Soil fatigue hazard screening analyses framework for spacio-temporally clustered induced seismicity with examples of damage potential due to liquefaction

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Abstract

Current studies that focus solely on the cause of the increase in seismicity neglect to include considerations for effects of small magnitude cluster events on federal infrastructure. These effects can be almost undetectable at first, but if left unchecked can evolve into a larger issue. The need to reassess and potentially modify the established risk assessment practices for evaluations of federal infrastructure needs to be reviewed to ensure the continued ability of the structure to function as intended. The U.S. Army Corps of Engineers (USACE) is responsible for hydroelectric power, flood protection, recreational areas, navigational channels and water supply along the waterways that were either constructed prior to seismic design requirements or designed to a lower seismic level than current seismic activity. The need to establish revised evaluation methods of critical infrastructure has become very apparent to ensure that risk assessments include the stability of these systems and the safety of those that depend on them.

Keywords Hazard screening analysis · Induced seismicity · Soil fatigue · Damage potential

1 Introduction

1.1 Induced seismicity

Over the past decade, the central United States has seen a large increase in the number of earthquakes. From 1973 to 2008 this area had an average of 25 earthquakes that registered at a moment magnitude of **M3** or larger. Beginning in 2009, that number increased to 362 per year and peaked in 2015 at 1010. Since then, the number has slightly declined from 690 to 364 for 2016 and 2017 respectively [1–4]. However, the number of earthquakes are still high and are ranging from **M3.0** to **M4.0** [5]. This scale of seismic activity is currently believed to rarely cause damage to

critical infrastructure despite damage observations to the contrary for other structures. For example, a series of shallow events in Alberta, Canada (largest event **M4.0**), caused some minor building damage [6, 7]. Residential damage has been observed within the Central United States, e.g., the 2012 Timpson, Texas sequence (largest event of M_{W-RMT} 4.8) [8] and the 2013 Azle, Texas sequence (largest event **M3.7**) [9]. In Cherokee, Oklahoma, there were several events on February 5, 2015 (largest event of **M4.2**) wherein the Alfalfa County Courthouse interior walls were damaged [10, 11]. In November 2014, an **M4.9** event occurred in the vicinity of Milan, KS with damage to the Harper County courthouse, surrounding churches and residences; events continued through the spring of 2015 wherein new

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cracks were generated and existing building cracks were enlarged [12–15]. May 2, 2015, an **M**4.2 event occurred in Michigan with residential and commercial damage, e.g., cracks in walls [16, 17].

This paper will focus on evaluating these small magnitude events based on the magnitude and impacts to the near surface foundations supporting federal infrastructure and show the potential impacts that could cause fatigue failure as well as the number of clustered small magnitude events that are required to impact the operational performance of earthen structures, either actual or perceived. The goal of this study is to assess if small clustered events have the potential to cause fatigue damage despite the single event not being of sufficient magnitude to cause catastrophic damage [18, 19]. This paper presents a parametric study of a modified fatigue analysis to identify the minimum number of clustered events to exceed a damage threshold for an earthen structure at varying magnitudes and fatigue threshold strains. For this analysis, small induced seismic events are treated as single loading impulsive events due to the low number of exceedances of a threshold acceleration during a single induced seismic event time history.

1.2 Seismic fatigue analyses

The current standard for seismic analysis on dams and levees includes only a single-magnitude earthquake event for embankment design with some additional small magnitude events for embankments located in high seismic area [20]. Quinn and Taylor [20] presented an evaluation method to identify a multitude of hazards on infrastructure stability and critical hazard combinations. The authors used the multi-hazard stability of a flood control earth embankment assessed by calculating a factor of safety (FS) which is provided by finite element (FEM) software. The new evaluation method used a multi-hazard topography using data from FEM results from seven earth embankment geometries commonly used for flood control. All models maintained the same subsurface conditions which consisted of 5 m of silty sand on 10 m of silt on glacial till with the same no-flow boundary condition. Much like the design approach of critical infrastructure, specific combination of loads in limit states are used in the design process. These hazards are rarely considered in a combined manner, especially in locations with low seismic levels. This new method will allow the evaluation of multiple hazard scenarios but use two variable hazards, floods and ground accelerations, to show potential failure of infrastructure and establish the reliability of each system. The results indicated that high seismic accelerations were not required to cause damage to earthen structures but an accumulation of factors, e.g., the concurrence of mild flooding and small

ground accelerations, can significantly reduce the factor of safety against instability to below unity. However, this study only focused on single seismic events and the joint probability of two separate factors occurring at the same spacio-temporal location is relatively low compared to a single moderate-to-severe event from any single hazard. Quinn and Taylor [20] exposed the potential for large earthen structural fatigue, defined as an accumulation of low hazard events with the potential to cause a structure to no longer perform as designed, to occur.

