storage capacity (from about 10 billion m3 in 1949 to over 400 billion m3 in 1979), but it also created a legacy of structures with highly variable design quality, limited mechanical compaction (much of it hand compacted or animal trampled), inadequate spillway capacity (often designed for historic flood peaks without safety margins), and in many cases, no formal geotechnical investigation of foundations. As modern safety assessments have shown, a large proportion of dams of this era now suffer from significant deterioration: internal erosion, crest settlement, slope instability and spillway degradation. This phase is thus the primary contributor to the ageing infrastructure problem that China is currently facing.

Phase III: Catch up (1980-1999)

The reform period of the opening to the outside world began systematic contact with international dam engineering practice. Chinese engineers got the latest design codes (such as the U.S. Army Corps of Engineers, the International Commission on Large Dams), construction technologies and quality control methods from Europe, North America and Japan. The use of heavy vibratory rollers (first imported, then locally built) revolutionised embankment dam construction, allowing for higher densities (relative compaction >98%), better uniformity and a drastic reduction of post construction settlement. The preferred design became concrete faced rockfill dams (CFRDs), which took advantage of the abundance of rock in China and reduced the need for the scarce clay core materials.

Major projects such as Shuibuya (CFRD, 233 m, completed 2008, but design in this period) demonstrated China's increasing ability to build world-class embankment dams. During the catch-up phase, systematic dam safety regulations, such as the first comprehensive "Design Code for Rolled Earth Rockfill Dams" (SL 274 2001) [3], were established, and the formal dam classification and registration were initiated. But in this age of new construction, the ongoing legacy of the Phase II dams got relatively little attention.

Phase IV: Breakthrough Development (2000 – present)

In the modern era, China has evolved into a real global leader in embankment dam engineering. China's earth core rockfill dams, face panel rockfill dams, asphalt lined rockfill dams and membrane lined rockfill dams are at a world leading or advanced level, which has been documented by Yang and colleagues [4]. The development of these dams has been a tortuous process of learning from others and breakthrough. Nuozhadu (261.5 m, 2014), Lianghekou (295 m, 2021) and Shuangjiangkou (314 m, late 2020s) have raised height limits successively above previous international records (the world's tallest embankment dam was the 305 m Nurek Dam in Tajikistan, but Shuangjiangkou will take that title).

At the same time, China has developed intelligent construction systems (GPS guided real time compaction monitoring, automated quality control dashboards and drone-based topography surveys) that represent a qualitatively new paradigm for embankment dam engineering. The rest of this review will address the technical substance of these accomplishments, while also critically evaluating the safety challenges that accompany such rapid progress, particularly the relative neglect of the vast inventory of ageing dams.

III. Classification and Technical Characteristics

A. Height Based Classification

The embankment dams of China are classified by structural height in a formal way according to the design code for Rolled Earth Rockfill Dams (SL 274 2020) [5]. Dams are classified as low (below 30 m), medium (30-70 m) and high (above 70 m). This classification guides regulatory requirements, design standards and safety inspection intervals. Increasingly stringent requirements are prescribed on increasingly higher structures (e.g. high dams require probabilistic seismic hazard analysis, while low dams may be designed with deterministic historical earthquake methods).

However, these definitions have been effectively superseded by current Chinese practice where 70 m is a modest threshold compared with the 300 m class of ultra-high dams being constructed. The technical discourse has seen the term 'ultra-high embankment dam' (>200 m) emerging to capture this categorical shift. A major omission in the height classification is that no explicit distinction is made between dams founded on rock and on deep alluvium, a difference that has a profound effect on deformation and seepage behaviour.

B. Material and Construction Classification

Embankment dams are classified according to the construction method and the material used. Historical methods include hydraulic fill (slurried soil deposited in water, used in some dams of the 1950s–60s) and directional blast placement (extremely rare), but current Chinese practice predominantly uses the rolled earth rockfill method [6], where materials are placed in controlled lifts (generally 0.5–1.0 m loose thickness) and compacted with heavy vibratory rollers (10–25 tonnes). The widespread use of rolled construction is a sign of the method's superior quality control, uniformity, and mechanical performance.

The more substantive engineering difference is the type of impervious element used. Based on the waterproofing component, embankment dam can be divided into four main types.

1. **Earth core rockfill dams (ECRD) --** With a core of clay or gravel clay, located at the center or slightly inclined. In the highest class (>250 m) they are dominant because the core is well protected by rockfill shoulders. Examples: Nuozhadu, Lianghekou, Shuangjiangkou.

2. **Concrete face rockfill dams (CFRD) --** The impervious element is a reinforced concrete slab placed on the upstream slope. CFRDs use less clay and can be built more quickly but are more susceptible to foundation settlement and cracking of the facing slab. Example: Shuibuya (233 m).

3. **Asphalt concrete core rockfill dams –** With hot mixed asphalt concrete core. They are very ductile and have self-healing properties but are more expensive. A few examples in China.

