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Geo-engineered induced seismicity and the effects on federal infrastructure

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GEO-ENGINEERED INDUCED SEISMICITY AND THE EFFECTS ON FEDERAL INFRASTRUCTURE

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PUBLICATION DISSERTATION OPTION

This dissertation consists of the following three articles, formatted in the style used by the Missouri University of Science and Technology:

Paper I, found on pages 12-39 *"Soil Fatigue from Induced Seismicity"* has been published in the journal of *Advances in Civil Engineering.*

Paper II, found on pages 40-74 *"Soil fatigue hazard screening analyses framework for spacio-temporally clustered induced seismicity with examples of damage potential due to liquefaction"* has been accepted for publication to the journal of *SN Applied Sciences.*

Paper III, *"Understanding the Multiple Small Magnitude Induced Seismic Soil Fatigue Potential on Hazard Assessments"* found on pages 75–96, is intended for journal submission.

ABSTRACT

The study of human-induced seismicity and the effects on civil engineering systems are not completely understood or often studied. Moreover, existing studies are focused on the cause of the seismicity and not on the potential damage to infrastructure from these seismic events. There are recent studies that are beginning to focus on shallow induced seismic activity and the effects on infrastructure by establishing innovative ways to quantify that damage. These studies that focus on the potential damage neglect to included considerations for small magnitude cluster events. As geo-induced seismic events increase, soil fatigue becomes of greater concern to structures within the seismic zone. Short duration impulse loads affect foundations and structures to the point of potential failure. Although these events can be almost unnoticeable at first, over time have the capability to become a larger issue that has the potential to fail.

There is a need for quantitative data to identify potential risk to structures from induced seismic events as well as a need to reassess and potentially modify existing risk assessment evaluations of infrastructure, most importantly critical infrastructure. 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 potential damage from human-induced seismic activity is becoming more urgent as the increase in seismic events occur.

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NOMENCLATURE

Symbol	Description
β	Angle of Attack
α	Change in Coupler Angle
Mw	Moment Magnitude
S	Cyclic Stress Ratio
ε_{da}	Double Amplitude Axial Strain
VS30	Time-Averaged Shear-Wave Velocity to 30 M Depth
k_y	Yield Coefficient
S_a	Spectral Acceleration
Θ	Stress Dependent Variable
θ	Stress Independent Variable
Γ	Stress Dependent Function
N_{fn}	Number of Simultaneous Impulsive Events at S
$N_f\ (S)$	Number of Cycles of the Stress Ratio to Failure
N_e	Number of Spacio-Temporally Clustered Induced Events
S_{lim}	Cyclic Stress Ratio
ε_{lim}	Minimum Threshold Exceedance Strain
σ_v	Vertical total stress

$\frac{a_{max}}{g}$	Ratio of Maximum Horizontal Acceleration to Gravity
r_d	Shear Stress Reduction Factor
$T_s\ (s)$	Degraded Period

1. INTRODUCTION

1.1 BACKGROUND

Little is known about the effects of shallow, repetitive, short-term impact loads from hydraulic fracturing, pile driving, etc., on federally owned dams and levees and the soil and rock foundations that support it. The main consideration is not necessarily the ground motion but the degradation of soil with these repetitive loads. As the use of geo-engineered induced seismic activity increases through hydraulic fracturing, wastewater injections wells and pile driving, the potential for ground motion increases. The assumption for stability calculations is that one large seismic event is the impetus. This is to say that if a structure can survive one event that any number of small events will have no impact on that structure which contradicts the idea of fatigue loading. The intent is to detect and quantify subsurface fatigue and changes to the structure caused by repetitive seismic activity. It is understood that a single induced seismic event can create a ground motion strong enough to fail a dam however the question still remains as to whether short-term repetitive impact loading can cause the failure as well.

The increase in human-induced seismic activity, such as hydraulic fracturing, pile driving and wastewater injection wells, in the central United States has increased damage potential for buildings, critical infrastructure and can even affect non-structural components of buildings such as chimneys (Liu, T et al 2019, Khosravikia et al. 2018, and Khosravikia et al. 2020). Seismic activity in the central United States, between 1973 and 2008, averaged 25 seismic events that registered at a moment magnitude (Mw) of M3 or larger (Peterson, et al 2016, Ellsworth, 2013, Taylor et al. 2015 a, b; McGarr 2014).

After 2008, the number if seismic events increased to 362 per year and then peaked in 2015 at 1,010. These events have slowly declined from 2015, however the number of seismic events with an *Mw* ranging from M3-M4 is still around 364 (USGS 2018).

Common seismic inducing methods are hydraulic fracturing, pile driving and wastewater injection wells. These methods combined with a close proximity to federal flood control structures such as dams and levees may cause severe damage to these critical infrastructure. This is of great concern for infrastructure that is aging and are beyond their life spans or that lacked a design that incorporated current seismicity standards. (Taylor, Lester, & McKenna, 2018)

This research will focus on evaluating these small magnitude events based on the magnitude and impacts to the near surface foundations supporting infrastructure, with specific focus on 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 (Taylor et al. 2018).

1.2 RESEARCH OBJECTIVES

The lack of information regarding hazardous effects of short-term impact loads leaves critical infrastructure vulnerable to failure. Damage to critical infrastructure such as dams and levees can lead to larger issues if and when they fail due to the mission these structures support to maintain the safety of those around it. To understand the limits of failure will enable us to verify the level of protection the structure can adequately maintain. The existing process to access damage to dams and levees from induced seismicity is not adequate as it requires a better understanding of the failure modes and threshold limits within the seismic hazard and vulnerabilities structures that are not well equipped to survive seismic loading. Moreover, the difficulty in quantifying the seismic hazard for induced event continues as the hazard is not completely understood and changes in geo-engineered locations, activities and technologies are constant. As the dams and levees that are maintained by USACE lower the exceedance threshold (i.e., the return period is reduced) further complicating the process of defining the vulnerability of the structure. Once the exceedance is lowered within the seismic hazard, the increase in the reduction of system reliability within the vulnerability creates a greater seismic risk for smaller seismic events. The level of exceedance is the estimate of the probability of exceeding from a specific amount of ground motion or ground shaking in 50 years. This makes it very difficult to try and define whether a single or multiple induced seismic events cause damage to dams and levees and requires further studies. Recent studies show that geo-engineered induced events do cause damaging degradation to the subsurface and should not be overlooked. (Taylor, Lester, & McKenna, 2018)

The objective of this study is to define soil fatigue with respect to short duration cluster event loading and the effects on dams and levees. Assessing soil behavior during ground motion with effects on both vertical and horizontal infrastructure. Research on quantitatively reconciling fluid-based geo-engineering induced seismicity source theories with observational and physical data thereby, providing a new means to assess the impact of this emerging hazard to federal dams and levees.

1.3 DISSERTATION OUTLINE

This dissertation is presented as a publication option that consists of journal articles that are presented in sections. After the introduction, Section 2 presents a literature review which was included as part of the study. Paper I discusses soil fatigue from human-induced seismic activity as determined through a literature review. There are many new studies that are beginning to focus on these low impact events as they are increasing in areas that are not accustomed to seismic loading. As human-induced seismic activity increases so does the need to find new ways to assess damage on infrastructure. Paper II discusses a new hazard screening analyses from induced seismic loading and compares multiple impulsive loads to single events with respect to damage potential. As stated above, there are many new studies arising that focus on human-induced seismic loading however they are only looking at them from a single seismic event. The neglect to include the study of spacio-temporal small magnitude events which will be identified in this paper to potentially cause damage. Paper III discusses earthen structure design considerations as determine from soil fatigue derived from induced seismicity. The intent of the paper is to compare three varying soil profiles and input the specific profile data into the modified induced seismic fatigue equation created in Paper II and discussed in depth in Paper III.

1.4 SUMMARY AND CONCLUSIONS

Based on research conducted for this work, there is a need to identify soil fatigue so that engineers are able identify when the system is not functioning as it is intended prior to liquefaction. Current damage models are focused on liquefaction from cyclic loading as well as new studies emerging that focus their efforts on shallow low impact seismic events. As human-induced seismic activity increases the need to reassess foundations that are affected by the increased seismic loading becomes more prevalent, especially in aseismic zones.

My research focused on the investigation of small magnitude cluster events and the effects on the infrastructure at the subsurface. I conducted an analysis to better understand the effects of shallow induced seismic loading on Federal infrastructure. I completed 40 triaxial tests, consisting of 20 under cyclic loading and 20 under impulsive loading to determine if impulsive loading should be treated differently than cyclic loading. Lab tests verified that impulsive loading events should be treated differently as well as the fact that single shallow small magnitude seismic events (M3-4) would not cause a determinate amount of damage. These tests did identify that although a single shallow small magnitude seismic loading would not cause damage, small magnitude cluster events do have that capability and should be further studied. Since there are very few quantifiable methods to determine soil fatigue from induced events, I modified the damage equation from the Allotey and Naggar (2007) model, to observe impulse loads vs cyclic loads as well as included a nonlinear function with loading cycles with a stress dependent variable for confining and applied stress. I further compared the modified equation to similar simplified methods to identify liquefaction based on existing soil profiles from Idriss and Boulanger. These parameters were incorporated into the Seismic Landslide Movement Modeled using Earthquake Records (SLAMMER) program created for the USGS (Jibson et al. 2014) to identify any damage potential from small magnitude events. I executed several SLAMMER tests to compare the modified damage equation to the Bray and Travasarou (2007) method as well as the Idriss and Boulanger (2008) Liquefaction Triggering Method to verify the validity of the equation. The modified damage equation, an original contribution to this field of study, provides a better understanding of potential damage from soils at near surface that are under small magnitude cluster events.