Fatigue occurs at the point where the stress level is just below the number of cycles it can sustain without failure. Moreover, there are several induced seismic events that occur near critical infrastructure that can increase residual pore water pressure in saturated soils [2, 3, 19–23]. That increase will ultimately cause a decrease in effective stress which causes the shear strength to decline and a create fatigue scenario.

To better understand the impacts of small magnitude cluster events to critical infrastructure, a new induced seismic fatigue equation is presented to identify potential damage associated with these events. Current risk assessment practices assume larger tectonic events are an adequate representation for smaller geo-engineered induced seismic events despite substantial differences in shaking durations, frequencies, amplitudes, and focal depths [24–27]. Moreover, geo-engineered induced events occur at rates far in excess of equivalent tectonic counterparts [2, 3, 21, 25]. These fundamental differences suggest that spacio-temporally clustered induced seismic events can potentially cause soil fatigue, not ultimate failure, resulting in unexpected degradation of critical infrastructure.

2 Modified fatigue analysis

Short duration impulse loads are usually defined as less than **M**4.0 but can be at a higher magnitude depending on location and activity. These are not thought to cause a determinate amount of damage however when considered in cluster events, there is a potential for displacement of the foundation that supports critical infrastructure. To investigate this issue, we looked at idealized earthen dam structures using the Bray and Travarasrou [28] examples. Most of the same design parameters were used with the data modified to include earthquake events ranging from **M**2.5 to **M**4.0 for each limiting strain. While it accepted that each geolocation and seismic event will yield different characteristics, e.g., amplitude, frequency and duration as a function of source slippage, focal depth, epicentral distance, propagational pathways, etc., for the purposes of this analysis recorded events and earthquake characteristics are used. These parameters were incorporated into the Seismic

Landslide Movement Modeled using Earthquake Records (SLAMMER) program created for the USGS [29] to identify any damage potential from small magnitude events, see Table 1. The results of the SLAMMER program indicate that it is not sensitive enough to register varying degrees of damage for low magnitude events, i.e., **M2.5–M4.0**, Fig. 1. Due to the limited sensitivity of SLAMMER at these low magnitudes, another damage assessment means is required. To this extent the stress controlled damage potential equation,

Eq. 1, from Allotey and Naggar [30] was investigated wherein the fatigue damage, D , is a deterministic, non-decreasing function of the number of cycles, N at a cyclic stress ratio and the number of cycles at the stress ratio to failure, $N_f(S)$

$$D = D(N, N_f(S)) = [Ng_1(S)]^{\theta} \quad (1)$$

where the cyclic stress ratio, S , is the applied cyclic shear stress divided by the initial mean effective confining stress

Table 1 Comparison of computed displacement using SLAMMER program and Bray and Travarasrou [28] Examples