4. **Geomembrane faced rockfill dams --** Using a synthetic geomembrane [7] as a watertight layer. Cost effective for moderate height but less proven for very high dams.

Different types exhibit different deformation behaviour, stress distributions and failure modes. For example, earth core dams may be hydraulically fractured in the core under rapid drawdown if the core material is brittle or stresses are low.

Uneven foundation settlement can compromise concrete face dams by causing slab cracking and joint separation. Selecting between these alternatives requires careful consideration of site-specific materials, construction schedule, seismic hazard, and long-term maintenance capacity. Literature lacks comparisons of the performance of these types under extreme seismic loading for heights greater than 250 m. The existing records are limited to moderate earthquakes.

C. Advantages and Limitations of Embankment Dams

The reasons for the continued preference of embankment dams for Chinese projects include their well-known advantages:

- **Availability of materials --** Use of locally available earth and rock, reducing transportation costs and reliance on manufactured materials (cement, steel, timber).
- **Foundation adaptability --** Wide bases and drainage blankets allow the dam to be built on weak, compressible or irregular foundations, not suitable for concrete gravity or arch dams.
- **Simplicity of construction --** Requires no complicated form work or cooling systems, construction can be undertaken with semi-skilled labour.
- **Seismic performance --** Embankment dams tend to have better seismic performance than rigid concrete dams, as they can sustain deformation without brittle failure, if they do not liquefy.

On the other hand, material related disadvantages are:

- **Overtopping vulnerability --** Embankment dams are not designed for throughflow like concrete dams and so overtopping quickly results in erosion and breaching. Spillway capacity must be very reliable.

- **Weather sensitivity --** Clay cores cannot be placed in freezing conditions or heavy rain; this can delay construction in alpine western China.
- **Settlement --** Significant settlement after construction (0.5-1.5% of height for rockfill) requires careful management & crest freeboard.
- **Internal erosion --** The possibility of piping through the core, contacts or foundation defects may go unnoticed until late stages.

Each of these limitations requires robust design and operational protocols: adequate spillway capacity, weather resistant construction scheduling, comprehensive instrumentation (settlement cells, piezometers, seepage weirs) and vigilant monitoring throughout operational life.

IV. Key Theoretical Frameworks And Design Methods

A. Material Characterization and Constitutive Modelling

The mechanical behaviour of coarse granular materials (rockfill, gravel and pebble mixtures) is a fundamental theoretical problem of embankment dam engineering. Unlike concrete or steel, which have a relatively predictable stress strain relationship, coarse granular materials are characterised by marked pressure dependence (stiffness increases with confining pressure), stress path dependency (behaviour differs between loading, unloading and reloading) and scale effects (laboratory specimens cannot represent the largest particles present in the field). One research group summarised the difficulties of 300 m class rockfill dams, including unclear meso mechanical mechanisms, incomplete simulation methods, and imprecise parameter selection (National Key R&D Program project description).

Recent work from China has pushed the state of the art further by combining experimental and computational approaches. Laboratory platforms combining macroscopic triaxial testing (up to 800 mm specimen diameter) with meso scale particle imaging (high speed cameras, X ray CT for granular assemblies) enable researchers to observe internal particle rearrangement (rotation, fracture, crushing) under load. At the same time numerical methods, e.g. discrete element method (DEM) [8] and generalised plasticity models have been customised for rockfill materials.

Recent studies have highlighted the limitations of conventional constitutive models. Liu et al. (as cited in the original review) proved that the popular Duncan–Chang E B model cannot be used to describe the vertical and horizontal deformation simultaneously and the inverse parameters for the model are not suitable for dynamic analysis. On the contrary, static dynamic unified generalised plasticity models are more successful in producing computed displacements in good agreement with field measurements (e.g., at Nuozhadu) and can serve as a basis for seismic response prediction directly from static inverse analyses.

But there are still questions. Particle scale effects still make it difficult to extrapolate from laboratory scale specimens (maximum particle size 60-80 mm, or up to 200 mm in very large apparatus) to field rockfill (up to 800-1,000 mm). Dilation, shear band formation and creep are scale dependent phenomena whose representation in design calculations is still imperfectly constrained. These limitations are still being addressed in current research, e.g., instrumented field test fills (e.g., test embankments 20 m thick were constructed at Lianghekou and monitored for 2+ years to calibrate numerical models against in situ performance).

B. Deformation Control and Prediction

Probably the most important design consideration for high embankment dams is deformation control. Excessive settlement may cause crest elevation to be compromised (loss of freeboard and increased risk of overtopping), cracking of impervious elements (core or face slab), differential settlement of appurtenant structures (spillway, outlet works), and compromised operational performance (gates misaligned). The challenge becomes more serious with increasing dam height as the rockfill compressibility is approximately proportional to the logarithm of stress and the foundation settlement will add to the embankment settlement.

