

Seismic Deformation and Stability of Earth Dams: A Comprehensive Review with an Application to Iraq

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Abstract:

Seismic action can seriously endanger hydraulic infrastructure, particularly in areas where large water-retention dams are built on the ground characterized by complex geotechnical conditions. Iraq, situated near the tectonically active Zagros-Bitlis seismic belt, has several strategic earth dams whose response to high-level ground shaking is vital for regional water security and public safety. Despite significant progress in geotechnical and earthquake engineering, earth dams remain inherently vulnerable to seismic loading. Recent global and regional seismic events continue to demonstrate the limitations of current design and assessment approaches. Earth dams, whether natural or constructed from compacted soil materials, remain vulnerable. With Iraq's growing dependence on ageing dams like Mosul, Darbandikhan, Dokan, and Haditha, system-wide seismic assessments are vital. The paper presents a worldwide review of the seismic behavior of earth dams, and then relates it to the geological and seismic situation in Iraq. The report reviews recorded dam behaviour during past earthquakes to determine common failure modes, mechanisms of deformation, and controlling influences on seismic response. It examines analytical, empirical, and numerical techniques for estimating seismic deformation, ranging from simplified Newmark sliding-block prescribing to sophisticated nonlinear effective stress finite-element analysis and finite difference models. Incorporating the international experience with local conditions, this article enables the engineers and researchers in Iraq to use a structured assessment tool of seismic deformation analysis through existing and newly constructed earth dams. The review emphasizes the significance of recently improved hazard analysis systems, full-scale material testing, and advanced state-of-the-art numerical modeling methods to tackle this pressing geotechnical engineering problem in Iraq.

Keywords: Earthquakes, Dams, Seismic Deformation, Geotechnical Engineering, Deformation Mechanisms.

1. Introduction

Earthquakes are among the most destructive natural hazards, posing constant challenges to civil infrastructure, especially in regions with frequent tectonic activity. These events result from the rapid release of built-up strain energy along faults, generating seismic waves that travel through soil and rock. According to the National Earthquake Information

Center (NEIC) of the United States Geological Survey (USGS), tens of thousands of earthquakes are recorded globally each year, with several exceeding magnitude 7 and at least one surpassing magnitude 8. This level of seismic activity presents a significant threat to man-made structures, particularly those built on soil sediments. Such sediments can be prone to amplification, liquefaction, or cyclic degradation during intense ground motion [1-2]. Of the types of dams located throughout the world, earth dams are most common as they are relatively inexpensive to construct and can utilize local construction materials. Earth dams are particularly susceptible to seismic loading.

A small proportion of the world's dam failures are due to earthquake action, but the results can be devastating because earth dams store vast quantities of water. Unplanned flow releases and subsequent flooding with negative effects of erosion, internal cracking, slope instability, or loss of freeboard in structures result from the structural damage. This problem is especially exacerbated in seismically active areas and countries with deteriorating hydraulic infrastructure [3, 4]. This is particularly important in the case of Iraq. The country depends on big earthen and rock fill dams (such as Mosul, Darbandikhan, Dokan, Haditha, Hemrin, and Al-Adhaim) for its water supply, irrigation projects, hydroelectric power, and flood control. Some of these dams are located in the area that is under the influence zone of the Zagros-Bitlis relief seam belt, with regular occurrence of intermediate to strong seismic events. A number of the old Iraq dams have been designed using static or pseudo-static methodology, ignoring the use of equivalent seismic coefficients and conventional factors of safety, which do not always simulate deformation demands under strong shaking [5,6].

Progress in the field of earthquake engineering has led from stationary, stability-oriented methods to deformation-based calculations. The field practice has been adjusted according to the seismic performance of these dams, and it is recognized that permanent displacements combined with a cyclic pore-pressure build-up and geometry change are more adequate than applying only factor-of-safety calculations. Therefore, diverse types of analytical, empirical, and sophisticated numerical methods have been developed to predict seismic deformation, which differ in complexity and applicability [7, 8]. Global and regional knowledge is synthesized by reviewing the observed performance of earth dams during previous earthquakes, as well as state-of-the-art approaches to predict seismic deformation. The purpose has been to create a fundamental understanding among engineers, researchers, and policy makers in Iraq of the dam failure mechanisms under seismic loading that will support the development of better strategies for improved seismic safety performance of Iraq's critical water infrastructure [9].

2. Documented Seismic Behaviour of Earth Dams in Historical Earthquake Events

Dynamics of earth dams during historical earthquakes is very important to assess their seismic vulnerability and improve current design and safety criteria. Case histories from different parts of the world have provided valuable knowledge on typical deformation patterns, failure modes as well as specific site-related geological and seismological impact. Iraq, for example, hosts several large earth and rock fill dams in the vicinity of the active Zagros-Bitlis seismic belt and knowledge from global seismic performance directly applies to local engineering requirements [10]. Historical records of dam responses to earthquakes span over a millennium, especially from seismically active regions such as China, Japan and eastern Mediterranean.

Historical records show that relatively few, if any, embankment dams have failed due to earthquakes; but there have been cases of damage and deformation. The majority of disastrous failures in the past were associated with hydraulic-fill dams that aged over time, or small homogenous embankments being built from old technology with low levels of compaction or placed on inherently unstable alluvial materials [11]. In contrast, the embankments in zoned embankments built without special treatment and had a good foundation condition have performed relatively well even under a moderate level of earthquakes. While globally a low fraction of dams fail directly due to earthquakes, the implications for failure are disproportionately critical. Flash floods caused by sudden release of the reservoir water can cause severe downstream flooding, endangering life, property, and critical infrastructure. This risk is especially important to address in Iraq where large dams, such as Mosul, Darbandikhan and Doka store significant volumes of water and are situated in areas of high seismic activity [12]. Recorded case histories continue to serve as critical benchmarks in the seismic safety assessment process, primarily by imparting insight into foundation displacement patterns, liquefaction potential, cracking characteristics, and slope instabilities that may be generated during strong ground shaking. Table 1 provides dam type, height, earthquake effects and description of damage, providing a summarized resource for representative seismic responses of earth-core rockfill dams [13, 14].