2. SAMPLE PREPARATION OF SAND FOR FATIGUE TESTING

2.1 LABORATORY BACKGROUND

It is important to ensure soil samples tested in the laboratory are a good representation of in situ conditions. The method of construction and energy applied to the specimen greatly influences the behavior of the samples. It is optimal to use undisturbed cohensionless samples in soils however it is costly and resource intensive. It is important to follow established protocols that are similar to in situ conditions such as stress, density, and the placement of the soil particles. The procedure used for this research is from Taylor et al. (2016), wherein a procedure was developed that controls three main components of sample reconstruction to include the type of material, amount of water and quantity/means of energy applied to the sample. In addition, other properties are considered to include but not limited to, density and void ratio. So by controlling the three main components, repetitive samples can achieve comparable results between varying laboratory tests by ensuring similar soil fabric is used during testing.

Laboratory tests were conducted to identify if there was a difference in dynamic behavior of near-surface partially saturated sand in reference to the potential for soil fatigue from both cyclic and impulse loading. The outcome of these tests identified the effects of near-surface soils with equivalent sinusoidal loads do not show the same strains as impulse loads to represent seismic waveforms that are irregular and need to be treated differently.

It is understood that the resistance to potential failure is greatly affected by the methods of sample preparation in the laboratory (Taylor et al. 2016). Soils are best studied under in situ states however to obtain an undisturbed of high quality directly from the field can be difficult to obtain and some methods very costly. So, it is necessary to reconstruct these samples in the laboratory to study the resistance of silts to soil fatigue.

For this effort, a standardized protocol for preparation of the samples using a 152-mm diameter, 300-mm in height triaxial sample. The reconstructed saturation was identified as 24%, this is dryer than what is determined as optimal of SDA and SDB however it was wetter than moisture contents at observed bulking. Calculations of normalized densities per Taylor et all (2012) and the sample created with specific amounts of dry soil and water to mix followed by a number of layers to build the specimen with blows per layer, rammer weight, drop height and diameter hammer base.

2.2 TRIAXIAL TESTING PROCEDURE

This study investigated the performance of 40 samples of a poorly graded sand (SP), as classified by the Unified Soils Classification System (ASTM 2011) that I executed using a GCTS triaxial device was used for soil tests using the setup detailed in Table 2.1. 20 partially-saturated triaxial tests were conducted under both cyclic loading and impulse loading. For the cyclic condition, I varied the degrees of sinusoidal stress ranging from 100kPa peak-to-peak, 75kPa peak-to-peak, 60kPa peak-to-peak and 50kPa peak-to-peak cyclic stress was applied, at a frequency of 1-Hz. Impulse loads were conducted as a series of single compressional peak amplitude impulses of the same magnitude as the cyclic stress at 1-minute intervals. Triaxial specimens were constructed using the moist tamping methods (Taylor et al. 2017) with four layers to a loose dry density of 1.634 g/cm^3 with a moisture content of 5.59% and 25% saturations. The samples measured 71.09 mm in diameter and 145.00 mm in height.

Failure was determined as either the onset of uncontrollable straining or 2.5% axial strain, whichever occurred first. For all test cases, elevated pore pressure of 5 kPa was applied through a 3-bar high-entry ceramic stone at the bottom of the specimen to simulate elevated pore pressure from the fully saturated zone and to investigate fluid migration during loading scenarios. Prior samples were tested to verify equalization between the specimen and the applied pore pressure to simulate in-situ conditions. Once testing was complete, moisture content samples were taken from the top, middle, and bottom of the specimen to determine the final moisture profile.

2.3 RESULTS

The results of the testing are presented in Table 2.2 are based on 10 of the best samples for both cyclic and impulsive loading. In all cases the material behaved in accordance with the literature in that fatigue, where the onset of uncontrolled straining, was not observed in the classical sense. However, for the failure criterion of 2.5% axial strain, it was observed that all the impulsive loads exceeded this between 9 and 19 cycles, with a mean of 12 cycles. In the cyclic case, only 1 test reached 2.5% axial strain (at 96 cycles) and the mean behavior did not achieve the failure criteria within 100 cycles.

The main focus of this research is on the use of an equivalent sinusoidal load to investigate seismic resistance of near-surface materials. For activities similar to pile driving or blasting, where the imparted load is more impulsive than cyclic, the strains that develop within the soil vary greatly. This may also be prevalent for other induced-seismic events where waveforms are shorter in duration with a short dominate peak acceleration.

The results are based on a loading stress of approximately 84% of the monotonic axial stress at failure along with the same 2.5% axial strain failure criteria. This large loading criteria is expected from naturally occurring earthquakes however would not be expected from localized high impact sources. This research shows that impulse loads must be studied separately from cyclic loads to ensure potential failure from these different loading criteria are captured appropriately.

Table 2.1. Dynamic Response

	Cell Pressure	Seatinng Load	Pore Pressure beneath a 3-Bar Ceramic Disk	Dynamic Stress	Maximum Axial Compressive Stress	Frequency	Number of Cycles
Cyclic Testing	100 kPa	5 kPa	5 kPa	100 kPa peak-to-peak	65 kPa	1 Hz	100
Impulse Testing	100 kPa	5 kPa	5 kPa	50 kPa	62 kPa	0.017 Hz	60
Cyclic Testing	75 kPa	5 kPa	5 kPa	75 kPa peak-to-peak	65 kPa	1 Hz	100
Impulse Testing	75 kPa	5 kPa	5 kPa	37.5 kPa	62 kPa	0.017 Hz	60
Cyclic Testing	10 kPa	35 kPa	5 kPa	60 kPa peak-to-peak	65 kPa	1 Hz	100
Impulse Testing	10 kPa	2 kPa	5 kPa	60 kPa	62 kPa	0.017 Hz	60
Cyclic Testing	50 kPa	5 kPa	5 kPa	50 kPa peak-to-peak	65 kPa	1 Hz	100
Impulse Testing	50 kPa	5 kPa	5 kPa	25 kPa	62 kPa	0.017 Hz	60

Table 2.2. Testing results for equivalent impulse and cyclic loads

Specimen	Test Program	Initial Water Content	Post-Test Water Content				No. Cycles to
			Top	Middle	Bottom	Average	2.5% ε_a
20170911 A	Impulse	5.53%	4.20%	6.24%	7.63%	6.02%	13
20170912 A	Impulse	5.58%	4.85%	5.13%	8.45%	6.14%	11
20170912 B	Impulse	5.61%	4.49%	5.38%	7.33%	5.73%	16
20170912 C	Impulse	5.57%	5.75%	8.33%	10.09%	8.06%	14
20181205 A	Impulse	5.53%	8.70%	11.51%	15.18%	11.80%	11
20181205 B	Impulse	5.51%	4.87%	5.89%	6.83%	5.86%	15
20181205 C	Impulse	5.55%	4.77%	5.77%	7.77%	6.10%	16
20181206 D	Impulse	5.51%	4.69%	5.85%	9.07%	6.54%	9
20181207 B	Impulse	5.54%	7.80%	4.71%	9.60%	7.37%	10
20181207 C	Impulse	5.48%	22.12%	17.73%	19.72%	19.86%	11
Average	Impulse	5.54%	7.22%	7.65%	10.17%	8.35%	12
20170913 C	Cyclic	5.52%	4.91%	6.17%	6.87%	5.98%	96
20170913 D	Cyclic	5.68%	4.14%	5.62%	7.05%	5.60%	n/a
20170914 A	Cyclic	5.48%	4.59%	6.19%	7.50%	6.09%	n/a
20170914 B	Cyclic	5.58%	4.47%	5.77%	6.87%	5.70%	n/a
20181204 A	Cyclic	5.70%	6.06%	7.60%	16.82%	10.16%	n/a
20181204 B	Cyclic	5.62%	22.58%	0.00%	0.00%	7.53%	n/a
20181206 A	Cyclic	5.62%	6.06%	7.60%	16.82%	10.16%	n/a
20181206 C	Cyclic	5.73%	17.84%	15.34%	22.02%	18.40%	n/a
20181206 F	Cyclic	5.28%	20.50%	21.80%	18.00%	20.10%	n/a
20181207 D	Cyclic	5.49%	16.67%	21.57%	20.78%	19.67%	n/a
Average	Cyclic	5.57%	10.78%	9.77%	12.27%	10.94%	n/a

PAPER

I. SOIL FATIGUE FROM INDUCED SEISMICITY

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ABSTRACT

Induced seismicity and the effects on civil engineering systems are not completely understood and infrequently studied. One specific area that is not well known is soil fatigue which include factors such as understanding the natural conditions of the subsurface as well as operational parameters under short duration impulse loads. With the increase of geo-induced seismic activity, soil fatigue becomes of greater concern to structures in the vicinity of this seismic load. The foundations of these structures can be affected by impulse loads which can ultimately cause failure. The lack of quantitative data puts the reliability of these civil engineering systems at risk as they are not fully

evaluated to determine if they are functioning as they are intended in the environments they are designed to support.

1. INTRODUCTION

Soil fatigue occurs prior to failure which makes it difficult to define as it is determined based on the acceptable level of risk the system can sustain. Determining factors for failure are usually based on social benefits and/or economic judgments that are difficult to quantify (Harr et al. 1996). For purposes of this paper, soil fatigue can be defined as the magnitude of strain that a material can endure for a given number of cycles until a point of maximum strain where the soil begins to weaken. Similar to fatigue for other engineering structures bridges, roads, metals, etc., it is further defined as losing strength over time without catastrophic failure. However, such fatigue can ultimately lead to failure if left unchecked as it will continue to grow as the amount of applied impact load increases.

The increase in geo-engineered induced seismicity has created concerns for several civil engineering systems such as dams and levees. To date, the study of impacts from induced seismicity has been rare with indeterminate conclusions with significant volumes of research into the causality of geo-engineered induced seismicity. However, little research has been completed into the accumulative effects of frequent co-located events as a single geo-engineered event is assumed to minor to cause any damage or degradation of the overlying soil structure (Taylor et al. 2015a, b; Taylor et al. 2018).