A Chinese research program on key technologies of full life cycle deformation control and prediction of high rockfill dams has created four types of innovation:

1. **Meso macro experimental platforms and multi-scale constitutive models --** Coupling DEM simulations of particle scale behaviour with continuum finite element model for global analysis.
2. **Innovative numerical simulation methods --** Such as realistic particle shape libraries (from 3D scanning of real rockfill particles) and parameter estimation methods reducing the reliance on back analysis.
3. **Integrated deformation monitoring technologies --** combination of satellite InSAR [9] for regional displacement mapping, robotic total stations for monitoring the crest and face, internal settlement gauges (using magnetic rings along a vertical access tube) and pipeline robotic systems for internal inspection of drainage galleries.
4. **Deep learning based intelligent deformation prediction frameworks --** Use the historical monitoring data of the completed dams (e.g., Shuibuya, Pubugou, Houziyan etc.) to train the neural networks for the prediction of settlement of the new designs under similar site conditions.

The resulting “meso-macro, multiscale, full cycle, intelligent” system has been used in the engineering design, construction and operation of 12 major rockfill dams. The only remaining gap is the lack of long term (post 10 year) settlement data for dams higher than 250 m, none of which has yet reached that age. Creep can continue at low rates for decades; extrapolations from short term monitoring have large uncertainty.

C. Seismic Analysis and Response Prediction

The seismic performance of high embankment dams [10] is particularly challenging due to the tectonic setting of western China. As can be seen in the analysis case of Lianghekou Dam, China’s water power resources are mainly distributed in the west which is a strong earthquake zone. Seismic safety of high embankment dams is one of the most important issues to hydropower development in this area. The design earthquake for large dams [11] in this region can reach peak ground accelerations (PGAs) of 0.3 g to 0.5 g (i.e., very violent shaking), requiring rigorous analytical treatment.

The conventional pseudo static approach, which treats the seismic loading as equivalent inertial forces acting at the centre of mass, is only a crude approximation, suitable only for preliminary screening. It cannot reproduce: (a) nonlinear deformation mechanisms (strain dependent modulus and damping), (b) permanent displacement accumulation (sliding block deformation), (c) local failure propagation (progressive weakening) and (d) pore pressure generation in saturated zones.

Modern Chinese practice is to use nonlinear dynamic analysis [12] with finite element (e.g., ABAQUS, GEODYNA) or finite difference (FLAC) methods and suitable constitutive models for rockfill (e.g., generalised plasticity, bounding surface plasticity) and foundation materials. For example, the analysis of the Lianghekou Dam resulted in site specific ground motions (spectral matching to the design response spectrum) and 3D nonlinear seismic response predictions. The main outputs are the amplification factors of the crest acceleration, the permanent settlement distribution and the stress states in the core and face slab.

A major gap in knowledge is the validation of these advanced models against strong motion records from high embankment dams that have experienced a major earthquake. So far, PGA > 0.2 g has not occurred for any dam in China with dam height > 200 m. The 2008 Wenchuan earthquake (Mw 7.9) caused damage to many dams but the nearest large embankment dam (Zipingpu CFRD, 156 m, ~17 km from epicentre) experienced estimated PGA ~0.5 g at crest and performed remarkably well, providing valuable but limited calibration data. Extrapolation to 300 m dams on deep overburden remains an unknown.

D. Seepage and Internal Erosion Control

The second basic pillar of the design of embankment dams is control of seepage. The basic requirement is to maintain through flow velocities low enough to prevent internal erosion (suffusion, piping, contact erosion) and to ensure that any seepage that does occur is safely captured and discharged without endangering the structure. Seepage control for embankment dams includes:

1. **The impervious element (core or face slab) -** Provides primary water proofing.
2. **Upstream and downstream transition and filter zones -** Graded granular layers to prevent migration of particles from the core but sufficiently permeable to relieve the pore pressures.
3. **Foundation cutoff and grout curtain -** Reduces under seepage through permeable foundation materials.

The design of filters (the provision of graded layers of granuals that retain the particles of the core soil but are still permeable) is a complex engineering problem. Terzaghi's filter criteria (Fannin, 2008) formulated in the 1930s are still fundamental: $D_{15}(\text{filter}) / D_{85}(\text{base}) < 4\text{-}5$ for retention, and $D_{15}(\text{filter}) / D_{15}(\text{base}) > 4\text{-}5$ for permeability.

However, these criteria were developed for uniform sands and gravel. The cores of many Chinese dams are broadly graded soils (glacial tills, weathered granite residual soils or gravel clay mixtures) with a wide particle size distribution (Cu > 20). In such materials, at certain hydraulic gradients, fine particles may be transported through the coarse matrix, this phenomenon is called suffusion or internal instability. Modified filter design criteria (e.g., dual filter zones: a finer zone adjacent to the core, and a coarser outer filter) have been established through Chinese research, but uncertainties remain in the long-term evolution of particle retention under cyclic hydraulic loading (e.g., reservoir fluctuations).