Representative Observed Seismic Performance of Earth Dams During Major :Table 1 Earthquakes

Dam (Country)	Type	H (m)	Earthquake (Date)	M	Distance (km)	Observed Damage	Reference
San Andreas (USA)	E	8.5	San Francisco, 1906	8.3	0	Minor crest cracking	[15]
Ono (Japan)	E	49	Kanto, 1923	8.2	51	Severe crest cracking; downstream slope slides	[16]
Lower San Fernando (USA)	HF	42.7	San Fernando, 1971	6.5	11.2	Extensive liquefaction; upstream slope collapse; near-overtopping	[17]
Lower San Fernando (USA)	HF	38.1	Northridge, 1994	6.7	9.4	Crest settlement; longitudinal cracking; sand boils	[18]
La Villita (Mexico)	ECRD	60	Michoacán, 1985	8.1	44	Minor cracking on crest and slopes	[19]
Austrian (USA)	E	56.4	Loma Prieta, 1989	7.1	11.5	Crest cracking and settlement	[20]
Masiway (Philippines)	E	25	Luzon, 1990	7.7	5	Significant upstream slumping; crest cracking	[21]
Los Angeles (USA)	E	39.6	Northridge, 1994	6.7	9.5	Minor crest cracking and settlement	[22]
Koyoen (Japan)	E	9.1	Kobe, 1995	6.9	—	Full structural collapse due to sliding	[23]

Dam (Country)	Type	H (m)	Earthquake (Date)	M	Distance (km)	Observed Damage	Reference
Shui-Chih (Taiwan)	E	30	Chi-Chi, 1999	7.6	—	Minor crest cracking	[23]
Chang (India)	E	15.5	Bhuj, 2001	7.7	13	Crest cracking; upstream slope failure	[24]
Zipingpu (China)	CFRD	156	Wenchuan, 2008	7.9	7	Moderate crest settlement; localized face-slab distress	[25]
Fujinuma (Japan)	E	18.3	Tohoku, 2011	9.0	8	Complete failure and downstream flooding	[26]
Dokan (Iraq)	ECRD	145	Halabjah–Suleimani, 1988	5.9	40	No major damage; minor cracking reported in later inspections	[27]
Darbandikhan (Iraq)	ECRD	128	Halabjah, 2017	7.3	30	Pronounced crest cracking; spillway distress; reservoir-side displacement	[28]
Duhok (Iraq)	E	60	Local seismicity (2012–2014)	≤ 5.0	≤ 20	Minor settlement; no structural concerns	[29]

* *E* = Earthfill, *HF* = Hydraulic fill, *ECRD* = Earth-core rockfill, *CFRD* = Concrete-face rockfill.

These observations indicate that the seismic behavior of earth dams is governed by interactions among structural, geotechnical and seismic influences. In particular, the response of these works under earthquake action depends quite significantly on embankment zoning and compaction quality reached in the field; geologic-geotechnical characteristics of foundation deposits, especially in the presence of loose alluvium or saturated sandy layers; reservoir water level at earthquake occurrence time, which greatly affects the effective stresses within the dam body [30]. Besides, the strong shaking level and attributes of seismic input, such as earthquake magnitude, distance from the fault source, and effective duration of strong movements have an important effect on the induced deformation (Yong 1992). The possibility of liquefaction or cyclic softening in the embankment and foundation soils adds to the potential for instability and neutral net effect, these are essential parameters in any comprehensive evaluation of seismic performance. For Iraq, the 2017 Mw 7.3 Halabjah event was an important contemporary benchmark since it showed that even high quality dams such as Darbandikhan can suffer to a great extent from crest deformation and cracking in strong ground shaking. These experiences highlight the requirement for sophisticated earthquake resistance evaluations depending on the local geological situation and the behaviour of embankment materials that are utilized in Iraqi dam building [31].

3. Seismic Impacts on the Structural Performance of Earth Dams in Iraq

Experiences from international case histories and lessons learned from recent seismic evaluation of several major Iraqi dams have revealed that earthquakes can ultimately affect the performance and safety level of earth dams [32]. The latter impacts are mainly due to high seismic deformation, hillslope instability and liquefaction induced failure in vulnerable

structures. Although a full melt-induced failure has not been reported in Iraq, many studies have attested that most of Iraq's dams lie in seismic zones, where this mechanism must be taken into account [33].

3.1 Deformation and Cracking of Embankments

During shaking, earth dams experience dynamic loads of magnitudes that generally dwarf those under steady conditions. The cyclic horizontal and vertical features of earthquake loading can produce a host of deformation mechanisms – including crest settlement, longitudinal and transverse cracking, and lateral spreading – in embankments that are composed of materials with inherent or variable compaction characteristics. These deformation mechanisms are reported worldwide and have recently received increased attention in the case of Iraqi dams. Recent seismic risk assessments at major Iraqi embankment dams (including Badush, Al-Adhaim, Dukan and Darbandikhan) reveal numerous common damage mechanisms for progressive deformation. First, crest settlement has become a significant issue; particularly for dams managing frequent summer flood releases with limited freeboards; even relatively small amounts of settling can render them vulnerable to overtopping [34]. Second, oblique cracking failures have been seen or predicted near abutment contacts where sizable stiffness contrasts between the embankment material and contiguous bedrock create stress relay during an earthquake. The third type of internal erosion is longitudinal cracks near the weir crest, which becomes preferential seepage paths at high water levels in reservoirs and whose occurrence can enhance potential for internal erosion. In total, these modes of deformation can represent a considerable risk to structural integrity in view of diminishing freeboard as well as setting-off internal erosion phenomena such as piping or concentrated leak erosion. Table 2 compiles common seismically induced deformed shapes recognized in major Iraqi earth dams according to recent engineering evaluations and numerical analysis [35].