There is an abundance of literature regarding the study of single seismic event loading (Seed and Idriss 1970; Idriss and Boulanger 2008), as well as the behavior of partially saturated soils under cyclic loading (Okamura and Soga 2006; Eseller-Bayat et al. 2013). However, these studies assume that the loading from geo-engineered induced seismicity can be treated as isolated single events where the soil structure can fully recover before the next loading. Induced seismicity records from throughout the Central United States illustrate regions of close spacio-temporal small magnitude events, i.e., swarms, wherein any isolated event would typically be considered insufficient to cause any surficial expression of damage (Taylor et al. 2015a, b). However, the cumulative effect of the close spacio-temporal swarms is not well understood and can potentially cause a fatigue condition within the soil.

To study soil fatigue, this paper presents a modified damage equation to account for degradation of soil structure as a result of low frequency impulsive loading, i.e., a proxy for spacio-temporal small magnitude events.

2. GEO-ENGINEERED ACTIVITY AND INDUCED SEISMICITY

Concerns regarding induced seismic activity have increased exponentially since 2009 due to the increase in the number of induced earthquakes magnitude (M) of 3.0 or larger (Folger and Tiemann 2016). Overall the number of earthquakes in the central United States, M3.0 or larger, increased showing an average of around 300 earthquakes per year from 2009 to January 2016 (Mahani 2015). In 2009 there were approximately

29 M3.0 or larger earthquakes with a large increase between 2009 and 2016 increasing to 330 M3.0 or larger earthquakes per year in 2016 (Folger and Tiemann 2016).

A study was conducted in the western boundary of the stable Canadian craton using the three largest ground motion events: M4.0 and M4.2 near Fort St. John (FSJ), British Columbia, and an M3.9 in close proximity to the Rocky Mountain House (RMH) in Alberta that occurred between 30 July 2014 and 9 August 2014. The location selected for the study is a low-to-moderate seismic region which poses a large risk to infrastructure as they may not have been designed to resist strong ground motions because of the low probability of naturally occurring strong ground motions in the area (Atkinson et al. 2015). In early investigations, the authors determined that moderate induced events (M4-5) could damage nearby infrastructure due to the shallow focal depth that can result in concentrated strong ground motions. The study was conducted using a sparse seismograph network to record the two events at FSJ, located anywhere from 15 km to several hundred km away. The recordings from these three events of M ~ 4 were then used to examine their ground motions along with their weakening with distance. When this study was conducted, the M4.2 event was the largest event related to hydraulic fracturing in the world. Through the assessment of intensities and ground motions of the two events at FSJ were determined, based on focal depth, to be likely induced from hydraulic fracturing. They occurred at shallow (2-5km) depths that and could be felt at distances over 200 km at a maximum intensity of M4.2 for the largest event. The third event at RMH was M3.9 and was the strongest event in Alberta in more than a decade. The focal depths were determined to be between 4 km and 8 km and the area shows no records of oil and gas drilling in recent years. The RMH event was felt by nearby residents and had a reported intensity of M4-5 and caused a shutdown of a nearby gas plant and a power outage that lasted for many hours. All of these events were widely felt and had the potential to cause damage to infrastructure.

A study in Oklahoma (Folger and Tiemann 2016) shows a definite increase in earthquakes beginning in 2009 with a steep increase from 2014 to 2015. Oklahoma does have a history of seismicity but recent studies show that it is highly unlikely that these are caused through natural fluctuations in the rates of earthquakes. Central Oklahoma has created cause for concern especially since they have had more than 60 earthquakes at M4.0 to M4.8 starting in 2009 to the middle of 2016. There were larger events recorded in the same timeline that are currently under investigation due to the potential damaging effects of the seismic activity associated with the magnitude. One major earthquake was in Prague, Oklahoma that registered at M5.6 and was recorded (Keranen et al. 2013) in November 2011. It destroyed 14 homes, injured two people, buckled some parts of the highway and 17 other states could feel the tremble (Kuchment 2016). The largest earthquake documented was in Pawnee, Oklahoma which was recorded at M5.8 causing substantial damage to infrastructure (Folger and Tiemann 2016). The M5.8 earthquake in Pawnee, OK in September 2016 was the biggest recorded in the state and could possibly be related to wastewater injection.

There is statistical data that supports this conceptual model that shows the seismic activity linked to the distance between the basement and the injection point. This data provides regulators with information on how pore pressure develops through the knowledge of existing faults and ambient stress levels (Candela et al. 2018). The study included a gas extraction process as studied in Groningen, Netherlands. The process established for gas production compacts the reservoir that causes the build-up of stress along faults. Because of preexisting offsets, compartment reservoirs that have varying compaction levels meet along the faults. The compaction differences can increase the built-up stress at the faults which can in turn increase the occurrence of earthquakes (Candela et al. 2018). Through subsidence measurements used to calibrate reservoir compaction in models, it identified seismicity concentrated in locations of high subsidence and compaction. These induced events are recorded after a reduced reservoir pore pressure by ~10 MPa with the outcome of an increase in rock stress that is of similar magnitude (Candela et al. 2018). This conflicts with observations in Oklahoma that shows pressure disturbances of ~0.1 MPa initiating earthquakes. This shows that the crust is critically stressed and has a subset of faults that are near failure that can cause activation through a small amount of disturbance of stress (Candela et al. 2018).

In both of these activities, location and timing of the induced seismic activity is controlled by the distribution of space and the make-up of preexisting faults with existing stress conditions prior to subsurface work (Candela et al. 2018). The current assumption regarding the size of induced events is that failures from induced activity is confined within the volume of rock that is affected by changes in stress of fluid pressure. However, recent studies by Van der elst et al. (2016), Galis et al. (2017), contradict this assumption and show that earthquakes induced from human activity could potentially fail outside of the volume that is affected. So that size of the induced earthquake can be manipulated through preexisting natural fluctuations of stress along the fault similar to natural events (Candela, et al. 2018). In either case, evidence suggests the need to understand preexisting faults as well as their stress level. Mitigation measures need to include both operational parameters, i.e., volume produced and volume injected, but must also include knowledge of the status of faults within the subsurface. This can be identified through hydro mechanical modeling, operation parameters calibrated by independent measures through the use of InSAR to identify surface deformations (Candela et al. 2018).

A study was conducted by Zalachoris and Rathje (2019) to develop ground motion models (GMMs) for small to moderate sized, potentially induced earthquake events in Texas, Oklahoma and Kansas. The team created a database with events with epicenters in those specific locations through the use of the Incorporated Research Institutions for Seismology, IRIS, (2018). Events that had at least 3 ground motions and at magnitudes that were greater than 3.0 were used for this effort which included 4,528 ground motions that were recorded during 376 events with hypocentral distances at less than 500km. In an effort to quantify site amplifications, the team used the P-wave seismogram method that uses theoretical wave propagation considerations as well as recordings from seismic stations to estimate the VS30 at 251 seismic station locations within the defined area. In addition, the team investigated the relationship between geologic conditions and VS30 estimates at each location. This new model predicts smaller ground motions than other models as well as predicts an increase in ground motions at hypocentral distances less than or equal to 20 km. The newly scaled VS30 was determined to be weaker than other models and less amplified at VS30 < 600 m/s. (Zalachoris and Rathje, 2019). It should be noted that there is an abundance of research into the source initiation and spectral characteristics of induced seismicity (e.g., Walter et al. 2018; Quinones et al. 2019; Khosravikia and Clayton 2020; Khosravikia et al. 2019)

There have been several notable studies investigating the seismic vulnerability of structures to induced seismicity (e.g., Barba-Sevilla et al. 2018; Chase et al. 2019; Khosravikia et al. 2018; Lui et al. 2019; Khosravikia et al. 2020). These studies illustrate there exists the potential for structural susceptibility for moderate to slight damage from induced seismicity. While the severity of the potential damage to structures from induced seismic events may not be as significant as HAZUS models based on the New Madrid Seismic Zone, these results clearly indicate that the potential damage in not insignificant. To further illustrate damage potential on structures from the increase in seismicity in parts of the central United States, a recent study by Liu et al (2019) identified that nonstructural components of structures have the potential to sustain damage from induced events as well as increased risk towards potential building collapse. In particular Chase et al. (2019) indicated that in the case of light-frame wood structures the structural damage and fragility did not seem to be accumulating with sequential seismic loadings. Liu et al (2019) calculates life-safety risk from the USGS 2016 one-year seismic hazard model as well as the fragility curves that are defined in the 2015 NEHRP (National Earthquake Reduction Program) Provisions. These results indicate that life-safety risks for modern buildings, in areas that are close to active induced seismic zones, have the potential to exceed the risks calculated from in the 2015 NEHRP provisions report that considers natural seismicity alone (Liu et al. 2019). Therefore, if nonstructural components can sustain damage and increase the potential risk of structural collapse from induced seismicity then the logical question is, “Can the fatigue of the subsurface yield similar increased risk?” Moreover, do sequential induced seismic events have an accumulative effect on the fragility or fatigue of the subsurface?

3. LABORATORY OBSERVATIONS OF SOIL FATIGUE FOR IMPULSIVE VERSUS CYCLIC LOADING

To determine the reliability of a system, an object is assessed to determine failure which is the lack of ability of a system to function normally under the same specified conditions for the same amount of time (Harr et al. 1996). In the case of soil mechanics, the point of failure is determined via an ultimate, or peak, failure condition, typically occurring when the strains exceed between 2-5%. However, failure of the soil structure can occur at a significantly lower strains (Taylor et al. 2019a, b). This loss of soil structure stiffness can result in small-scale collapses, i.e., small-strain compression, yielding, or settlement, as the soil element transitions to the next quasi-stable soil structure. If the excitation sources, e.g., impulses from pile driving, occur at a rate where the soil structure is continually forced to transition to the next quasi-stable state the summation of the small-strain compression can cause superstructures, e.g., buildings and infrastructure, to exceed allowable design tolerances without causing an ultimate failure, e.g., structural collapse. This behavior defines the soil fatigue process. As subjective as failure is, soil fatigue is as well and far more difficult to identify as the experience which is usually known as the factor of safety is unknown (Harr et al.1996). This makes it difficult to quantify soil fatigue from close proximity spacio-temporal small magnitude events.