System	ky^a	$T_s(s)^b$	Site class	$S_a(1.5T_s)(g)^d$	M^e	Est. disp	
						$P(D=0)^f$	$1-P(D=0)^g$
BuenaVista LF	0.26	0.64	Alluvium	0.36	2.50	0.73	0.27
BuenaVista LF	0.26	0.64	Alluvium	0.36	3.00	0.73	0.27
BuenaVista LF	0.26	0.64	Alluvium	0.36	3.50	0.73	0.27
BuenaVista LF	0.26	0.64	Alluvium	0.36	4.00	0.73	0.27
Guadalupe LF	0.20	0.64	Rock	0.21	2.50	0.95	0.05
Guadalupe LF	0.20	0.64	Rock	0.21	3.00	0.95	0.05
Guadalupe LF	0.20	0.64	Rock	0.21	3.50	0.95	0.05
Guadalupe LF	0.20	0.64	Rock	0.21	4.00	0.95	0.05
Pacheco Pass LF	0.30	0.76	Rock	0.12	2.50	1.0	0
Pacheco Pass LF	0.30	0.76	Rock	0.12	3.00	1.0	0
Pacheco Pass LF	0.30	0.76	Rock	0.12	3.50	1.0	0
Pacheco Pass LF	0.30	0.76	Rock	0.12	4.00	1.0	0
Marina LF	0.26	0.59	Alluvium	0.30	2.50	0.9	0.1
Marina LF	0.26	0.59	Alluvium	0.30	3.00	0.9	0.1
Marina LF	0.26	0.59	Alluvium	0.30	3.50	0.9	0.1
Marina LF	0.26	0.59	Alluvium	0.30	4.00	0.9	0.1
Lopez Canyon C-A LF	0.27	0.64	Soft rock	0.48	2.50	0.4	0.6
Lopez Canyon C-A LF	0.27	0.64	Soft rock	0.48	3.00	0.4	0.6
Lopez Canyon C-A LF	0.27	0.64	Soft rock	0.48	3.50	0.4	0.6
Lopez Canyon C-A LF	0.27	0.64	Soft rock	0.48	4.00	0.4	0.6
Lopez Canyon C-A LF	0.35	0.45	Soft rock	0.43	2.50	0.87	0.13
Lopez Canyon C-A LF	0.35	0.45	Soft rock	0.43	3.00	0.87	0.13
Lopez Canyon C-A LF	0.35	0.45	Soft rock	0.43	3.50	0.87	0.13
Lopez Canyon C-A LF	0.35	0.45	Soft rock	0.43	4.00	0.87	0.13
La Villita Dam	0.20	0.60	Alluvium	0.20	2.50	0.98	0.02
La Villita Dam	0.20	0.60	Alluvium	0.20	3.00	0.98	0.02
La Villita Dam	0.20	0.60	Alluvium	0.20	3.50	0.98	0.02
La Villita Dam	0.20	0.60	Alluvium	0.20	4.00	0.98	0.02
La Villita Dam	0.20	0.60	Alluvium	0.33	2.50	0.5	0.5
La Villita Dam	0.20	0.60	Alluvium	0.33	3.00	0.5	0.5
La Villita Dam	0.20	0.60	Alluvium	0.33	3.50	0.5	0.5
La Villita Dam	0.20	0.60	Alluvium	0.33	4.00	0.5	0.5

^a ky = Yield coefficient

^b $T_s(s)$ = Degraded period

^cSite class = Type and properties of soils

^d $S_a(1.5T_s)(g)$ = Spectral acceleration

^e M = Moment magnitude

^f $P(D=0)$ = Probability of zero displacement

^g $1 - P(D=0) = 1 -$ Probability of zero displacement

Fig. 1 Damage potential from earthquake magnitudes **M2.5–M4.0** via SLAMMER

and N is the number of elapsed cycles at this stress ratio. However, Eq. 1 is stress-dependent only via the g_i function, which defines the relationship of the applied cyclic stress curve to reach a given damage equivalence of 1.0 for a given number of loading cycles for a given soil, to and Θ is a stress-independent variable (see Allotey and Nagggar [30] for full details). Thus, the damage rate varies similarly at each stress level and the Palmgren–Miner rule of superposition [31, 32] is assumed valid. The P–M approach to understanding liquefaction through metal fatigue was established around 1924 by Palmgren and then developed again by Miner around 1945. This method uses low amplitude but a high number of cycles so the amplitude of the load is so the response from the material is restricted to the elastic range. So the study of low cycle fatigue, where the ground is subjected to strong ground shaking is identified with a high plastic strain. There is a need to modify the initial P–M formula to account for nonlinear behavior of soil and is described by Green and Terri [26] as an alternative procedure to show the dissipation of soil while under a seismic load and uniform cycles. They were able to show an alternative function of the P–M hypothesis and show the uniform cycles at a specific stress ratio to start liquefaction that can vary as a function of the magnitude of the earthquake, depth of the soil profile and distance of the site-to-source [26]. When damage is equal to “1”, failure occurs. The definition of the failure of part varies. It could mean that a crack has initiated on the surface of the part. This is the basis for assessment of damage for an equivalent number of cyclic stress cycles for a given event and is central to the cyclic stress approach for assessing liquefaction susceptibility in engineering practice. For scenarios where the Palmgren–Miner rule is not valid and a stress dependency of Θ exists. Allotey and Nagggar [30] suggest a stress-dependent formulation of Eq. 1, assuming that the damage rate is variable at different stress levels:

$$D[Ng_1(S)]^{\Theta(S)} \quad (2)$$

Equation 2 would be true of induced seismicity wherein single events of the same magnitude yield different ground-motion characteristics due in part to the spatio-temporal variance in the originating source compared with tectonic events where the Palmgren–Miner rule is valid [2, 3, 31, 32]. Unlike previous fatigue models, which assume a singular originating event from which an equivalent number of cycles can be determined, induced seismic events typically yield, a single high-amplitude ground motion characteristic, e.g., ground acceleration, velocity, or displacement, over a short duration time history that would exceed a threshold acceleration needed to cause slippage in a Newmark seismic analysis [33]. Within the framework of seismic hazard assessments the cyclic stress ratio and the cyclic resistance ratio are based on the number of cycles of loading at an equivalent duration as a function of the magnitude wherein earthquake below M5.2 are considered to have the same number of equivalent cycles, 1–2, and therefore treated equally [34]. This has led to the determination of a lower magnitude limit, as associated with liquefaction, wherein it has been concluded that earthquakes, induced or tectonic, of magnitude 4.5 and greater are needed to trigger liquefaction [35–38]. As noted in Green and Bommer [38] what is discussed is a threshold limit, of a single event, to trigger liquefaction. While there have been studies to show that induced and shallow tectonic events have similar ground motions [39], these motions typically yield a single peak acceleration that will exceed a Newmark threshold for movement [33]. As such it can be assumed that any single induced event is more akin to a single impulsive event, i.e. pile hammer strike or initial blast impulse, than the prolonged dynamic excitation used for typical seismic analyses of tectonic events. Thus, any single induced event is equivalent to a single fatigue cycle in Eqs. 1 or 2. Therefore a single induced event would yield the low probability of damage potential for most structures and reinforces the findings that a minimum magnitude threshold of M4.5 is required to trigger liquefaction.

If however, when induced seismic events are spatio-temporally clustered, occurring within a 5 km radius of the structure of interest [see 2, 3], they should not be treated as unrelated single occurrences but rather as a set of n stress-dependent loadings that have an accumulative effect on the damage potential, Eq. 3:

$$D = \sum_{i=0}^n [N_m(S_n)]^{\Gamma_n} \quad (3)$$

where N_m is number of simultaneous impulsive events at the cyclic stress ratio S . This general form is modified from the Allotey and Nagggar [30] stress-dependent equation, Eq. 2, through a variable stress-dependent function, Γ , to account for the spacio-temporal cyclic stress ratio and felt intensity variability of clustered induced seismic events of approximately the same magnitude. For example, the maximum “Did-You-Feel-It” [DYFI] intensity, i.e., a proxy for observed damage, for the 20–26 June 2015 Edmond, OK clustered seismicity is presented in Fig. 2, wherein the maximum felt intensity ranged from I (low) to VI (moderate) despite a narrow range in clustered event magnitude (M3.5–M4.0).

For the analysis in this investigation, Γ , is determined for a given M as a mean stress-dependent function for use as a hazard screening tool based of a fatigue strain limit based on the structural tolerance. A single induced event is treated as a single impulsive load wherein only a single loading cycle will exceed a threshold strain (which is structurally dependent) once per induced ground motion time history. Typically, cyclic soil failure is determined from laboratory tests based on a double amplitude strain, ϵ_{da} , of 5% thereby, providing a damage baseline for comparison with SLAMMER results. However, fatigue is defined to be the magnitude of strain that a material can endure for a given number of cycles until a point of maximum strain where the soil no longer functions as intended and not necessarily failure. This necessitates the requirement that Γ is functionally dependent

on the limiting strain where fatigue is initiated as shown by Taylor [21] for subsurface subsidence deformations during pile driving activities.

Newmark [33] references transient forces in a series of displacement pulses instead of slope failure wherein it is necessary to choose a seismic coefficient that is a fraction of the maximum seismic demand. In this work that reduction, applied to the event magnitude, is found to be $M - \frac{\epsilon_{lim}}{0.1}$ such that the damage quotient is comparable to the SLAMMER baseline at a M4.0 event. However, if the threshold or limiting strain is decreased for the same magnitude event, e.g., from $\epsilon_{da} = 5\%$ to $\epsilon_{da} = 1\%$, the number of exceedances of an equivalent threshold acceleration in a Newmark analysis increases. This translates into a reduced value in the event magnitude reduction of Γ as applied to the damage quotient, i.e., an increase in the contribution of event magnitude. Therefore, the modified Allotey and Nagggar [30] equation, Eq. 3, can be reduced to:

$$D = [N_e S_{lim}]^{\Gamma} \quad (4)$$

$$\Gamma = \frac{1}{S_{lim} \left(M - \frac{\epsilon_{lim}}{0.1} \right)} \quad (5)$$

where N_e is the number of spacio-temporally clustered induced seismic events, S_{lim} is the cyclic stress ratio of the induced loading and ϵ_{lim} is the minimum threshold