A particular difficulty in many western Chinese sites is deep alluvial overburden (50–150 m thick) consisting of layers of loose sand and gravel that are highly pervious. The case of Luding Hydropower Station (see Section 7.2) demonstrates the difficulties: the deep sandy layers could not be sealed by conventional grout curtains under high dynamic water pressure. Ultimately, innovative solutions combining specialised grout additives (high density weighting cement, fast setting polyurethane), deep hole precision drilling, and downstream loading as a stability countermeasure were successful. The case also reveals that seepage remediation for deep overburden remains a high risk, technically demanding activity with no one size fits all solutions.

V. Representative Chinese Embankment Dam Projects

A. Nuozhadu Dam (261.5 m)

The first Chinese dam on a fill greater than 250 m: The Nuozhadu dam on the Lancang River, Yunnan Province Nuozhadu was finished in 2014 as a central earth core rockfill dam of 261.5 m maximum height. “There were few prior experiences for reference and many technical challenges were inevitably encountered in design”, such as requirements for soil material properties at 260 m class height, utilisation of excavated materials and dam zoning, treatment of the right bank weak zone (a fault gouge zone), hydraulic fracturing resistance of the core, and seismic response of the dam body.

Nuozhadu’s main innovations that set technical benchmarks for later projects are:

- **Optimized core material blending –** Used excavated materials from the diversion tunnel and spillway cuts as core components to reduce waste and quarrying.
- **Improved filter criteria** for widely graded soils using dual stage filter zones (fine and coarse) verified by laboratory gradient ratio tests.
- **Seismic design measures –** Widening of the crest (from 12 m to 14 m) and reinforcement of zones (additional rockfill with higher density) in the upper 1/3 of the dam.

Post-construction monitoring (through 2020) indicates that crest settlement is ~1.2 m (0.46% of height), consistent with design expectations. There have been no reports of significant seepage anomalies.

B. Lianghekou Dam (295–303 m)

The Lianghekou Dam on the Yalong River in Sichuan Province is currently China’s highest completed embankment dam and the world’s highest earth-core rockfill dam. This gravelly soil core rockfill dam with a maximum height of 303 m (some references state 295 m due to different elevation datums) is the culmination of design methodologies, construction technologies, and quality control systems developed over two decades of ascending dam heights.Engineering achievement of Lianghekou includes:

(a) **Cold resistant construction system --** Allows winter placement of core materials at high altitude conditions (site elevation ~3,000 m) where temperatures drop down to −15 °C. The system provides heated water for compaction moisture adjustment, insulation blankets, and rapid covering of placed lifts prior to freezing.

(b) **Intelligent compaction system --** Provides real time monitoring of roller passes, lift thickness and material density with GPS and accelerometers providing a quality control that surpasses that of conventional spot testing (nuclear density gauges, sand cones).

(c) **Extensive monitoring system --** Satellite InSAR (every 6 days), robotic total stations (hourly at 120 crest points), internal settlement gauges (18 vertical lines), piezometers (85 locations) and seepage weirs.

(d) **Seismic design --** The probabilistic seismic hazard analysis (PSHA) resulted in a design basis earthquake with PGA 0.353 g and a maximum credible earthquake with PGA 0.527 g. It was predicted that the crest settlement under MCE would be 1.1 m in the nonlinear dynamic analysis, which was acceptable.

“The leap from digital construction to intelligent construction of 300 m class ultra-high earth core rockfill dams has been realised in the project”, said Chinese Academy of Engineering Academician Ma Hongqi. However, long term performance data are still rare (operational only since 2021).

C. Shuangjiangkou Dam (314 m)

When finished (expected in the late 2020s), the Shuangjiangkou Dam on the Dadu River (now being built) will replace Lianghekou as the world’s highest embankment dam, with a maximum height of 314 m. This project surpasses the technical limits of the past and requires solutions for even more extreme mechanical and hydraulic conditions. As mentioned in the literature, “physical and mechanical properties testing and blending of gravel admixed core materials are still critical in the engineering design and research of representative high earth core rockfill dams including Nuozhadu (261.5 m), Shuangjiangkou (314 m), Lianghekou (295 m), and Rumei (315 m planned).”

Shuangjiangkou faces the following specific technical challenges:

- **Extreme foundation depth --** Alluvial overburden greater than 130 m with lenses of loose sand and gravel requiring deep grout curtains and perhaps of concrete cut off walls.
- **Very high seismic hazard --** Near the Longmenshan fault zone, design PGA 0.36 g
- **Logistical restrictions --** Narrow river valley, limited access for construction and high altitude (2,500 m).

The dam is built with large field trial embankments (100 m long, 30 m wide and 25 m high) to calibrate the parameters of compaction and deformation. A remarkable innovation is the application of intelligent unmanned roller fleets [13] for consistent nighttime and adverse weather compaction.

VI. Safety Challenges and Failure Incidents

A. Aging Infrastructure and Deterioration

The safety of China's embankment dam portfolio is sharply two-sided. The high-profile mega dams built in recent decades (post 2000) benefit from state of the art design, construction, monitoring and dedicated operating staff. However, most dams (around 90,000) are from the Phase II (1950–1970) era and raise serious safety concerns. A comprehensive study [14] found that over 60% of these ageing dams have recorded "defects" in one or more safety categories: seepage anomalies, crest settlement above allowable limits, spillway degradation (concrete spalling, erosion), and loss of freeboard from sedimentation and settlement.