In a study conducted by the Engineering Research and Development Center, Geotechnical and Structures Laboratory, (ERDC-GSL), laboratory tests were conducted to show the difference in dynamic behavior of near-surface partially saturated sand in reference to the potential for soil fatigue from both cyclic and impulse loading (Taylor et al, 2018). The outcome of these tests identified the effects of near-surface soils with equivalent sinusoidal loads do not show the same strains as impulse loads to represent seismic waveforms that are irregular (Taylor et al, 2018). The 0.3% axial strain yield threshold is used based on a study conducted by (Taylor 2011) to identify significant limiting strain at the beginning of movement from pile strikes that began around $0.3\%\varepsilon_{da}$. The study consisted of a series of cyclic tests shown in Table 1.3 with the number of cycles needed to attain a certain double amplitude axial strain, ε_{da}, Figure 1. The results suggest that an exponential increase in the rate of strain starts to occur at around $0.3\%\varepsilon_{da}$, which is prior to the ultimate failure threshold of $5\%\varepsilon_{da}$. Additionally, it was observed that 47% of the completed tests reached $0.1\%\varepsilon_{da}$ within the first cycle which suggests that the use of 0.1% as a yield initiation threshold would be overly conservative. Further tests identified that the capacity at $0.3\%\varepsilon_{da}$ 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, Figure 1. (Taylor 2011). Therefore, a yield initiation, or fatigue, threshold of 0.3% ε_{da} as the maximum allowable fatigue stain for saturated dynamic loading is justified.

Taylor et al. (2018) identify changes in dynamic behavior of near surface partially saturated sand illustrating the strain potential from comparable cyclic and impulse loading wherein ten partially drained triaxial impulse and cyclic tests were conduction on poorly graded medium-fine beach sand with 24% saturation with a confinement of 10 kPa. An ultimate failure criteria of 2.5% axial strain was imposed based on samples tested through triaxial testing to for a qualitative comparison of the loading requirements needed to cause an ultimate failure condition, Figure 2 and Table 4 (Taylor et al. 2018). The test results showed no signs of liquefaction or symptoms of uncontrolled straining as observed in saturated conditions, e.g., Taylor (2011), however the impulse tests did reach the 2.5% straining threshold where an equivalent cyclic load did not. All of the impulse load tests exceeded the failure criteria of 2.5% ε_{da} at between 9 and 19 cycles with an average of 12 cycles to failure. Only three of the cyclic test reached the 2.5% failure criteria with an average of 100 cycles to failure. This study identifies the need to study cyclic and impulse loads with respect to near-surface seismic resistance. As shown by the data, cyclic loads, the increase in axial strain is nonlinear and has a logarithmic trend with a low number of cycles followed by a large increase at 50 cycles which identifies the potential for softening of the soil however not enough to reach liquefaction. On the other hand, impulse loads showed the increase in strain to be linear after an initial loading spike which identifies a constant strain (Taylor et al. 2018).

Laboratory tests identified the difference in dynamic behavior of near-surface partially saturated sand in reference to the potential for liquefaction from both cyclic and impulse loading (Taylor et al, 2018). The outcome of these tests identified the effects of near-surface structures, equivalent sinusoidal loads do not show the same strains as impulse loads to represent seismic waveforms that are irregular (Taylor et al, 2018). Based on this study, it is important that cyclic and impulse loading tests are treated differently so the below equation (1) is introduced to identify a more accurate picture of liquefaction from induced seismic events.

4. DETERMINING DAMAGE POTENTIAL FROM SOIL FATIGUE

It is feasible through innovative processes to determine damage from soil fatigue that will allow engineers to identify when the system is not functioning as it should. Most studies are focused on the effects of cyclic soil degradation on soil strengths but neglect to include potential damage from impulse loads. In addition, the damage accumulation effects from earthquake swarm events is largely unknown. Newmark's (1965) sliding block analysis touches on this concept but focuses on a single earthquake with a distinct number of times the acceleration exceeds the threshold. The focus of this paper is to consider multiple events in close proximity where each event has a single time the acceleration exceeds a threshold value. In a study conducted by the Engineering Research and Development Center, Geotechnical and Structures Laboratory, (ERDC, GSL), laboratory tests were conducted to show the difference in dynamic behavior of near-surface partially saturated sand in reference to the potential for liquefaction from both cyclic and impulse loading (Taylor et al, 2018). The outcome of these tests identified the effects of near-surface structures, equivalent sinusoidal loads do not show the same strains as impulse loads to represent seismic waveforms that are irregular (Taylor et al, 2018). Based on this study, it is important that cyclic and impulse loading tests are treated differently so the below equation (1) is introduced to identify a more accurate picture of liquefaction from induced seismic events. To consider the seismic design of a structure in this paper, a conceptual model is provided to analyze the equations presented in this paper.

The pseudostatic slope stability method is a commonly used procedure to determine slope stability under seismic loading that was introduced by Seed (1979). It was further improved by Bray and Travasarou (2009) to better rationalize the identification of the seismic coefficient used in the analysis. This method uses a probabilistic seismic slope displacement model to determine slope stability under seismic loading. It uses the yield coefficient (k_y), the initial fundamental time period of the sliding mass(T_s), along with a degraded time period of spectral acceleration $(S_a)1.5T_s$, (M) is the moment magnitude of the earthquake and ϵ is the normal distributed random variable. The below Eq. (1) represents the number of nonzero seismic displacement (D) events:

$$\ln(D) = -1.10 - 2.83\ln(k_y) - 0.333(\ln(k_y)^2) + 0.566\ln(ky)\ln(S_a(0.39)) + 3.04\ln(S_a(1.5T_s)) - 0.244(\ln(Sa(1.5T_s)))^2 + 1.50T_s + 0.278(M - 7) \pm \epsilon) \quad (1)$$

The example presented in this paper is created as an example for potential settlement from earthquake swarm events on a standard office building. The below slope stability analysis was completed through the use of the Seismic Landslide Movement Modeled using Earthquake Records (SLAMMER) program created for the USGS (Jibson et al. 2014). The program is used to analyze permanent deformations of slopes to identify how they behave during an earthquake. I used the Bray and Travasarou simplified method for this analysis with the use of existing data incorporated into the SLAMMER system as well as assumptions that were used to calculate displacement. Using the data included in the SLAMMER system, Figures 3 and 4, the below record was used as a sample product for the calculations used in the Bray and Travasarou flexible (coupled) method with a modification of the earthquake magnitude from M7 to M4 to represent the potential for damage at small magnitudes (Jibson et al. 2014).

The Bray and Travasarou flexible coupled method was selected to estimate permanent displacement from a single deterministic event or the probability of exceeding specific permanent displacements (Jibson et al. 2014). The flexible analysis estimates the non-zero displacement as well as the probability of zero displacement. Figure 5 shows the correlation of the yield coefficient to the median displacement from data shown in Table 1. The data shows little to no displacement based on the above parameters.

In an effort to identify soil fatigue from earthquake swarms and show that induced seismic events have shorter dominating peak accelerations as well as shorter durations the below Eq. (2) was modified from Allotey and Naggar (2007) damage equation to replace cyclic loading with impulse loading as well as adding an additional a non-linear stress dependent variable:

$$D = D\left(N, N_f\,(S)\right) = (N_f\,(S))^{\Theta(S)} \tag{2}$$

where D is the constant stress-controlled loading, fatigue damage function that is assumed to be a single valued deterministic figure that is non-dimensional as well as non-decreasing part of the stress ratio under a given number of cycles. N is the current number of cycles elapsed at the stress ratio, S and $N_f\,(S)$ is the number of cycles of the stress ratio, S, to reach failure. Failure is defined as soil fatigue which is determined 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. The stress ratio, S, is the initial mean effective confining stress and Θ is a nonlinear function with loading cycles that is a stress dependent variable in the applied stress (CSR) and confining pressure. As the stress levels vary, the damage rate changes, depending on the sequence of loading, the life of fatigue can be less than or greater than one. (Van Paepegem and Degrieck 2002). With a threshold of 0.3% strain, which allows a comparison of cyclic loading vs impulse loading. (Taylor 2011).

In contrast to the previous analysis from Bray and Travasarou (2007) that did not register damage, Table 2 and Figure 6 show that when modified from cyclic loading to impulse loading, the damage rate changes at varying stress levels. These results identify degradation to the soil structure that might not be seen immediately but overtime can cause failure if left unchecked. This level of damage can be catastrophic in infrastructure that is constructed to a certain level based on the existing seismic design criteria. Using this method, the data identifies the potential failure from settlement due to earthquake swarms and should be considered in seismic evaluations.

5. CONCLUSIONS

Induced seismicity or induced earthquakes have become of great concern in recent years as rates of these events continue to grow. The inducement of seismicity from underground and surface mining, extraction of oil and gas, reservoir impoundments, and injection of fluids into geologic formations at the subsurface has been understood for some time now, however these studies neglect to incorporate the potential effects these impulse loads may have on civil engineering systems. One of these potential effects is soil fatigue which can be considered a slow weakening of material because of sources external to the structure that act upon the reliability of it. This should be considered in current evaluation standards and studied to determine if the structure can sustain impulse loading that occurs at shallow depths to identify issues with the foundation prior to failure.