Fig. 2 Clustered events in the Edmond, OK area from 20 to 26 June 2015. The maximum “Did-You-Feel-It” intensity scale (DYFI) is shown as a measure of observed damage for the number of reported cases (NOR)

exceedance strain for the structure under consideration for a single event. The cyclic stress ratio can be estimated from the Seed–Idriss simplified Liquefaction Procedure as:

$$S_{lim} = 0.65 \frac{\sigma_v}{\sigma_v'} \frac{a_{max}}{g} r_d \quad (6)$$

where σ_v = vertical total stress at depth z , $\frac{a_{max}}{g}$ is the ratio of the maximum horizontal acceleration at the ground surface to gravity, and r_d is the shear stress reduction factor that accounts for the dynamic response of the soil profile [34]. For this study, the $\frac{\sigma_v}{\sigma_v'}$ ratio is assumed 1.0 and r_d is taken as 0.7. The magnitude of $\frac{a_{max}}{g}$ for each event is based on the observations and a ground-motion prediction equation assuming a site-to-source distance of less than 5 km and focal depths of 1 km, for induced seismicity [2, 3, 6, 24, 25]: **M**4.0 = 0.45, **M**3.5 = 0.35, **M**3.0 = 0.25, **M**2.5 = 0.15. These are PGA values for epicentral distances of less than 5 km radially from the site under consideration. It should be understood that the quantification of $\frac{a_{max}}{g}$ is site dependent and the presented values are used for illustrative purposes for the fatigue framework.

3 Results

In this study, it is assumed that the impulsive events are similar in characteristics so that the first order variable is the number of cluster events, therefore Eqs. 4 and 5 can be evaluated over Eq. 3. While this is an idealized representation of actual events it allows for a first order evaluation of the required potential of induced seismic event to cause foundational fatigue, not just a failure state. Therefore, a parametric sweep was conducted on Eqs. 4 and 5 for a range of event magnitudes (**M**2.5–**M**4.0 at magnitude

intervals of 0.5), limiting strains (0.1%, 0.3%, 1%, 3% and 5%) and number of spacio-temporally clustered events (1 to 10 events) to determine the fatigue potential of induced seismic loads on foundational soils and earthen structures, Tables 2, 3, 4, and 5.

For the case of **M**2.5 events, Table 2, irrespective of the threshold strain, the damage quotient never achieves unity, suggesting that **M**2.5 events are not significant in ground motion characteristics to cause damage even with spacio-temporally located swarms. This is in agreement with the consensus of the state-of-practice concerning small magnitude seismicity. Table 3 shows the damage quotient slowly increases and exceeding the threshold at 9 cluster events providing a minimum event magnitude where damage could be possible from spacio-temporally clustered events on the example structure. Tables 4 and 5 indicate that the damage threshold is exceeded at 7 and 5 cluster events for **M**3.5 and **M**4.0 respectively. These findings are in agreement with the intensity measurements

Table 3 Changes in D for various threshold strains as a function of clustered events for $M=3$ seismic events, $S_{lim} = 0.113$

N_e	D for various ϵ_{lim} as a function of clustered events [Eq. 4]				
	0.10%	0.30%	1%	3%	5%
1	0.00168	0.00161	0.00137	0.00084	0.00048
2	0.01286	0.01249	0.01124	0.00806	0.00548
3	0.04238	0.04149	0.03842	0.03018	0.02281
4	0.09874	0.09721	0.09189	0.077	0.06272
5	0.19029	0.18818	0.18074	0.15923	0.13746
6	0.32526	0.32281	0.31412	0.2883	0.26099
7	0.51176	0.50946	0.50123	0.47623	0.44879
8	0.75783	0.75642	0.75134	0.73559	0.71774
9	1.07145	1.07195	1.07375	1.07942	1.08604
10	1.46052	1.46425	1.47779	1.52117	1.57309

Table 2 Changes in D for various threshold strains as a function of clustered events for $M=2.5$ seismic events, $S_{lim} = 0.068$