Common degradation mechanisms are:

- **Progressive internal erosion --** Can evolve over decades undetected as fines move from the core through defect zones or along contacts to form voids that eventually collapse. (b) Degradation of filter and transition materials -- Filter materials that were initially well-graded may have become clogged with migrated fines or may have been poorly specified to begin with.
- **Settlement and cracking --** Transverse cracking may develop in the core due to ongoing creep of the rockfill and foundation and can provide preferential seepage paths through the core.
- **Spillway deterioration --** Lack of maintenance or design errors (e.g., inadequate dissipation of energy) may cause erosion of the plunge pool and undermining of the spillway structure.
- **Biological intrusion --** Termites (covered separately) and burrowing animals create voids and preferential pathways.

The challenge for dam safety [15] management is to detect incipient failure modes before they progress to emergency conditions. This is complicated by limited funding for instrumentation and inspection of smaller dams, many of which do not even have basic piezometers. China has embarked on a national dam safety [16] remediation program since 2010, reinforcing some 50,000 "at risk" dams in some way, but the scale of remaining need is immense.

B. Recent Failure Incidents (2010–2024)

Dam failures and safety incidents have happened often in recent years, affected by extreme weather, as summarised in internal safety reviews. Some regular trends are slowly becoming clear. New issues and directions (including the effects of beyond design floods, overtopping without breaching' of embankment dams, and emergency response mechanisms) need in depth investigation.

Case 1: Tailings dam collapse, Chongqing, 2023 -- A tailings dam (an embankment dam for mining waste) collapsed, killing three people. The investigation has revealed several factors leading to the failure. Excessive water content in the accumulated waste soil (saturation causing reduced shear strength), instability to retain dam No. 1 itself (inadequate foundation treatment) and collapse under the action of water saturated waste. The direct causes were compounded by poor design (no formal stability analysis for saturated conditions), inadequate monitoring (piezometers absent), and failure to follow inspection protocols (23 inspections had previously been conducted without any hazard identification). This event highlights systemic vulnerabilities of smaller embankment structures, which may be subject to less rigorous design standards, more variable quality of construction, and less intensive institutional oversight than large reservoirs.

Case 2: 2024 Pingjiang Jiufeng Reservoir incident (Hunan Province) -- Turbid water is leaking from the culvert at an embankment dam with a dam elevation of 98.0 m (reservoir water level 125.30 m). The water is yellow, cold and sandy and gravelly. These features (turbidity, coarse particles and temperature anomaly (cold water indicating deep seepage path)) are indicative of active internal erosion and possible piping. Emergency measures included grouting and lowering of reservoir level. This incident shows that new problems of seepage may occur even after operating for many decades due to deterioration of materials or an increase of the hydraulic gradient caused by sedimentation induced rise of the water level.

C. Seismic Vulnerability

In western China, where severe seismic hazards exist, the damage caused by earthquakes remains a long-term safety concern for embankment dams. The 2008 Wenchuan earthquake (Mw 7.9) damaged several dams in Sichuan Province, some of them with large crest settlements (up to 1.0 m), longitudinal cracking (2-5 cm wide cracks along the crest), and damaged spillway structures (gate damage, concrete cracking). The Zipingpu Dam (a concrete face rockfill dam, 156 m high, located ~17 km from the epicentre) suffered significant deformation (crest settlement ~0.5 m, slab compression and bulging) but remained intact, showing the seismic resilience of well-constructed embankment dams. Most notably, there was no catastrophic failure of high embankment dams (height >100 m) during Wenchuan, although some did require post-earthquake repairs.

The potential failure of the foundation increases the seismic hazard for embankment dams found on liquefiable alluvial deposits. Li et al. [17] study the sites with saturated sand layers (loose to medium dense) vulnerable to liquefaction induced strength loss (up to 90% strength reduction) and settlement (up to 0.5 m additional settlement). With a coupled effective stress analysis (including pore pressure generation models such as Byrne or Seed Idriss [18]) and excess pore pressure dissipation, analytical methods can predict deformation under design earthquake loading. However, validation is still difficult due to the scarcity of strong motion records on instrumented embankment dams with liquefiable foundations, and no such case has been documented in China so far.

D. Biological Hazards: The Termite Problem

Biologic agents, in particular termites (Odontotermes formosanus and Reticulitermes spp.), are an unusual but largely unrecognised hazard to the safety of embankment dams in China. Official figures show that more than 90 percent of China’s 98,000 dams are of the embankment type. A thousand li like collapses due to an ant hole breach. Termites are a major hidden danger to the safe operation of hydraulic engineering projects (Ministry of Water Resources, internal safety communiqué).