The introduction of a new damage equation is an extension of the Allotey and Naggar (2007) model that modifies the loading criteria to impulse in lieu of cyclic to get a better depiction of soil degradation from induced seismic events. It was further modified to include a nonlinear function with loading cycles that is a stress dependent variable for both the applied stress and confining pressure. The limitation of the Allotey and Naggar (2007) model to determine soil degradation from induced seismic events was based on cyclic loads which do not depict strains that develop from impulse loads. Based on the reformulation of the equation, a better picture of potential damage effects to soils near the surface under impulse loading can be attained. This redundancy is needed as the existing process to access damage to infrastructure from induced seismicity is not adequate as it requires a better understanding of the failure modes and threshold limits within the Seismic Hazard and vulnerabilities structures that are not well equipped to survive seismic loading. Moreover, the difficulty in quantifying the seismic hazard for induced event continues as the hazard is not completely understood and changes in geo-engineered locations, activities and technologies are ever present. However, through 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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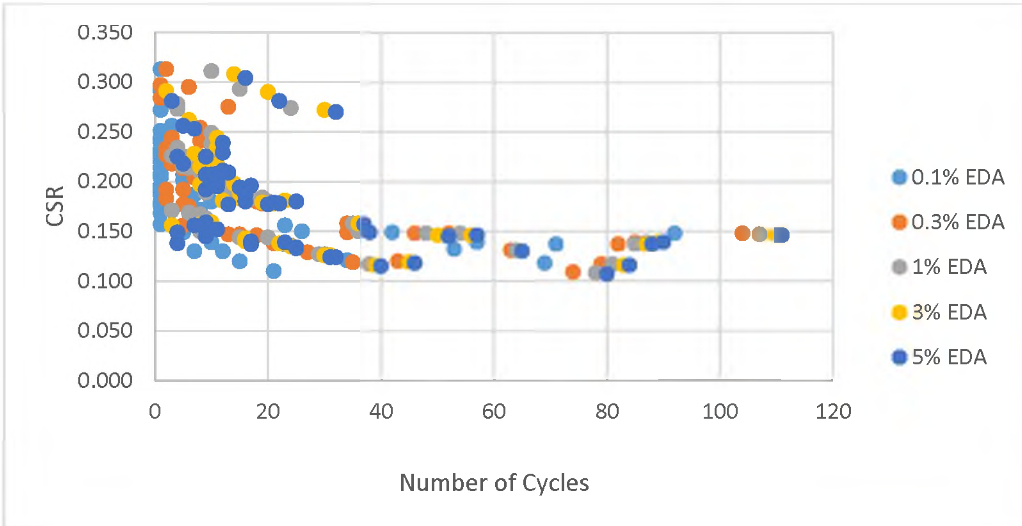

Figure 1. Data from Taylor (2011) Comparing Number of Cycles to Initiate Varying Strains

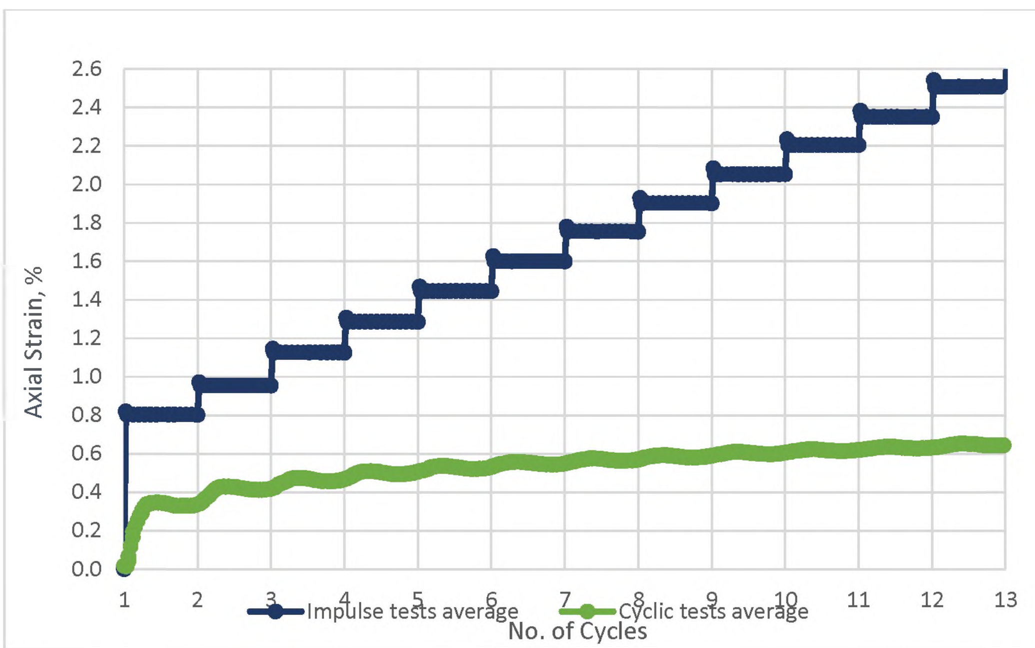

Figure 2. Comparison of Impulse Loading and Uniform 1 Hz Cyclic Loading

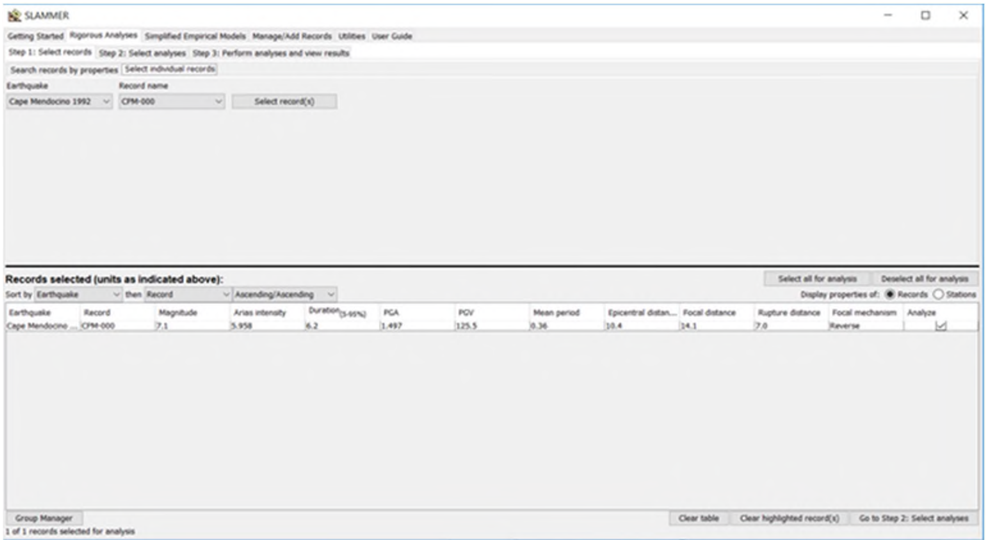

Figure 3. Soil Properties from SLAMMER

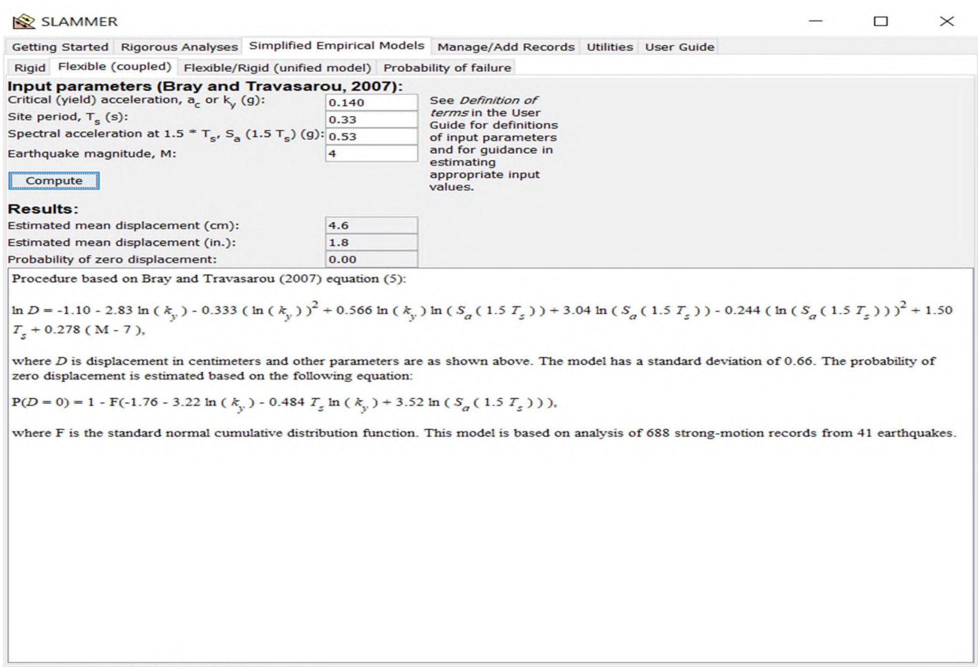

Figure 4. Bray and Travasarou (2007) Displacement Analysis from SLAMMER

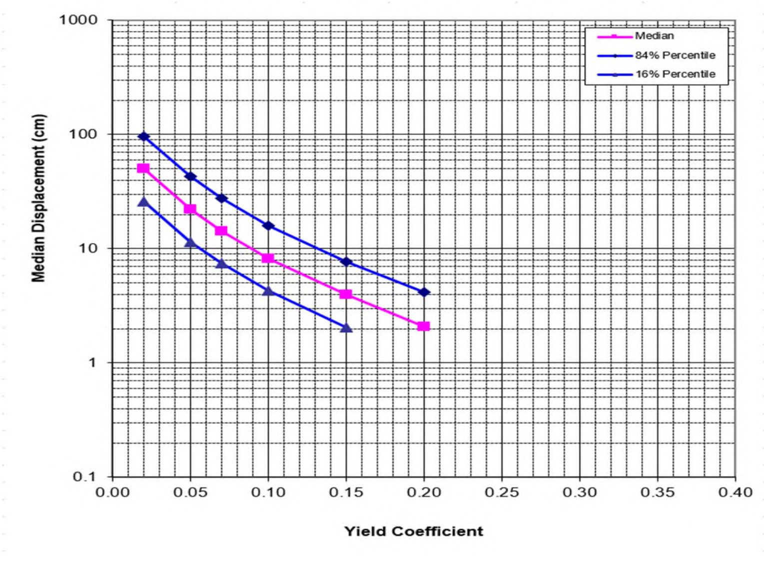

Figure 5. Bray and Travasarou (2007) comparison of displacement to yield coefficient