N_e	D for various ϵ_{lim} as a function of clustered events [Eq. 4]				
	0.10%	0.30%	1%	3%	5%
1	1.4E−07	1.1E−07	7.6E−08	1.7E−08	2.9E−09
2	8.1E−06	6.9E−06	5.2E−06	1.7E−06	4.6E−07
		7.8E−05	6.2E−05	2.6E−05	9E−06
4	0.00048	0.00043	0.00036	0.00018	7.4E−05
5	0.00179	0.00162	0.00141	0.00078	0.00038
		0.00481	0.00429	0.00262	0.00144
7	0.01295	0.01204	0.011	0.0073	0.00447
8	0.02842	0.02666	0.02486	0.01777	0.01188
9	0.05683	0.05375	0.05103	0.03894	0.02815
10	0.10563	0.10064	0.09709	0.07855	0.0609

Table 4 Changes in D for various threshold strains as a function of clustered events for $M=3.5$ seismic events, $S_{lim} = 0.159$

N_e	D for various ϵ_{lim} as a function of clustered events [Eq. 4]				
	0.10%	0.30%	1%	3%	5%
1	0.03667	0.03598	0.0336	0.02718	0.02137
2	0.12763	0.12613	0.12086	0.10591	0.09119
3	0.26473	0.26271	0.25557	0.23469	0.21307
4	0.44422	0.44214	0.43478	0.41272	0.38908
5	0.66368	0.66212	0.65652	0.63948	0.6207
6	0.92136	0.92093	0.91937	0.91455	0.90912
7	1.21586	1.21723	1.22217	1.23759	1.25531
8	1.54606	1.54995	1.564	1.60833	1.6601
9	1.91102	1.91816	1.94406	2.02654	2.12424
10	2.30991	2.32108	2.36167	2.49198	2.64839

Table 5 Changes in D for various threshold strains as a function of clustered events for $M=4$ seismic events, $S_{lim} = 0.205$

N_e	D for various ϵ_{lim} as a function of clustered events [Eq. 4]				
	0.10%	0.30%	1%	3%	5%
1	0.14351	0.14212	0.13723	0.12326	0.10936
2	0.33525	0.33341	0.32691	0.30773	0.28769
3	0.55071	0.54906	0.54318	0.52555	0.50658
4	0.78317	0.7822	0.77876	0.76831	0.75682
5	1.02915	1.0293	1.02983	1.03147	1.0333
6	1.28647	1.28811	1.29397	1.31213	1.33265
7	1.55363	1.55708	1.56951	1.60822	1.65248
8	1.8295	1.83508	1.85518	1.9182	1.99095
9	2.11323	2.12121	2.15004	2.24087	2.3466
10	2.40413	2.41477	2.45329	2.57523	2.71826

from the Edmond, OK 20–26 June 2015 swarm which had 10 $M \geq 3.5$ earthquakes, see Fig. 2.

4 Discussion

The displacement identified in the Bray and Travarasou [28] examples is understood to be under cyclic loading and would eventually regain stability from the displacement as pore pressures dissipate and the soil stiffens. In this parametric study it is assumed that the events are (1) temporally similar such that minimal pore pressure dissipation occurs and (2) similar in characteristics such that the first order variable is the number of clustered events followed by the Γ which is based on the magnitude of the event. It must be noted that the timescale by which to determine if a cluster is temporally similar would be a function of the soil characteristics for a specific site of interest, e.g., sands would be on the order of hours and clays on the order of weeks to achieve pore pressure dissipation. However, as a rough estimate if seismic activity time interval exceeded 24 h between events great than M2.0 then the events should not necessarily be considered temporally similar. More research is required to better define this estimate as a function of soil type, permeability and saturation.

For hazard screening one would calculate the number of events N_e required for D to exceed unity. When using the Bray and Travarasou [28] method to determine damage based on their criteria, Pacheco Pass (Table 1) has the lowest probability of zero displacement, or damage, at 0. There is no potential for displacement as the probability of exceedance is less than or equal to 1.0, Fig. 1. When the same data is incorporated into Eqs. 4 and 5, it shows the potential for soil structure degradation and is a representative example for potential settlement from earthquake

swarms, Figs. 3, 4, 5 and 6. Specifically, the data generated in Tables 2, 3, 4 and 5, the first few clustered events did not yield a significant damage potential at any ϵ_{dar} , however the damage quotient continued to increase as the number of clustered events and magnitude increased. For events in excess of M2.5, the damage quotient exceeds unity for all threshold strains, however it is observed that if ϵ_{lim} is 5%, the results illustrate because the structure has a high strain fatigue tolerance the damage quotient is lower than more sensitive ϵ_{lim} structures. This is expected and provides a logical check for the damage prediction from Eq. 4. However, for a M3.0 event 9 or more spacio-temporally clustered events are needed to exceed the damage threshold of unity. As the magnitude increases to M3.5 the number of cluster events required for damage decreases to more than 6 and then M4.0 would need more than 4 events to reach the damage threshold. This explains why the overwhelming majority of induced seismic events do not yield damages; even for an M2.5 event that doesn't surpass the damage threshold for 10 clustered events, however, based