Table 2: Representative Seismic Deformation Concerns for Major Iraqi Earth Dams

Dam	Observed / Predicted Seismic Deformation	Primary Contributing Factors	Engineering Implications	Reference
Dukan Dam	Crest settlement (10–25 cm, predicted)	Heterogeneous embankment zoning; high reservoir level	Reduced freeboard; increased overtopping risk	[36]
Darbandikhan Dam	Longitudinal crest cracking (observed historically)	Differential stiffness; steep abutments; strong regional seismicity	Potential seepage pathways; internal erosion risk	[37]
Al-Adhaim Dam	Transverse cracking near abutments (predicted in models)	Loose foundation alluvium; cyclic softening potential	Localized stress concentration; reduced overall stability	[38]
Badush Dam	Lateral spreading and crest deformation (scenario-based analysis)	Saturated foundation sands; liquefaction susceptibility	Embankment distortion; potential for hydraulic failure	[39]

3.2 Liquefaction Potential in Iraqi Foundations

Flow liquefaction in Iraqi dam foundations emerges when seismic shaking elevates pore water pressures and reduces effective stress, leading to a rapid loss of soil strength

.Although embankment materials at most Iraqi dams are generally not susceptible to liquefaction foundation zones downstream of Dukan, Darbandikhan, and Mosul Dam contain loose alluvial and weathered deposits that may undergo strength loss under strong ground motion particularly in regions of elevated seismicity across the Kurdistan sector where geological surveys have identified loose granular layers, high groundwater tables and variable sedimentary conditions Karstic limestone foundations, such as those at Mosul Dam [40], may not liquefy yet can experience stiffness degradation, joint dilation and increased seepage under dynamic loading which collectively threaten the stability of the structure case histories demonstrate that flow failures triggered by liquefaction have caused catastrophic dam collapses and similar mechanisms remain central to safety assessments in Iraq especially for dams situated near active faults associated with the Zagros Taurus tectonic system. Within this context [41], the primary seismic concerns articulated in Seed and Fell's framework and reinforced by recent Iraqi investigations include the instability of upstream and downstream slopes due to transient reductions in shear strength differential settlement along active or potential fault traces particularly for Dams[42].The deformation or misalignment of outlet works and deep conveyance structures as observed in assessments of Al Adhaim and Hamrin Dams the generation of reservoir seiches that reduce effective freeboard in narrow valleys such as Darbandikhan and the triggering of landslides along steep reservoir margins in northern Iraq which may produce impulse waves capable of impacting the dam crest and critical appurtenances as shown in Table 3 [43].

Table 3: Major Seismic Mechanisms and Their Relevance to Key Iraqi Earth Dams

Dam	Primary Seismic Vulnerabilities	Supporting Evidence	Reference
Mosul Dam	Opening/enlargement of karstic voids; internal erosion; foundation instability; outlet deformation	Multiple international technical reports; USACE assessments	[44]
Dukan Dam	Abutment cracking; slope instability; crest deformation; differential settlement	Historical inspections post-moderate earthquakes	[45]
Darbandikhan Dam	Slope instability; seiche-induced freeboard reduction; abutment cracking; fault-related differential movement	Regional seismic hazard studies	[46]
Al-Adhaim Dam	Outlet works deformation; slope settlement; cracking near rigid structures	Iraqi Ministry of Water Resources evaluations	[47]
Hamrin Dam	Deformation of conduits; differential movement at interfaces; crest settlement	Engineering condition assessments	[47]
Badush Dam (incomplete)	Foundation instability; potential void dilation; deformation risks similar to Mosul though less severe	Geological investigations	[48]
Haditha Dam	Landslide-generated waves; potential overtopping due to impulse waves or slope failures	Local geomorphological st	[48]

3.3 Integrated Assessment of Seismic Risk and Design Requirements for Earth Dams in Iraq

Seismic vulnerability of earth dams in Iraq is influenced by the interaction of regional tectonics, geological setting, structural and operational factors. The northern and north-eastern

parts – located along the active Zagros-Bitlis seismic belt – are classified as a high-hazard zone, in which strong ground shaking is considered a realistic design basis for major embankment dams [49]. The background geology is also significant, and this includes the case where structures are founded on karstic limestone, gypsum or, less commonly, on loose alluvial deposits that can provide loss of strength or differential settlement under cyclic loading. Most of the Iraqi dams built between the 1950s and 1970s were designed based on a pseudo-static approach, which does not consider dynamic deformation or nonlinear soil behavior that results in enhanced settlement, cracking and internal erosion during earthquakes. Seasonal variations in the reservoir water level also affect the pore pressures in embankment and foundation soils, which increases the susceptibility to liquefaction or cyclic softening during earthquakes. Variations in the quality of construction and zoning, which are typical natural properties of older Iraqi dams, also lead to further uncertainties in their seismic performance [49]. In order to prevent these dangers, modern seismic-resistant design standards stipulate measures such as offsetting development from the active fault traces in the Zagros area, allowing for adequate freeboard to cope with earthquake-induced settlement and loading by waves created in reservoirs, providing well-graded filter and transition sections to avoid internal erosion and reduce potential crack propagation. Wide and ductile core zones that can selfheal are suggested to resist differential movement, and strict stability checks on embankment saddles and reservoir confining walls are needed, especially in deep valleys where earthquake-induced horizontal landslides/seiches may result in overtopping. The importance of such measures is that they can improve the seismic resistance, which is severely affected in many Iraqi earth dams since their location in geologically complex and seismically active mountainous regions leads to combinations of reservoir geometry and foundation conditions that increase risks of earthquakes [50].

4. Criteria for Evaluating the Seismic Performance of Earth Dams in Iraq

The seismic performances for the earth dam's stability in Iraq are based on construction material suitability and compaction, embankment geometry, foundation characteristics, and anticipated level of earthquake loads in the high-hazard Zagros–Bitlis region. Materials should be non-liquefying and free of sensitive clays, with embankments compacted at minimum 95 % MDD or >75% RD. Gradient 2.5:1 (H: V) or flatter slopes, accompanied by good control of seepage conditions, mitigates the likelihood of instability during an earthquake [51]. According to the current seismic hazard, the design PGA in northern Iraq can be up to 0.35 g, thus, large static factors of safety (FOS) should be used higher than 1.5 for pre-earthquake pore pressures conditions. A freeboard of 3–5% embankment height (minimum 0.9 m) is to be provided for seismic settlement and reservoir surface oscillations. All other appurtenant structures must resist limited differential movement without causing internal erosion. These standards can be used as a reference for seismic rehabilitation and safe operation of the existing and new Iraqi earth dams as shown in Table 4 [52].