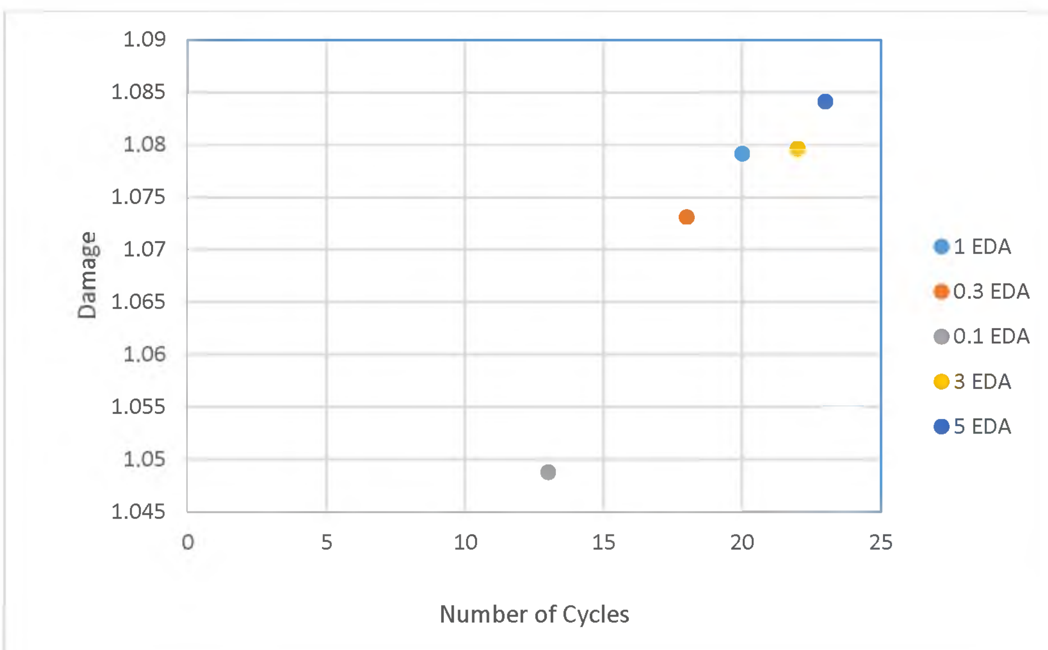

Figure 6. Comparison of change in D to strain

Table 1. Bray and Travasarou Dependence on ky (Bray and Travasarou 2007)

Dependence on ky					
ky	**P(D="0")**	**D (cm)**	**Dmedian (cm)**	**D1 (cm)**	**D3 (cm)**
0.020	0.00	50.1	50.1	96.5	26.0
0.05	0.00	22.2	22.2	42.7	11.5
0.07	0.00	14.3	14.3	27.5	7.4
0.1	0.00	8.3	8.3	15.9	4.3
0.15	0.01	4.0	4.0	7.7	2.0
0.2	0.07	2.2	2.1	4.2	0.9
0.3	0.47	0.9	0.3	1.3	<1
0.4	0.82	0.4	<1	0.2	<1

Table 2. Changes in D

Number of Cycles (N) to failure	ϵda	S	Θ(S)	D
13	0.1	0.147	0.0735	1.048752
18	0.3	0.146	0.073	1.073081
20	1	0.144	0.072	1.079136
22	3	0.138	0.069	1.07964
23	5	0.139	0.0695	1.084126

Table 3. Summary of Cyclic Triaxial Tests Results Taylor (2011)

Test No.	N	CSR	NEC	N	CSR	NEC	N	CSR	NEC	N	CSR	NEC	N	CSR	NEC
		0.1% Eda			0.3% Eda			1% Eda			3% Eda			5% Eda	
CYC-10-56	13	0.147	0.0012	18	0.146	0.0017	20	0.144	0.0019	22	0.138	0.0021	23	0.139	0.0021
CYC-10-57	69	0.118	0.0035	79	0.117	0.0039	81	0.117	0.0040	83	0.116	0.0042	84	0.116	0.0042
CYC-10-58	2	0.175	0.0005	6	0.170	0.0017	7	0.164	0.0022	8	0.157	0.0024	9	0.151	0.0026
CYC-05-10	1	0.193	0.0008	2	0.183	0.0021	3	0.158	0.0041	3	0.158	0.0041	4	0.138	0.0053
CYC-05-11	9	0.150	0.0010	15	0.147	0.0024	16	0.143	0.0037	16	0.143	0.0037	17	0.140	0.0037
CYC-05-12	1	0.179	0.0004	5	0.177	0.0016	6	0.169	0.0027	7	0.156	0.0044	7	0.156	0.0044
CYC-05-13	53	0.132	0.0029	63	0.131	0.0036	64	0.131	0.0040	65	0.130	0.0046	65	0.130	0.0046
CYC-05-14	1	0.195	0.0006	2	0.192	0.0013	3	0.171	0.0033	4	0.149	0.0055	4	0.149	0.0055
CYC-05-16	34	0.121	0.0014	43	0.120	0.0019	45	0.119	0.0022	45	0.119	0.0022	46	0.118	0.0023
CYC-05-32	1	0.176	0.0004	6	0.175	0.0020	8	0.167	0.0032	9	0.159	0.0038	9	0.159	0.0038
CYC-05-33	10	0.139	0.0011	22	0.138	0.0025	24	0.136	0.0031	25	0.134	0.0034	25	0.134	0.0034
CYC-05-34	12	0.130	0.0010	27	0.129	0.0024	29	0.127	0.0028	30	0.126	0.0030	31	0.124	0.0032
CYC-05-35	15	0.120	0.0010	35	0.119	0.0024	38	0.117	0.0028	39	0.116	0.0030	40	0.115	0.0032
CYC-05-36	21	0.110	0.0010	74	0.109	0.0033	78	0.108	0.0037	80	0.107	0.0040	80	0.107	0.0040
CYC-05-43	1	0.157	0.0003	5	0.156	0.0013	8	0.150	0.0026	9	0.145	0.0029	9	0.145	0.0029
CYC-06-19	5	0.149	0.0005	13	0.147	0.0013	15	0.144	0.0015	16	0.140	0.0015	17	0.137	0.0015
CYC-06-20	1	0.168	0.0002	7	0.167	0.0013	9	0.163	0.0018	10	0.159	0.0020	11	0.152	0.0020
CYC-06-21	7	0.130	0.0004	27	0.129	0.0014	30	0.127	0.0016	31	0.126	0.0016	32	0.124	0.0017
CYC-06-28	10	0.139	0.0007	21	0.138	0.0015	23	0.137	0.0017	24	0.135	0.0017	25	0.133	0.0017
CYC_10_82	57	0.139	0.0024	85	0.139	0.0029	87	0.139	0.0031	89	0.139	0.0032	90	0.139	0.0032
CYC_10_68	26	0.150	0.0014	34	0.149	0.0020	36	0.150	0.0023	38	0.149	0.0024	38	0.149	0.0024
CYC_10_63	10	0.180	0.0011	18	0.180	0.0021	20	0.180	0.0026	21	0.179	0.0029	21	0.179	0.0029
CYC_10_60	1	0.208	0.0003	7	0.209	0.0016	9	0.208	0.0023	10	0.207	0.0027	10	0.207	0.0027
CYC_10_66	1	0.228	0.0006	2	0.227	0.0013	3	0.226	0.0026	4	0.225	0.0039	4	0.225	0.0039
CYC_10_101	1	0.297	0.0013	1	0.297	0.0013	2	0.291	0.0052	2	0.291	0.0052	3	0.281	0.0069
CYC_10_59	1	0.207	0.0003	7	0.207	0.0017	9	0.204	0.0025	10	0.200	0.0027	11	0.195	0.0027
CYC_10_79	71	0.137	0.0020	82	0.137	0.0025	85	0.137	0.0027	87	0.137	0.0028	88	0.137	0.0029
CYC_10_67	42	0.149	0.0019	52	0.148	0.0026	54	0.148	0.0028	56	0.146	0.0029	57	0.146	0.0030
CYC_10_70	38	0.149	0.0020	46	0.148	0.0025	48	0.148	0.0028	50	0.146	0.0029	52	0.145	0.0030
CYC_10_88	23	0.166	0.0031	34	0.168	0.0041	35	0.168	0.0044	36	0.168	0.0049	37	0.167	0.0056
CYC_10_53	7	0.187	0.0008	14	0.186	0.0017	17	0.183	0.0021	19	0.179	0.0023	20	0.177	0.0023
CYC_10_89	8	0.172	0.0012	19	0.178	0.0029	20	0.178	0.0032	21	0.178	0.0038	22	0.178	0.0047
CYC_10_52	5	0.207	0.0009	10	0.205	0.0018	12	0.203	0.0023	14	0.198	0.0024	15	0.194	0.0025
CYC_10_51	3	0.225	0.0008	8	0.225	0.0021	10	0.221	0.0029	11	0.217	0.0030	12	0.211	0.0031
CYC_10_99	1	0.225	0.0003	8	0.224	0.0021	10	0.219	0.0029	11	0.214	0.0031	13	0.209	0.0034
CYC_10_54	1	0.244	0.0003	8	0.241	0.0023	10	0.238	0.0030	11	0.234	0.0032	12	0.229	0.0032
CYC_10_100	3	0.256	0.0008	8	0.254	0.0023	10	0.249	0.0032	11	0.244	0.0034	12	0.239	0.0056
CYC_10_98	1	0.251	0.0006	3	0.244	0.0021	4	0.234	0.0029	5	0.218	0.0032	5	0.218	0.0032
CYC_10_95	1	0.284	0.0012	1	0.284	0.0012	4	0.278	0.0035	6	0.262	0.0044	7	0.253	0.0046
CYC_10_97	1	0.291	0.0009	2	0.288	0.0012	4	0.273	0.0038	5	0.256	0.0042	5	0.256	0.0042
CYC_10_71	92	0.148	0.0039	104	0.148	0.0045	107	0.147	0.0046	110	0.146	0.0047	111	0.146	0.0048
CYC_10_62	5	0.201	0.0008	11	0.187	0.0019	13	0.182	0.0022	15	0.183	0.0024	18	0.180	0.0026
CYC_10_65	1	0.230	0.0004	4	0.226	0.0015	6	0.214	0.0022	8	0.197	0.0026	9	0.192	0.0030
CYC-05-49	1	0.186	0.0003	14	0.186	0.0021	19	0.184	0.0031	23	0.181	0.0038	25	0.18	0.0041
CYC-05-48	1	0.204	0.0004	7	0.204	0.0019	10	0.202	0.0029	14	0.198	0.0042	17	0.198	0.005
CYC-05-47	1	0.220	0.0006	3	0.218	0.0018	5	0.215	0.0027	9	0.211	0.0043	11	0.208	0.0049
CYC-05-46	1	0.240	0.0008	2	0.233	0.0014	4	0.233	0.0027	7	0.228	0.0043	9	0.225	0.0051
CYC-06-01	1	0.191	0.0005	5	0.182	0.0017	9	0.189	0.0031	12	0.181	0.004	13	0.177	0.0041
CYC-06-02	1	0.196	0.0002	10	0.195	0.0016	13	0.193	0.0029	15	0.190	0.0036	16	0.186	0.0038
CYC-06-03	1	0.214	0.0004	5	0.213	0.0015	8	0.21	0.0028	10	0.204	0.0037	11	0.199	0.0039
CYC-06-04	1	0.238	0.0005	3	0.232	0.0014	6	0.225	0.0033	8	0.215	0.0042	9	0.207	0.0043
CYC-06-10	1	0.272	0.0004	13	0.275	0.004	24	0.274	0.0087	30	0.272	0.0125	32	0.27	0.0134
CYC-06-11	1	0.313	0.0007	2	0.313	0.0013	10	0.311	0.0071	14	0.308	0.0112	18	0.304	0.0129
CYC-06-12	1	0.294	0.0006	6	0.295	0.003	15	0.293	0.0086	20	0.290	0.0131	22	0.281	0.0146