Fig. 3 Damage potential from cluster events based on various threshold strains for M2.5 events

Fig. 4 Damage potential from cluster events based on various threshold strains for M3.0 events

Fig. 5 Damage potential from cluster events based on various threshold strains for **M3.5** events

Fig. 6 Damage potential from cluster events based on various threshold strains for **M4.0** events

on the data provided damage could register at a higher number of cluster of events. The model data suggests that a **M3.0** event has low damage potential for clustered events less than 9 for any threshold strain, with minor damage potential for higher number of clustered events.

The threshold strain is functionally dependent of the soil-structure interactions within the screening analysis and the determination of the threshold strain is not trivial. As the SLAMMER results did not yield any variability for these magnitude events the mean plus two standard deviations, Table 1, is used to determine the upper bounds equivalent threshold strain limit, i.e. the 95th-percentile, for comparison with the outputs from Eqs. 4 to 5. The mean and the 95th-percentile damage quotient, as calculated via SLAMMER, are 0.2088 and 0.6648 respectively. The single event results from Eqs. 4 to 5, at **M4.0** corresponding to the SLAMMER sensitivity limit identified from Table 1 and Fig. 1, are lower but are within the data variability of Table 1, thus it was determined that Eqs. 4 and

5 are in agreement with SLAMMER results. However, the determination of the applicable ϵ_{lim} threshold cannot be identified through comparisons of Table 1 with Tables 2, 3, 4, and 5. Therefore, findings from Taylor [21] were used to identify the onset of significant strain, a ϵ_{lim} threshold, as the beginning of movement from spacio-temporally clustered pile hammer strikes. That study consisted of a series of cyclic tests wherein an exponential increase in the rate of strain starts to occur at around $0.3\% \epsilon_{da}$, which is significantly lower than the ultimate failure threshold of $5\% \epsilon_{da}$. Additionally, it was observed that 47% of the completed tests reached $0.1\% \epsilon_{da}$ within the first cycle which suggests that the use of 0.1% as a yield initiation threshold could be overly conservative [21]. Further tests identified that the capacity at $0.3\% \epsilon_{da}$ to be about half of the difference of 0.1% and 5% ϵ_{da} and is about the mean of the distribution of the capacity-strain threshold [21]. Therefore, a yield initiation, or fatigue, threshold of $0.3\% \epsilon_{da}$ as the maximum allowable fatigue strain for saturated dynamic loading is justified to calculate the mean fatigue damage quotient from Eqs. 4 and 5.

The soil type is as a general screening tool to which the use of a 0.3% threshold value is used to identify significant limiting strain at the beginning of movement from seismic activity. So the structure is contained in the threshold value. An earthen structure would have a higher threshold value and would be associated with a higher number cluster events needed to exceed the damage threshold whereas a weaker structure would see damage at a much lower number because it is a less robust structure.

It is observed in Figs. 3–6 that the initial onset of a linear increase in D , defined when the change in rate of D can be represented as constant with subsequent events, occurs for $N_e = 6$ suggesting that this is a critical swarm event number for the modeled earthen embankment wherein the soil resistance has reached a critical state or fatigue failure condition. Site specific analysis, following Eqs. 4 and 5, can provide a refined screening measure for how many spacio-temporally clustered events can reasonably be expected before fatigue is initiated within the structure if it can be reasonable expected that the identified fatigue event threshold (N_e) will be exceeded.

To the author's knowledge, at the time of this work, there have been no reports of damage to large earthen structures from induced seismic events, either singularly or as a result of seismic swarms. However, the event epicenters are typically not in close proximity (< 5 km) to earthen infrastructure or they are a low number of clustered events. Combined with numerical analyses of single low magnitude events, the current state-of-practice assumes that low magnitude (**M2.5–M4.0**) events are not of consequence to earthen structures. While the overall probability of clustered low-magnitude seismic events in close

proximity to earthen structures is observationally low [see 3], the assumption that low-magnitude event are of little to no hazard may not be valid.