Termites dig extensive networks of galleries (several hundred metres long, with nests containing millions of individuals) within embankments. This compromises the structural integrity, provides preferential seepage pathways (galleries become concentrated flow paths that can initiate piping) and in extreme cases precipitate sudden failure during high reservoir levels when galleries collapse or hydraulically fracture. The problem is particularly severe in warm and humid southern China (the provinces of Guangdong, Guangxi, Fujian, Hunan, and Jiangxi) where climatic conditions favour the proliferation of termites.

Traditional detection methods (visual inspection for mud tubes on the surface, probing with steel rods, and localised excavation) are laboured intensive and often ineffective for deep seated infestations (nests can be 2–5 m below the crest). Recent technological innovations have filled this gap through integrated solutions:

- **Development of optimised bait formulations** (e.g. hexaflumuron, chlorfluazuron) for termite control, which can be placed in bait stations around the dam to eliminate colonies.
- **Geophysical detection methods --** Ground penetrating radar (GPR) and electrical resistivity tomography (ERT) can detect termite nests and galleries non-invasively with moderate accuracy (70–85% detection rate in field trials).
- **Light trap systems --** To catch swarming alates (winged termites) prior to their establishment of new colonies on the dam face.

These technologies have been used in major projects, such as the Xiaolangdi Reservoir on the Yellow River and Nuozhadu Dam but are not yet widely deployed in China's large inventory of embankment dams. There is no quantitative assessment of termite induced failure probability in literature. No probabilistic risk model has included biological hazards.

VII. EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

A. Intelligent Construction and Quality Control

The progress from digital construction to intelligent construction is a paradigm shift in the Chinese embankment dam engineering. An intelligent compaction system based on GPS positioning (horizontal accuracy ±2 cm), accelerometer-based vibration measurement (compaction meter value, CMV) and real time data transmission (4G/5G to a cloud platform) at the Lianghekou Dam allowed continuous quality monitoring rather than discrete spot tests. The system automatically records roller passes, lift thickness, compaction energy and material moisture (via near infrared sensors) and produces colour coded maps identifying zones requiring additional roller coverage. As one government announcement describes it, this is "the first domestic application of intelligent technology throughout the entire process to control ultra-high embankment dam quality.

The National Key Research and Development Program project “Complex Conditions of Extra High Embankment Dam Construction and Long-Term Safety Guarantee Key Technologies” (2018–2022) systematically tackled problems of 300 m class structures. The research included:

- Constitutive theory of coarse granular materials (from particle scale to embankment scale) and multiscale testing.
- Deformation failure mechanisms and computational theory of extra high embankment dams with complex conditions (uneven foundations, wetting induced collapse).
- Simulation theory of the service performance evolution of the impervious system (core cracking, hydraulic fracturing).
- Construction and safety technology of extra high embankment dams on deep overburden.

Challenges remain to standardise data formats from different equipment manufacturers, cyber security of real time control systems, and training personnel to interpret the vast amounts of data generated.

B. Advanced Seepage Remediation Technologies

A major new advance is in deep overburden foundation embankment dam seepage remediation. The technical challenge is exemplified by the case of the Luding Hydropower Station, where the dam foundation on deep alluvium (thickness 110–130 m) revealed a fine sand layer at a depth of 110–130 m. In high pressure dynamic water conditions (head pressure >100 m, flow velocities up to 1 m/sec) the conventional cement grouts would wash out before setting. The problem was defined as a world class technical challenge of ‘cannot be injected, cannot be expanded, and cannot be retained’.

The solution was a multi-faceted approach:

- 2013: breach of the suspension type cutoff curtain at 150 m depth (causing boil and sand piping problems downstream); systematic remediation (comprehensive safety evaluation (geophysical surveys, borehole camera inspection), expert consultation (including international specialists), eight months of production scale testing of grout mixes).
- Targeted grouting with specialised additives: high density weighting cement (to improve dispersal and prevent washout), fast setting polyurethane (to seal high flow zones) and nanosilica modified grouts (to penetrate fine sand).
- Grouting pipe systems adapted to deep hole precision, such as double packer systems which allow for a sequential injection of the 110–130 m sand layer without contamination of adjacent zones.
- Downstream riverbed loading as a stability countermeasure (a 5 m thick gravel berm) to increase the confining stress and decrease the hydraulic gradient.

Ultimately the successful completion of staged grouting (over 18 months) solved the deep sealed seepage problem. This case is an example of the possibility of targeted remediation to extend the service life of embankment dams founded on problematic geological conditions, although the cost was high (estimated at 15% of the original dam construction cost).

C. Frontier Height Limits: 300 m and Beyond

The trend to higher embankment dam heights raises questions about physical upper limits. Current Chinese practice has proven feasibility at the 300 m scale with Lianghekou (completed) and Shuangjiangkou (under construction). Future projects such as Rumei (315 m planned on the Jinsha River) will test whether fundamental physical constraints (rockfill compressibility (which increases non linearly with stress), core material stress states (high pore pressures could induce hydraulic fracturing), foundation bearing capacity (alluvial materials under 300+ m of fill)) impose absolute limits or merely increasing difficulty and cost. Yang et al. project the ongoing height development of high earth core rockfill dams to 300 m class, high concrete face rockfill dams to 250 m class, asphalt concrete core rockfill dams to 200 m class, and high geomembrane faced rockfill dams to 100 m class.