Table 4. Test Results From Equivalent Cyclic and Impulsive Loading (Taylor et al. 2018)

Specimen	Test Program	Initial Water Content	Posttest Water Content				No. Cycles to
			Top	Middle	Bottom	Average	2.5% ε_a
SP200-I-1	Impulse	5.53%	4.20%	6.24%	7.63%	6.02%	13
SP200-I-2	Impulse	5.51%	4.87%	5.89%	6.83%	5.86%	11
SP200-I-3	Impulse	5.55%	4.77%	5.77%	7.77%	6.10%	16
SP200-I-4	Impulse	5.54%	4.69%	5.85%	9.07%	6.54%	14
SP200-I-5	Impulse	5.56%	4.75%	5.85%	6.92%	5.84%	11
SP200-I-6	Impulse	5.55%	4.37%	5.25%	7.87%	5.83%	15
SP200-I-7	Impulse	5.37%	4.95%	5.89%	7.49%	6.11%	16
SP200-I-8	Impulse	5.59%	4.36%	5.33%	7.25%	5.65%	9
SP200-I-9	Impulse	5.55%	4.86%	5.63%	7.99%	6.16%	10
SP200-I-10	Impulse	5.58%	4.41%	6.56%	8.15%	6.37%	11
Average	**Impulse**	**5.53%**	**4.62%**	**5.83%**	**7.70%**	**6.05%**	**12**
SP200-C-1	Cyclic	5.53%	4.91%	6.17%	6.87%	5.98%	96
SP200-C-2	Cyclic	5.71%	4.14%	5.62%	7.05%	5.60%	n/a
SP200-C-3	Cyclic	5.68%	4.59%	6.19%	7.50%	6.09%	n/a
SP200-C-4	Cyclic	5.48%	4.47%	5.77%	6.87%	5.70%	n/a
SP200-C-5	Cyclic	5.59%	5.54%	8.04%	9.40%	7.66%	n/a
SP200-C-6	Cyclic	5.59%	4.65%	5.17%	6.25%	5.36%	n/a
SP200-C-7	Cyclic	5.58%	4.52%	5.51%	7.35%	5.79%	n/a
SP200-C-8	Cyclic	5.54%	4.38%	5.89%	7.03%	5.77%	n/a
SP200-C-9	Cyclic	5.57%	4.60%	5.07%	7.04%	5.57%	74
SP200-C-10	Cyclic	5.53%	4.63%	4.89%	7.29%	5.60%	63
Average	**Cyclic**	**5.58%**	**4.64%**	**5.83%**	**7.27%**	**5.91%**	**n/a**

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II. SOIL FATIGUE HAZARD SCREENING ANALYSIS 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 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 conducted 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.

1. INTRODUCTION

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 **M**3 or larger. Beginning in 2009, that number increased to 362 per year and peaked in 2015 at 1,010. Since then, the number has slightly declined from 690 to 364 for 2016 and 2017 respectively (Ellsworth 2013; Taylor et al. 2015 a, b; McGarr 2014). However, the number of earthquakes are still high and are ranging from M3.0 to M4.0 (USGS 2018). 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 (Atkinson et al. 2015, Ramsay 2014). Residential damage has been observed within the Central United States, e.g., the 2012 Timpson, Texas sequence (largest event of $M_{W\text{-}RMT}$ 4.8) (Frohlich et al. 2014) and the 2013 Azle, Texas sequence (largest event M3.7) (Malewitz 2014). 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 (USGS

2015a, Associated Press 2015). 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 cracks were generated and existing building cracks were enlarged (Lefler 2014, Bickel 2015, USGS 2015b, Davis 2015). May 2, 2015, an M4.2 event occurred in Michigan with residential and commercial damage, e.g., cracks in walls (Mack 2015, USGS 2015c).

This 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 (Taylor et al. 2018). 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.

2. SEISMIC FATIGUE ANALYSIS

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 (Quinn and Taylor 2014). Quinn and Taylor (2014) 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 (2014) 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 (Taylor 2011, Charlie et al. 2013, Quinn and Taylor 2014, Taylor et al. 2015 a,b, Chamberlayne 2015, Taylor et al. 2018). 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 (Frohlich et al. 2011; Atkinson 2015; Green and Terri 2005; Seed and Idriss 1970). Moreover, geo-engineered induced events occur at rates far in excess of equivalent tectonic counterparts (Taylor 2011; Taylor et al. 2015 a,b; Atkinson 2015). 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. 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.

3. MODIFIED FATIGUE ANALYSIS

Short duration impulse loads are usually defined at less than M4.0 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 Travasarou (2007) examples. Most of the same design parameters were used with the data modified to include earthquake events ranging from M2.5 to M4.0 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 (Jibson et al. 2014) 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 to M4.0, Figure 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 (2007) 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, $N_f(S)$.

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

where the cyclic stress ratio, S, is the applied cyclic shear stress divided by the initial mean effective confining stress and N is the number of elapsed cycles at this stress ratio. However, Eq. 1 is stress-dependent only via the g1 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 Naggar 2007 for full details). Thus, the damage rate varies similarly at each stress level and the Palmgren-Miner rule of superposition (Palmgren 1924; Miner 1945) 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 (2005) 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 (Green and Terri, 2005). 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 Naggar (2007) suggest a stress-dependent formulation of Eq. 1, assuming that the damage rate is variable at different stress levels:

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

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 spacio-temporal variance in the originating source compared with tectonic events where the Palmgren-Miner rule is valid (Taylor et al. 2015 a,b). 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 (Newmark 1964). 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 (Idriss and Boulanger 2008). 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 (see Atkinson et al. 1984; Kramer and Mayfield 2007; Goda et al. 2011; Green and Bommer 2019). As noted in Green and Bommer (2019) 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 (Huang et al. 2017), these motions typically yield a single peak acceleration that will exceed a Newmark threshold for movement. 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 Eq.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 spacio-temporally clustered, occurring within a 5 km radius of the structure of interest (see Taylor et al. 2015 a,b), 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:

$$D = \sum_{i=0}^{n} \left[N_{fn}(S_n)\right]^{\Gamma_n}) \quad (3)$$

where N_{fn} is number of simultaneous impulsive events at the cyclic stress ratio S. This general form is modified from the Allotey and Naggar (2007) 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 Figure 2, wherein the maximum felt intensity ranged from I (low) to VI (moderate) despite a narrow range in clustered event magnitude (M3.5 to 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 (2011) for subsurface subsidence deformations during pile driving activities.

Newmark (1964) 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 $M - \frac{\varepsilon_{lim}}{0.1}$ 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 $\varepsilon_{da} = 5\%$ to $\varepsilon_{da} = 1\%$, 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 Attoley and Naggar equation, Eq. 3, can be reduced to:

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

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

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 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 (Idriss and Boulanger 2010).

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 (Frohlich 2014; Taylor et al. 2015 a,b; Atkinson et al. 2015; Atkinson 2015): M4.0 = 0.45, M3.5 = 0.35, M3.0 = 0.25, M2.5 = 0.15. These are PGA values for epicentral distances of less than 5km 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.

4. 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 Eq. 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 Eq. 4 and 5 for a range of event magnitudes (M2.5 to M4.0 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 2-5.

For the case of M2.5 events, Table 2, irrespective of the threshold strain, the damage quotient never achieves unity, suggesting that M2.5 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 M3.5 and M4.0 respectively. These findings are in agreement with the intensity measurements from the Edmond, OK 20-26 June 2015 swarm which had 10 M>=3.5 earthquakes.