Table 4: Recommended Seismic Performance Criteria for Earth Dams in Iraq

Criterion	Recommended Value / Requirement	Rationale for Iraqi Conditions	Reference
Material suitability	Non-liquefiable soils; avoid sensitive clays	Reduces risk of strength loss during shaking; important for Mosul, Darbandikhan, Haditha foundations	[51]
Compaction / Density	$\geq 95\%$ maximum dry density or $> 75\%$ relative density	Addresses weak compaction in older dams (1950s–1970s)	[51]
Slope geometry	Slopes 2.5:1 (H:V) or flatter	Minimizes seismic instability; critical for high embankments	[52]
Seepage control	Phreatic line kept well below downstream slope	Prevents pore-pressure buildup and post-earthquake failure	[53]
Design seismic loading	PGA ≤ 0.35 g (northern/northeastern Iraq)	Based on regional hazard levels near Zagros–Bitlis belt	[53]
Factor of safety	Static FoS > 1.5 for potential crest-loss surfaces	Ensures stability under pre-earthquake conditions	[54]
Freeboard	3–5% of dam height; ≥ 0.9 m minimum	Allows for settlement and seiche waves during strong shaking	[55]
Appurtenant structures	Must tolerate minor differential movement	Prevents damage to spillways, tunnels, and intake towers	[55]

5. Analytical Methods for Assessing Seismic Deformation of Earth Dams in Iraq

Analysis of seismic deformations in the Iraqi earth dams has evolved from empirical observations to numerical simulation, and is important for assessing performance of the aging dams that were founded on sites with variable geological formations within active seismic areas. Although no analytical technique may accurately estimate either the intensity or the pattern of earthquake induced deformations a staged approach obtains the most credible estimation commencing from simple screening leading to more detailed [53]. empirical database approaches employ records of previous dams that have faced earthquakes and facilitate a quick estimation of the displacements provided there is a similar geometric and material comparison with reference cases These methods however are applicable in Iraq depending on whether soil properties and constructional features are found relatively comparable simplified mechanics based Simplified mechanics based rules are relied on by them, resting on a sliding block concept proposed by Newmark presume that general deformation is associated with 'inertial' forces during seismic action .A new technique in estimating slope displacement for use in design calculations was developed .The procedure is quite simple where heights can be in excess of 50 meters [54]. Advanced numerical techniques involving linear or nonlinear dynamic analysis using total stress or effective stress forms also offer comprehensive insights on pore pressure generation material nonlinearity and deformation coupling, which are particularly pertinent for dam sites like Mosul and Darbandikhan where highly heterogeneous materials and complex foundations require site specific modeling finite element and finite difference methods support formalized seismic response evaluation of critical structures to inform decisions related to retrofitting risk mitigation. In practice, a multi-tiered framework that starts with empirical or simplified analyses followed by advanced numerical models when the predicted deformation approaches acceptable limits or the structure is important for national water security ensures analytical efficiency, accuracy, and relevance to Iraqi hazard conditions while incorporating current material characterization local hazard maps along with continued field monitoring, enhances the overall reliability of seismic assessment [55].

5.1 Empirical Methods for Iraqi Earth Dams

The use of empirical approaches offers a simple means to estimate the deformation response of earth dams in seismic loading based on documented evidence from existing structures subjected to past earthquakes. Such approaches are especially useful for screening Iraqi dams, considering the availability of site-specific seismic records and in-depth numerical simulation may not always be economically viable [56]. Various empirical formulae have been developed worldwide, relying on post-earthquake performance data. One of the first contributions was established by Jansen [57], who introduced a relationship between seismic magnitude (M), maximal horizontal acceleration at dam crest (a_c) and yield acceleration for a potential sliding mass (a_y , being the horizontal acceleration that leads to an FOS = 1) or total crest settlement (Δ):

$$\Delta = [48.26 (M/10)^8 (a_c - a_y)] / \sqrt{(a_y)} \quad (1)$$

This relationship allows engineers to estimate potential crest displacements by combining seismic intensity, local soil strength, and dam geometry. Fig. 1 illustrates the correlation between crest acceleration amplification (a_c) and peak ground acceleration (a_{max}) during an earthquake. For Iraqi dams, such as Mosul and Dokan, local amplification effects must be considered, given the variability in embankment material stiffness and foundation conditions [58].

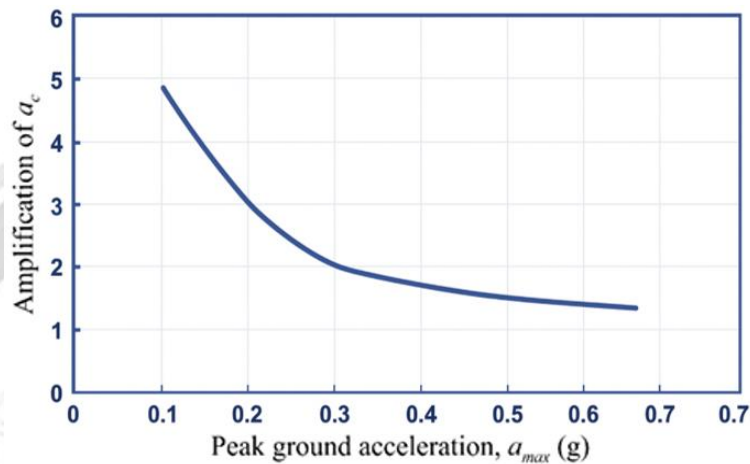


Fig. 1: Amplification of maximum acceleration at crest of dams during an earthquake [58]