But caution is warranted. As identified in the current research, a number of issues need to be addressed such as quality control standards for placement of rockfill in extra high earth core rockfill dams (current standards are extrapolated from lower dams), accuracy of laboratory scale down tests for oversized rockfill particles (scale effects are poorly quantified), and long term operational safety of extra high earth core rockfill dams (no long term data available). Each of those concerns points to the need for quality assurance, experimental methods, and safety monitoring to improve in lockstep with the height progression, rather than simply scaling up existing designs in a linear fashion. On alluvial foundations, there may be a practical limit to the height of earth core rockfill dams at about 350 m, beyond which concrete face rockfill dams or even concrete gravity dams are more economical.

VIII. Critical Knowledge Gaps And Research Priorities

Although considerable advances have been made, there are still major gaps in the knowledge of embankment dam science and engineering. Suggestions for future research include the following areas. Each gap is framed as a specific, answerable question or question set.

Long term performance of coarse granular materials under sustained loading (creep and environmental degradation)

The present understanding of creep (time dependent settlement), cyclic loading effects (from reservoir fluctuations, temperature cycles, small earthquakes), and environmental degradation (freeze thaw, wetting drying, chemical weathering) is based on laboratory tests of months to a few years, and field monitoring of up to three decades at most. The systematic monitoring period of any embankment dam over 200 m is shorter than the design service life of major dams (50–100 years). Priority research: (i) accelerated creep tests by using elevated temperatures (time temperature superposition), (ii) long term monitoring of existing high dams (Nuozhadu, Lianghekou) for at least 20 more years, and (iii) development of physics-based creep models incorporating particle breakage kinetics.

Laboratory material testing

The difference between the maximum particle size of the laboratory specimen (usually 60–80 mm, up to 200 mm in special test equipment) and the particle size of the rockfill in the field (often 800–1,000 mm in the main rockfill zones of 300-m dams) leads to systematic uncertainty in the strength and deformation parameters. Empirical scaling relations exist (e.g. based on parallel grading), but they have a weak theoretical basis and extrapolation beyond the calibration range is risky. Priority research: (i) development of large-scale testing facilities (1,000 mm triaxial), (ii) discrete element simulations with realistic particle shape libraries which can be validated against field test fills, and (iii) in situ characterisation using seismic geophysical methods (shear wave velocity profiling) to infer field scale stiffness.

Impacts of climate change on embankment dam safety

Recent failure cases (e.g., 2021 European floods, 2023 Chinese extreme rainfall) indicate that the increased intensity of rainfall events and increased occurrence of hydrological extremes are uncovering potential weaknesses in dams designed based on historical flood frequencies (stationarity assumption). Many smaller embankment dams have spillway capacities designed for 100-to-500-year floods; a 1,000-year flood under climate change may be less rare. A systematic assessment of climate change impacts on embankment dam safety is required, not only in terms of hydrologic loading (inflow floods), but also in terms of potential effects on material properties (e.g., increased core saturation due to more intense rainfall, faster deterioration of geomembranes due to UV exposure). Priority research: (a) nonstationary flood frequency analysis for all major watersheds, (b) scenario analysis of spillway adequacy under climate projections (RCP 4.5, 8.5), (c) development of adaptive risk management protocols.

Risk based decision frameworks for ageing infrastructure Current practice for dam safety management in China is still largely deterministic: each dam is assessed against given criteria (e.g. minimum required spillway capacity, maximum allowable seepage). If a dam fails to meet a standard, it must be remediated. This approach does not consider the millions of people exposed to potential failure, the different consequences (economic, environmental, loss of life), and the uncertainty in deterioration models. Consequently, remediation investments may be inefficiently allocated. Priority research: (a) Quantitative risk assessment methodology for embankment dams (failure probability estimation using fault trees or event trees, consequence analysis using downstream inundation mapping), (b) Uncertainty propagation across deterioration models (Monte Carlo simulation), (c) Risk cost benefit frameworks to prioritise remediation across the dam inventory.

Integration of monitoring data into predictive models

Embankment dams are producing an increasing amount of monitoring data (daily to hourly measurements of settlement, pore pressure, seepage flow, temperature, seismic acceleration, etc.). However, the application of such data in forward predictive models for safety assessment is still in its infancy. Most dam safety decisions are still made based on comparison of individual measurements with thresholds (e.g. seepage flow < 100 L/s). The development of data assimilation techniques (Kalman filters, particle filters), machine learning (neural networks, support vector regression) and Bayesian updating may allow the possibility of real time safety assessment and early warning systems, taking monitoring from passive recording to active risk management. Priority research a) development of digital twins (real time updating numerical models) for high dams b) training of machine learning models on historical failure and near failure cases c) field validation of early warning algorithms.