5 Effects on dams and levees

Figure 7 depicts the location of USACE facilities in seismic zones [23]. Many of these structures are in need of constant repair and it has been calculated that over half of these facilities have exceeded their 50-year service life [23]. The intent of these structures is to provide critical flood risk management support to the public across the nation and any failure could be catastrophic. The USACE uses a number of regulations to evaluate dams and levees for seismic activity. Some of these regulations are internal to USACE: U.S. Army Corps of Engineers Engineering Technical Letter (ETL) 110-2-569 "Design guidance for levee underseepage", Engineering Manual (EM) 1110-2-1902 "Engineering and design: Stability of earth and rock-fill dams", EM 1110-2-1806 "Earthquake design and evaluation for civil works projects" and EM 1110-2-1913 "Design and construction of levees" [40] Engineers also use FEMA regulations given in Code of Federal Regulations (CFR) Title 44, section 65.10 (44CFR 65.10) when evaluating levees [20]. However, there are several dams and levees that were constructed prior to implementation of the above mentioned regulations.

Induced seismic events create a concern to the natural fault lines that can be affected from the pressure of the short duration impulse loads. The additional pressures, while small, can cause localized fault slippage resulting

in settlement of rocks and overlying soils which can cause dam foundations to destabilize. Another concern is the placement of wastewater injection wells in seismic regions. As thousands of tons of wastewater is pushed into these wells, there is a concern that they can initiate an earthquake or cause slippage in fault lines [23]. The risk to USACE dams increases in location with low seismic activity as these structures were not constructed to account for the additional seismic activity.

According to the USGS [5], induced seismic events are mostly in the range of M3-4 which are large enough that they are felt by people but they are still small enough that they normally do not have the same hazards as a larger seismic events. For the larger seismic events the radial extent of the larger ground motions surpass what has been studied in regards to shallow induced seismicity. The relative risk to the dams and levees, of a single induced seismic event, would then decrease based on the below calculation:

$$\text{Seismic Risk} = \text{Seismic Hazard} \ominus \text{Vulnerability} \quad (7)$$

The vulnerability of the structure is determined by exposure or the proximity to the seismic event that may cause it damage, fragility is the likelihood that the structure will be affected by ground intensities and consequence which is the socio-economic impacts if the structure fails. Seismic Hazard is the probability of exceedance of the specific ground motion intensity. Relative to tectonic events, it can easily exceed induced events if tracking each event. But, the repetitive nature of the induced seismic events and the

Fig. 7 U.S. Map of USACE facilities and shale plays (shale plays shown in tan, dams in red, navigation locks in yellow, and levees as white circles) [23]

close proximity can increase the chance that an induced epicenter will happen within an adequate proximity to exceed a threshold acceleration through the increase of probability that an event will occur [19].

The data derived from Eqs. 4 and 5 identifies the potential for damage from short duration impulse load swarm events on earthen structures which can ultimately lead to failure. The damage may not be immediately apparent, however over time can lead to a catastrophic loss of stability. Currently there are no regulations that exist to provide guidance on the proximity that induced events can occur near critical infrastructure. The lack of regulation allows for geo-engineered induced activities to either create a seismic zone where it did not exist or increase the existing seismicity in the area. These events can ultimately decrease the life span of critical infrastructure in these zones and possibly lead to failure. Current assessment standards do not include the potential of subsurface damage from induced seismic events which can cause settlement to the foundation of critical infrastructure. This lack of oversight can lead to potential losses if the infrastructure fails. The information provided in this paper identifies a need to update existing seismic design and inspection criteria to include these events as a potential for damage.

6 Conclusions

Ongoing research is primarily focused on the geo-engineered causality of the exponential increase in seismic rates and magnitudes of events within the last decade. However, spacio-temporally clustered small magnitude events still have the potential to cause fatigue even though single events at the same magnitude do not cause damage. The results shown in this paper identify that although small in magnitude, it is the number of events that occur in cluster that can cause damage to aging infrastructure. The presented modified induced seismic fatigue equation, Eqs. 4 and 5, will allow for an additional assessment of seismicity of short duration swarm events that have the potential of causing fatigue damage to critical infrastructure. The duration and amplitude of a single induced seismic event is not significant enough to cause damage but the summation of clustered events could. Much like long duration tectonic events with lots of equivalent stress cycles.

Any damage to critical infrastructure such as dams and levees can lead to larger issues if they fail. If this criteria is included in further assessments on critical infrastructure it will allow a better understanding of the limits of failure which will enable us to verify the level of protection the structure can adequately provide. Innovative processes and further studies on this particular topic will allow for a

better assessment and determination of detrimental degradation to be observed at the subsurface.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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