Bureau [59] further proposed an empirical relationship connecting relative crest settlement (Δ/H), the friction angle of the dam material (ϕ), and the Earthquake Severity Index (ESI), defined as **Fig. 2** :

$$ESI = a_{max}^{3(M-4.5)} \quad (2)$$

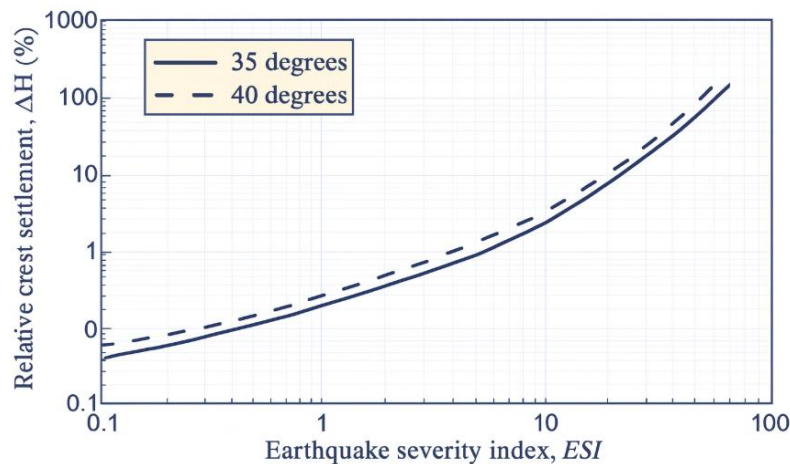


Fig. 2: Relative crest settlement versus earthquake severity index [59]

This technique provides a quick computation of expected settlements for different seismic intensities and dam materials. The use of this approach for Iraqi dams needs to be calibrated against specific seismic activity and local soil types that may not be similar to the global data set used to develop the original empirical equations. For instance, alluvium and colluvium foundations encountered in northern Iraq would likely result in slightly higher deformations at the same ESI because of lower cohesion and/or higher moisture content [59]. Empirical approaches are best suited for screening and rapid assessment, yielding order-of-magnitude approximations that can be used to decide whether more sophisticated analyses, such as Newmark sliding-block analyses or advanced finite-element modelling, are justified. They still remain a useful resource that can be used to prioritize seismic retrofitting and emergency planning of Iraq's vital hydraulic infrastructure [60]. Bureau further refined the empirical approach by correlating the normalized crest settlement, expressed as $\Delta(DH + AT)(\%)$, with earthquake moment magnitude (M) and peak ground acceleration (a_{\max}), using an extensive global database of dams subjected to seismic loading as shown in **Fig. 3**. This correlation provides a practical tool for estimating crest deformation based on earthquake intensity and dam geometry. However, for Iraqi earth dams—particularly older structures such as Dokan and Haditha—appropriate weighting factors must be adjusted to reflect regional conditions. These include the local dam height (H), operational water level (Z), and the geotechnical characteristics of the foundation soils beneath each dam section, ensuring that the method is reliably applied under Iraqi seismic and geologic settings [62].

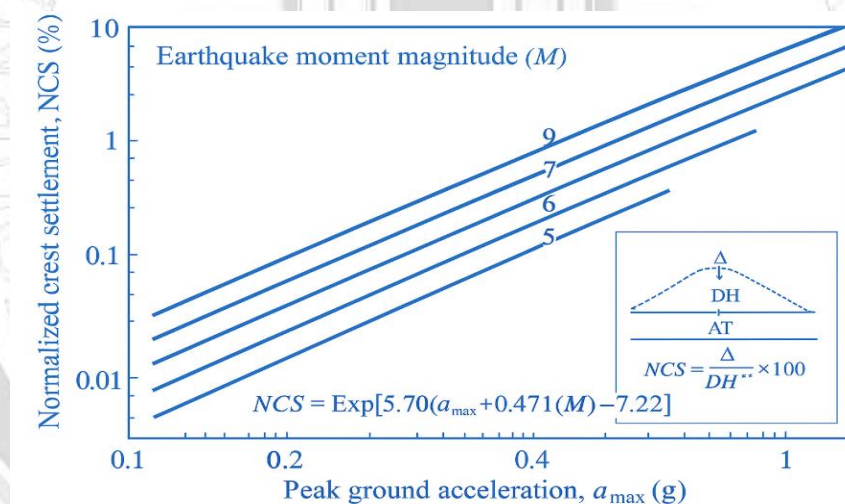


Fig. 3: Relationship between peak ground acceleration (PGA) and relative normalized crest settlement of the earth dam, where the crest settlement is normalized with respect to the dam height, illustrating the increase in permanent deformation with increasing seismic intensity [62]. [62]

This system can be used to classify potential seismic damage based on the magnitude (M), peak ground acceleration (a_{\max}), and dam material type [63]. The classification describes the six damage classes, which have been defined by upper bounds of relative crest settlements varying from "negligible" (5%), as shown in **Table 5**. This framework can be adopted for Iraq so

as to incorporate the local seismic hazard data which has been obtained based on the site-specific soil properties of embankments and foundations, and ground motion records from Zagros–Bitlis seismogenic belt. This enables engineers to predict the probable levels of damage and target retrofitting or operational measures for high risk dams [63].

Table 5. Crest settlement based on damage classification of dams under earthquake loading (Pells and Fell [59])

Damage Class	Number	Description	Maximum Relative Crest Settlement* (%)	Reference
0	No or slight	No or slight damage	< 0.03	[63]
1	Minor	Minor damage	0.03 – 0.2	[63]
2	Moderate	Moderate damage	0.2 – 0.5	[64]
3	Major	Major damage	0.5 – 1.5	[64]
4	Severe	Severe damage	1.5 – 5	[65]
5	Collapse	Collapse or near-collapse	> 5	[65]

* *Maximum relative crest settlement is expressed as a percentage of the maximum dam height (from the foundation to the dam crest).*

Singh and Debasis [64] presented an empirical correlation (using the ratio of yield acceleration to peak horizontal acceleration) that relates (y / a_{max}) with the crest settlement for embankment dams by considering 152 case histories. Their findings suggest that normalized crest settlements tend to increase rapidly after the ratio (y / a_{max}) falls below 0.6, with reported permanent settlements often leading up to 1% of the dam height under a strong seismic excitation. While such empirical relations do not describe all of the complex site-specific dam behavior, it provides adequate evaluation of earthquake-induced displacement for initial assessments. It is noted that application of this approach to Iraqi earth dams needs a careful assessment of the yield acceleration a_y in the light of local geology, foundation rigidity, embankment material properties, compaction quality and slope disposition. Integrated with regional seismic hazard analyses (with northern Iraq peak ground accelerations possibly reaching 0.30–0.35 g), this approach provides a practical screening mechanism to assess dams and select those that may be at risk from excessive crest settlement. Empirical predictions generally result in greater displacement estimates than those obtained by detailed numerical analyses for selected Iraqi dams, providing support to their conservative nature. On the whole, empirical methods are a useful screening tool for Iraqi dam engineers. These correlations could be used to quickly evaluate the likely effects of seismic events, identify when higher level dynamic analysis is required, and guide decisions on operational limits, emergency response planning and strengthening due to seismic action [65].