Termite control efficacy and risk quantification

Although termite detection and treatment technologies have improved, no systematic study has quantified the probability of termite induced failure for embankment dams as a function of climate, termite species and embankment material. Priority research: (a) controlled experiments on the development of termite colonies in test embankments, (b) probabilistic risk modelling, considering termite gallery growth rates and hydraulic loading, and (c) cost effectiveness analysis of different treatment strategies (baiting, soil barriers, monitoring).

IX. Conclusion and Recommendations

This critical review has covered the historical development, technical features, design concepts, safety issues, and new frontiers of embankment dam engineering in China. The main results can be summarised as follows:

First, China has made a great technological leap in embankment dam engineering. China has become a world leader in this field with the construction of 300 metre class ultra-high earth core rockfill dams at Lianghekou and Shuangjiangkou, projects that successfully dealt with extreme seismic hazards (PGA up to 0.5 g) and deep alluvial overburden (>100 m) and high-altitude climatic conditions. Innovations in intelligent construction (GPS-guided compaction, real-time quality control), deformation prediction (multiscale constitutive models, deep learning), and seepage remediation (speciality grouting under dynamic water conditions) have advanced the state of practice in ways applicable beyond China’s borders.

Secondly, there are significant safety concerns regarding the status of the larger embankment dam inventory (approximately 90,000 dams built in the 1950s-1970s). Many of these ageing structures now have exceeded their design service lives and are showing evidence of progressive deterioration: internal erosion, crest settlement, spillway degradation, and termite infestation. The recent incidents of failure, although rare, show that ongoing vigilance, investment and technical innovation are needed to effectively manage these risks. Termite is a unique biological hazard that is largely absent from the dam safety literature of temperate countries. Systematic deployment of countermeasures is warranted beyond the current pilot implementations.

Thirdly, there are still gaps in knowledge in a number of areas: long term rockfill creep behaviour (no dam >250 m has been monitored for longer than a decade), scale effects in material testing (laboratory specimens can’t represent field particle sizes), climate change implications for spillway adequacy (non-stationary hydrology), risk based decision frameworks (current practice is deterministic), and integration of monitoring data into predictive models (real time safety assessment remains underdeveloped).

From these findings the following policy, practice and research recommendations are proposed. Dam safety policy and management of:

1. **Prioritise risk-informed remediation for ageing dams**

With limited resources, China should shift from deterministic compliance toward quantitative risk assessment (estimating failure probabilities and consequences) to prioritise remediation investments for the highest risk structures (those with large downstream populations, high hazard potential and advanced deterioration).

2. **Systematically extend monitoring technologies across the dam inventory**

While high dams (height >70 m) are generally well-instrumented, medium and low dams often lack even basic piezometers or seepage weirs. A phased program to install low-cost wireless sensors (IoT based) on 10,000-20,000 medium hazard dams would allow early detection of incipient failure modes.

3. **Enhance termite control programs**

The use of GPR/ERT detection and bait systems should be scaled up from pilot projects to all embankment dams in termite prone areas (e.g., the provinces south of Yangtze River). Termite-specific checklists should be included as part of routine inspection protocols.

For engineering practice

4. **Performance based seismic design**

The existing code approach (design basis earthquake defined by PGA) should be complemented by performance objectives (e.g., permissible crest settlement, acceptable freeboard loss, no uncontrolled release of reservoir). This would be a better alignment of design with risk appetite.

5. **Include climate change allowances in spillway design**

For new dams and spillway upgrades, a “climate change allowance” (e.g., 10–20% increase in design flood) should be added to the probable maximum flood (PMF) or standard project flood (SPF), based on the latest climate projections for the watershed.

For further research

6. **Set up a long-term high dam observatory**

A consortium of dam owners and research institutes should fund continuous monitoring (minimum 20 years) of Lianghekou, Shuangjiangkou and Rumei with advanced instrumentation (including fibre optic strain sensing, automated total stations and seismometers) to develop a publicly accessible database for model calibration.

7. **Develop a national program on embankment dam risk assessment**

This program would create standardised approaches to failure probability estimation (including failure induced by termites), consequence analysis (economic, loss of life, environmental), and risk-informed prioritisation, supported by case studies of near failures.

8. **Develop digital twins for high-risk dams**

Real time updating numerical models (digital twins) should be developed for the 500 highest consequence dams. Monitoring data should be assimilated with data assimilation algorithms to provide forward predictions of safety margins.

In summary, the evolution of China's embankment dams is a fascinating story, ranging from the earliest earthen embankments (c. 600 BCE) to the forefront of 300 m structures, a story that has changed the face of the country, supported economic growth (irrigation, hydropower, flood control), and contributed to the global state of practice. Continuing this legacy into future decades will require sustained commitment to both engineering excellence and safety stewardship, guided by rigorous research, risk informed decision making, and systematic investment in ageing infrastructure.

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