5.2 Simplified Methods

5.2.1 General Principles

The simple procedures for estimating seismic deformations of earth dams are essentially derived from the classical work of Newmark [67], who presented a simplified method for assessing permanent or detrimental movements in slopes caused by an earthquake. In this method a hypothetical sliding mass is treated as a rigid block on an assumed slip surface acted upon by some constant gravity forces and temporary transient that is the seismic excitation. The block's yield acceleration (a_y)—horizontal acceleration at which the slope's F values decrease to 1.0—varies with dam geometry and the geotechnical properties of the embankment and foundation. In practice, its value is usually estimated by classical limiting equilibrium methods that consider soil strength, slope geometry, and pore-water pressures. The block will not slide downward, unless the earthquake exceeds the yielding acceleration as shown in Fig. 4 [67].

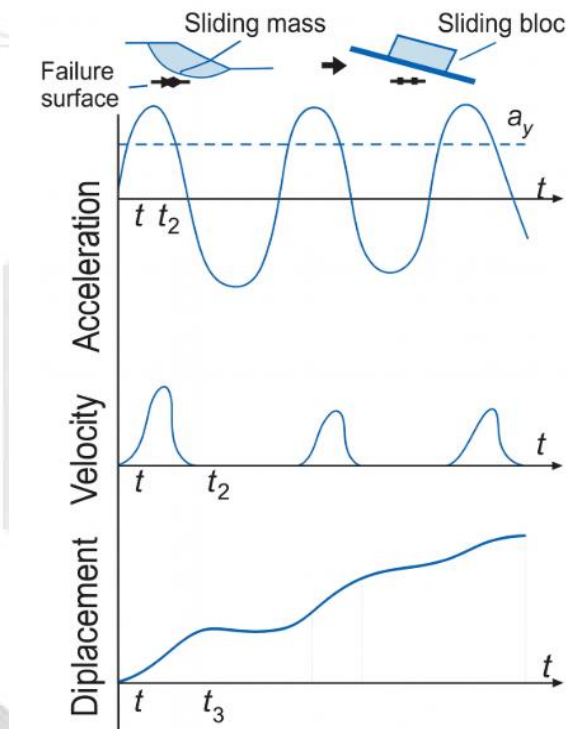


Fig. 4: Concept of the Newmark Approach [66]

In the case of Iraqi earth dams including Mosul, Darbandikhan, Dokan and Haditha, this methodology provides a generic first-order means to estimate the potential settlements of crests and seepage faces under earthquake ground motions typical for the Zagros–Bitlis seismic belt. However, when embankments or foundations are prone to liquefaction or considerable strain softening the Newmark's method is not applicable since it results in an underprediction of displacements. Nevertheless, the simple Newmark sliding block method continues to be popular in engineering practice because of its simplicity and ease of use [67]. Basic principles of the

method have been checked and validated in many studies for earth dams [66], proving that it may yield conservative estimates of permanent displacements in compact embankments not failing by liquefaction. For Iraqi dams more than 10 m in height, this approach can be used as a simple screening tool to prioritize cases requiring more rigorous numerical analyses or remedial actions (strengthen/raise upstream embankment) of existing aging facilities that are constructed prior to modern compaction and geotechnical standards [67].

5.2.2 Types of Simplified Methods

Analytical expectations for estimation earthquake-induced displacement of earth-fill dam Excitation calculations are separated into three types: (1) lumped-mass idealizations, which model the sliding block as rigid and assume no movement until the seismic acceleration exceeds the yield threshold decoupled procedures which recognize the dynamic behavior of a sliding mass but also consider it separate from any overall slope movement; and (3) coupled procedures, which integrate both aspects, dynamic reaction to ground motion in one setting procedure while allow instantaneous sliding acceleration in the way is to give an overall picture When slope characteristics, soil properties, and ground motion parameters are well defined, estimates for potential displacements fall within expectations with Newmark-simplified methods Impacting 2016 INTRODUCTION Earthquake induced displacement estimation and seismo hazard result respectively, has become demanded issues on bodies like ASCE (American Society of Civil Engineers). These are a function of both the dam's structural characteristics, such as yield; (2) decoupled procedures, which are [67]:

- **Peak ground acceleration** (a_{max})
- **Peak ground velocity** (v_{max})
- **Arias intensity** (I_a)
- **Predominant period of the acceleration spectrum** (T_p)
- **Spectral acceleration at a degraded period** ($S_{a(1.5T_1)}$)

Recorded displacements are then compared with the yield acceleration and one or more of the ground motion intensity measures in many cases through regression formulae based on earthquake databases. Table 6 summarizes the squares of the residuals better than other forms of comparing values for these simplified regressions. For Iraqi embankment dams, simplified Newmark-type techniques may be considered practical and safe for preliminary seismic safety assessment. They are used to screen dams which may require further detailed finite-element modeling, retrofit measures or operational changes needed to resist design-level earthquakes. This highlights the need to use regional seismicity data in conjunction with local geotechnical conditions to generate realistic displacement estimates and the practical implications for risk management [68] as shown in Table. 6.

Table. 6: Simplified methods

Type	Method	Equation	Reference
Rigid	Sarma (1975)	$\text{Log} \left(\frac{D}{C_{am} T p^2} \right) = 0.85 - 3.91 \left(\frac{ay}{amax} \right)$	[68]
Rigid	Franklin & Chang (1977)	$D = 35 \left(\frac{vmax^2}{amax} \right) e^{(-6.91 \left(\frac{ay}{amax} \right)) \left(\frac{ay}{amax} \right)^{-0.38}}$	[68]
Rigid	Ambraseys & Menu (1988)	$\text{Log} D = 0.90 + \text{log} \left[\left(1 - \frac{ay}{amax} \right)^{2.53} \right] \left(\frac{ay}{amax} \right)^{-1.09}$	[69]
Rigid	Yegian et al. (1991)	$\text{Log} \left(\frac{D}{NeqTD^2} \right) = 0.22 - 10.12r + 16.38r^2 - 11.48r^3$	[70]
Rigid	Watson-Lamprey & Abrahamson (2006)	$\text{Ln} Dcr = 5.470 + 0.451 \text{ln} Em - 0.581 \text{ln} \left(\frac{amax}{ay} \right) + 0.193$	[71]
Rigid	Jibson (2007)	$\text{Log} Dcr = 0.215 + \text{log} [(1 - r)^{2.341}] r^{-1.438}$	[71]
Rigid	Jibson (2007, alt.)	$\text{Log} Dcr = -2.710 + \text{log} [(1 - r)^{2.335}] r^{-1.478} + 0.424M$	[72]
Rigid	—	$\text{Log} Dcr = 2.401 \text{log} Em - 3.481 \text{log} ac - 3.230$	[72]
Rigid	—	$\text{Log} Dcr = 0.561 \text{log} Em - 3.833 \text{log} \left(\frac{ac}{amax} \right) - 1.474$	[72]
Rigid	Saygili & Rathje (2008)	$\text{Ln} Dcr = 5.52 - 4.43r - 20.93r^2 + 42.91r^3 - 28.74r^4 + 0.72 \text{ln} amax$	[72]
Rigid	Rathje & Antonakos (2011)	$\text{Ln} Dcr = \text{ln} DPDP, R + 3.69TD - 1.22TD^2$	[73]
Decoupled	Makdisi & Seed (1978)	$\frac{D}{amax TD} = f(r)$	[74]
Decoupled	Hynes-Griffin & Franklin (1984)	$\text{Log} Dcr = -0.116r^4 - 0.702r^3 - 1.733r^2 - 2.854r - 0.287$	[74]
Decoupled	Bray & Rathje (1998)	$\text{Log} \left(\frac{D}{k_{median}} \right) = 1.87 - 3.477r$	[75]
Coupled	Bray & Travararou (2007)	$\text{Ln} Dcr = -0.22 - 2.83 \text{ln} ky - 0.333 \text{ln} ky^2 + 0.566 \text{ln} ky \text{ln} amax + 3.04 \text{ln} amax - 0.244 (\text{ln} amax)^2 + 0.278(M - 7)$	[76]

D = permanent displacement **Dcr** = critical displacement **amax** = peak horizontal acceleration **ay** = yield * acceleration **r** = **ay/amax** **Em** = Arias intensity **ac** = critical acceleration **vmax** = peak ground velocity **Tp** and **TD** = predominant and degradation periods of ground motion **Neq** = number of equivalent cycles **ky** = yield coefficient **M** = moment magnitude.

5.3 Advanced Methods

Even though simplified procedures are appealing to make a preliminary assessment of earthquake-induced displacement, they cannot inherently consider complex soil-structure interaction, non-linear behavior of soil or the influence of pore-water pressure generation. In response to these restrictions, the powerful computational methods have been proposed, in particular finite element (FE), finite difference (FD), discontinuous element (DE) and discrete element (DEM). These techniques have made it possible to obtain a more detailed evaluation of seismic deformations and potential failure modes in earth dams. Practically, more advanced methods can generally be divided into two groups: total stress methods and effective stress methods (with different approaches to pore pressure generation) [76].

5.3.1 Total Stress Methods

Total stress analyses assume that changes in pore pressure during seismic loading are negligible and that the response of dam and foundation materials is entirely due to variations in total stresses, hence applicable to well-drained or cohesionless embankments where no liquefaction (or strain softening) occurs. Two main solutions have been implemented equivalent linear where a nonlinear cyclic behavior is represented by iteratively modifying soil stiffness and damping so as to compute acceleration time histories suitable for simple Newmark type displacement analysis like provided by QUAD4M, QUAKEW or non-linear method I which shows the inelastic stress-strain behavior distorting direct calculation of permanent deformation on the basis of originally adopted one dimensional constitutive models used in finite element applications such as DYNAFLOW[77] before being extended to more advanced two/three-dimensional studies involving complexity material stress relationships. For Iraqi earth dams like Mosul, Darbandikhan, Dokan, and Haditha, the success of nonlinear total stress analyses has significant advantage since it allows detailed examination on crest/slope displacements under strong ground motions identification critical areas need comprehensive prediction. The effectiveness assessment was derived from research carried out following the final sample evaluations, highlighting notable national-level operational consequences associated with moderate to large seismic events originating from the Zagros-Bitlis tectonic system.[78].

5.3.2 Effective Stress Methods

The effective stress approach offers the most conceptually rigorous methodology for analyzing earthquake-induced deformations in earth dams since it considers pore pressure generation and reductions in soil strength and stiffness in a full form [79]. The development, which is particularly important for Iraqi dams of overbank alluvial silty sand and clayey earth where seismic forces can lead to considerable excess pore pressure generation and cause the material to soften from which point on it behaves post liquefaction based upon variations other than just strains such as stress (e.g., the Moghadas et al. 9 model).⁸ These methods are generally divided into three categories: fully coupled, semi-approximate, and uncoupled approaches. Fully coupled solution represent soil by a two-phase medium with components solid and pore water phases using advanced elastoplastic constitutive frameworks describing cyclic response of stresses, strains together with dissipation rates in order to predict complete history of volcanic activity relatively high fidelity. However, sophisticated tools like DYNAFLOW PLAXIS ABAQUS FLAC are required and these approaches are especially required for older filled Iraqi embankments containing saturated zones or slurry cores exposed. It took a strong motion histories due to Zargos-Bitlis belt. Semi approximate solutions usually depend on empirical/semi empirical formulation then provide means PPR was developed baseFFs settlements not only history spring initial deformations but also may include some try case specific comprising stress amplitudes criteria selected entirely analysis propose old design allowable foundation input where occurrence resulting necessarily specific been programmed accommodate differences various curve implemented currently more under Good points discussed research complement each self-cross validated way. Levelling these findings research groups reviewed different interpretations referred subject-authority shear strain could serve simple example besides numerous variables can make difference right spot – up/down/nearby researchers anyhow were those deserve. These pressures in a nonlinear analysis that provides an acceptable compromise

between the efficiency of the numerical simulation and accuracy including unbounded codes like DIANA. The uncoupled methods calculate pore pressure independently through laboratory or empirical test data with application to a nonlinear elastoplastic model to determine permanent deformation - a convenient and widely applied method used nowadays, for instance in software tools such as FLAC (Finite Difference) for rapid appraisals of ageing Iraqi dams with limited monitoring data / scenario based seismic computations. Whilst overall effective stress formulations consider both dynamic loading and its influence on pore pressure build-up together soil strength erosion they are required for comprehensive evaluations of critical Iraqi facilities subject to significant ground motion [79].

6. Conclusion

This paper provides a summary of the state-of-the-art regarding seismic response of earth dams, including historical performance and recommendations for large hydraulic works in Iraq. Ground motion response of earth dams is a function of their geometry, material properties, foundation conditions, and the character of input ground motion. Thus, it is imperative to utilize an appropriate method for estimation of earthquake-induced displacements in a safety assessment. Three analytical approaches are identified. Experimental methods allow for inexpensive and conservative screening, offering preliminary insight into dam performance. Simple methods like Newmark type sliding-block analysis provide a first indication of deformation. For more complex problems, advanced effective stress finite element and finite difference models can be used to predict pore-pressure buildup, strength reduction, and post liquefaction behavior. Such methods are particularly pertinent for high-risk structures such as Mosul, Darbandikhan, Dokan and Haditha. Advances in numerical modeling have significantly enhanced prediction, albeit demanding expertise in soil dynamics, constitutive modeling and seismic risk studies. Among all methodological options, uncertainties in ground motion, material properties and dynamic soil properties persist. Enhancing the seismic safety of Iraqi dams will require updated approaches to seismic hazard assessment along the Zagros–Bitlis belt, better characterization and testing of dam and foundation materials, adoption of modern simulation models in combination with local geotechnical data, as well as national guidelines that integrate simplified (ZC) with more sophisticated (PE) risk analysis strategies. In summary, Iraq has sufficient expertise to design safe earth dams and improve the ability to predict earthquake behaviour, which will improve confidence in their long-term safety, functional reliability, and national water security.

7. Author Contributions Conceptualization:

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9. Conflicts of Interest

The authors have no conflicts of interests with regard to the publication of this paper.

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التشوهات الزلزالية واستقرارية السدود الترابية: مراجعة شاملة مع تطبيق على العراق

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الخلاصة

يمكن للنشاط الزلزالي أن يُشكّل تهديدًا جسيمًا للبنى التحتية الهيدروليكية، ولا سيما في المناطق التي تُشيد فيها السدود الكبيرة الخازنة للمياه فوق أراضٍ تتميز بظروف جيوتكنيكية معقّدة. يقع العراق بالقرب من الحزام الزلزالي النشط تكتونيًا (زاكروس-بيتليس)، ويضم عددًا من السدود الترابية الإستراتيجية التي تُعد استجابتها للاهتزازات الأرضية الشديدة عاملًا حاسمًا للأمن المائي الإقليمي والسلامة العامة. وعلى الرغم من التقدم المحقق في مجالي الهندسة الجيوتكنيكية وهندسة الزلازل، فإن الأحداث الزلزالية العالمية والإقليمية الحديثة ما تزال تُظهر هشاشة السدود الترابية — وهي منشآت مكونة من مواد تربة مدموكة طبيعية أو مُنشأة — والتي قد تتعرض لتشوهات دائمة، أو فقدان في الاستقرار، أو أضرار داخلية نتيجة التأثيرات الزلزالية.

ومع تزايد اعتماد العراق على السدود المتقدمة مثل سد الموصل، ودريندخان، ودوكان، وحديثة، تصبح التقييمات الزلزالية الشاملة على مستوى المنظومة أمرًا بالغ الأهمية. يقدّم هذا البحث مراجعة عالمية لسلوك السدود الترابية تحت التأثير الزلزالي، ويربطها بالوضع الجيولوجي والزلزالي في العراق. كما يستعرض السلوك المسجّل للسدود خلال الزلازل السابقة بهدف تحديد أنماط الفشل الشائعة، وآليات التشوه، والعوامل المتحكمة في الاستجابة الزلزالية. ويتناول البحث كذلك الأساليب التحليلية والتجريبية والعديد لتقدير التشوهات الزلزالية، بدءًا من الطرق المبسطة من نوع نيومارك (Newmark) لنموذج الكتلة المنزلقة، وصولًا إلى النماذج المتقدمة غير الخطية ذات الإجهاد الفعال باستخدام العناصر المحددة والفروق المحددة.

ومن خلال دمج الخبرات الدولية مع الخصائص المحلية، يوفر هذا البحث إطارًا منهجيًا يمكّن المهندسين والباحثين في العراق من إجراء تقييم منظم لتحليل التشوهات الزلزالية في السدود الترابية القائمة والمستقبلية. كما تؤكد المراجعة أهمية تطوير نظم تحليل المخاطر الزلزالية الحديثة، وإجراء اختبارات مواد على نطاق واسع، وتوظيف تقنيات النمذجة العددية المتقدمة لمواجهة هذه الإشكالية الهندسية الجيوتكنيكية الملحة في العراق.

الكلمات الدالة: - الزلازل، السدود، التشوه الزلزالي، الهندسة الجيوتقنية، آليات التشوه.