5. DISCUSSION

The displacement identified in the Bray and Travasarou (2007) 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 hours 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 Travasarou (2007) 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, Figure 1. When the same data is incorporated into Eq. 4 and 5, it shows the potential for soil structure degradation and is a representative example for potential settlement from earthquake swarms, Figures 3-6. Specifically, the data generated in Tables 2-5, the first few clustered events did not yield a significant damage potential at any, ε_{da}, 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 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 Eq. 4 and 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 Eq. 4 and 5, at M4.0 corresponding to the SLAMMER sensitivity limit identified from Table 1 and Figure 1, are lower but are within the data variability of Table 1, thus it was determined that Eq. 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 2-5. Therefore, findings from Taylor (2011) 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 $0.3\%\varepsilon_{da}$, which is significantly lower than the ultimate failure threshold of $5\%\varepsilon_{da}$. Additionally, it was observed that 47% of the completed tests reached $0.1\%\varepsilon_{da}$ within the first cycle which suggests that the use of 0.1% as a yield initiation threshold could be overly conservative (Taylor 2011). Further tests identified that the capacity at 0.3%ε_{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 (Taylor 2011). Therefore, a yield initiation, or fatigue, threshold of 0.3% ε_{da} as the maximum allowable fatigue strain for saturated dynamic loading is justified to calculate the mean fatigue damage quotient from Eq. 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 Figures 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 Eq. 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 (< 5km) 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 to 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 Taylor et al. 2015b), the assumption that low-magnitude event are of little to no hazard may not be valid.

6. EFFECTS ON DAMS AND LEVEES

Figure 7 depicts the location of USACE facilities in seismic zones (Chamberlayne 2015). 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 (Chamberlayne 2015). 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.” Engineers also use FEMA regulations given in Code of Federal Regulations (CFR) Title 44, Section 65.10 (44CFR 65.10) when evaluating levees (Quinn and Taylor 2014). 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 (Chamberlayne 2015). 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, 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:

$$Seismic\ Risk = Seismic\ Hazard\ \Theta\ Vulnerability \tag{7}$$

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 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. (Taylor, Lester, & McKenna, 2018)

The data derived from Eq. 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.

7. 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, Eq. 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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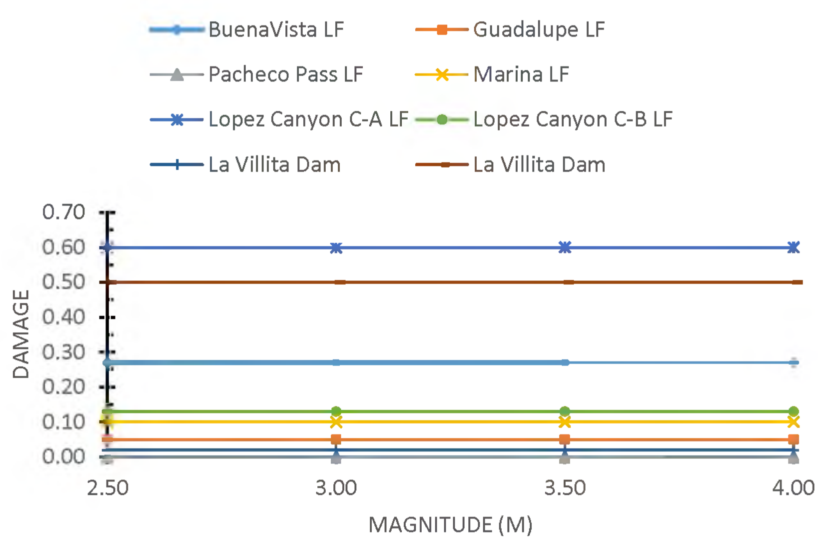
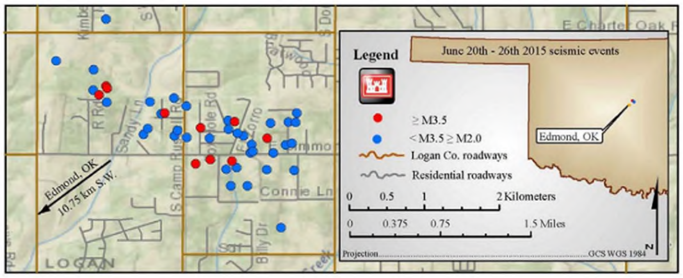


Figure 1. Damage potential from earthquake magnitudes M2.5 to M4.0 via SLAMMER



DYFI	MT	Mag	UTC Date	UTC Time	NOR
V	ML	3.6	6/20/2015	4:29:03	174
V	MW	4	6/20/2015	5:10:54	462
V	MW	3.5	6/20/2015	10:56:03	23
V	MW	3.6	6/20/2015	11:21:16	69
IV	ML	3.7	6/22/2015	4:00:34	56
V	Mwr	3.6	6/22/2015	21:06:30	69
I	MW	3.5	6/22/2015	21:09:27	0
V	MW	3.9	6/22/2015	22:16:20	146
V	MW	3.5	6/26/2015	4:35:56	24
VI	MW	3.7	6/26/2015	5:54:03	49

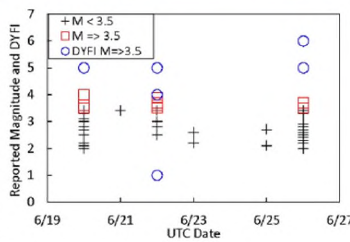


Figure 2. Clustered events in the Edmond, OK area from 20-26 June 2015. The maximum "Did-You-Feel-It" intensity scale (DYFI) is shown as a measure of observed damage for the number of reported cases (NOR)

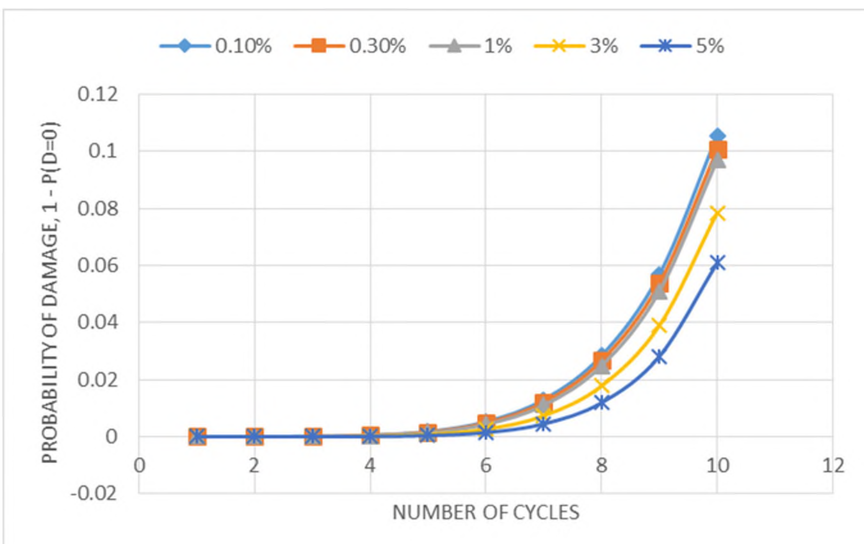


Figure 3. Damage potential from cluster events based on various threshold strains for M2.5 events

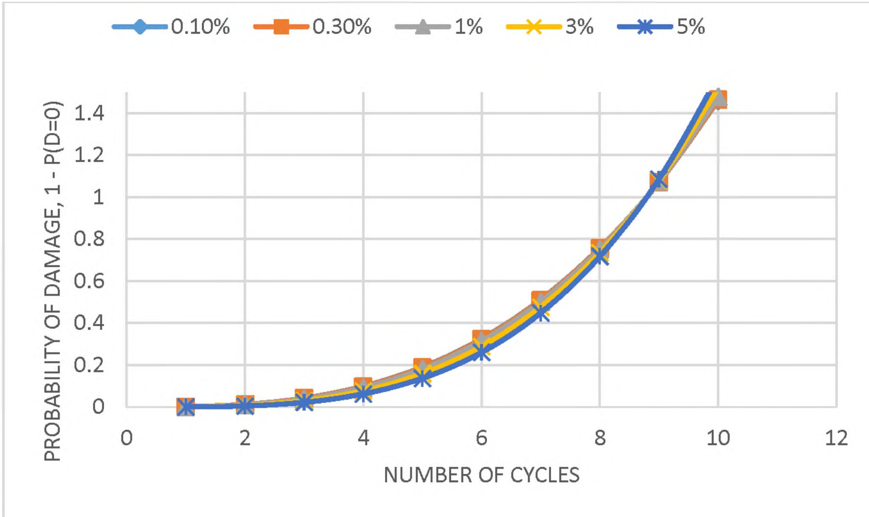


Figure 4. Damage potential from cluster events based on various threshold strains for M3.0 events

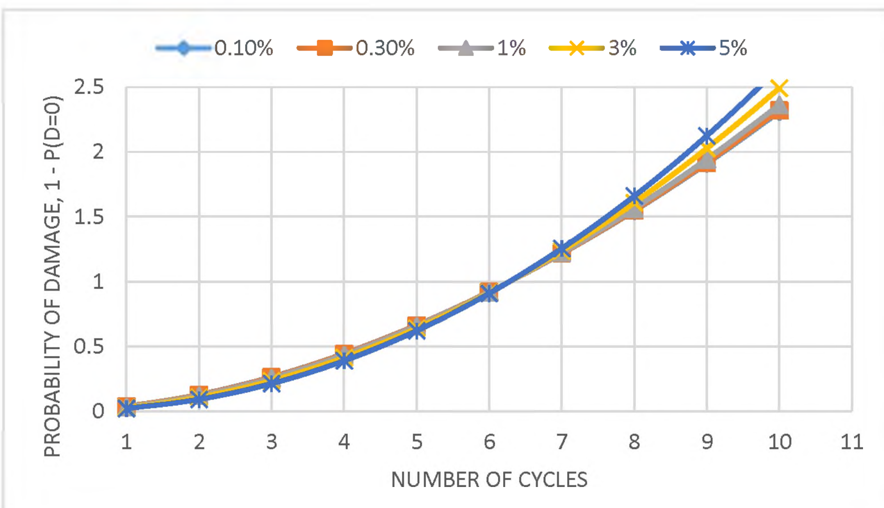


Figure 5. Damage potential from cluster events based on various threshold strains for M3.5 events

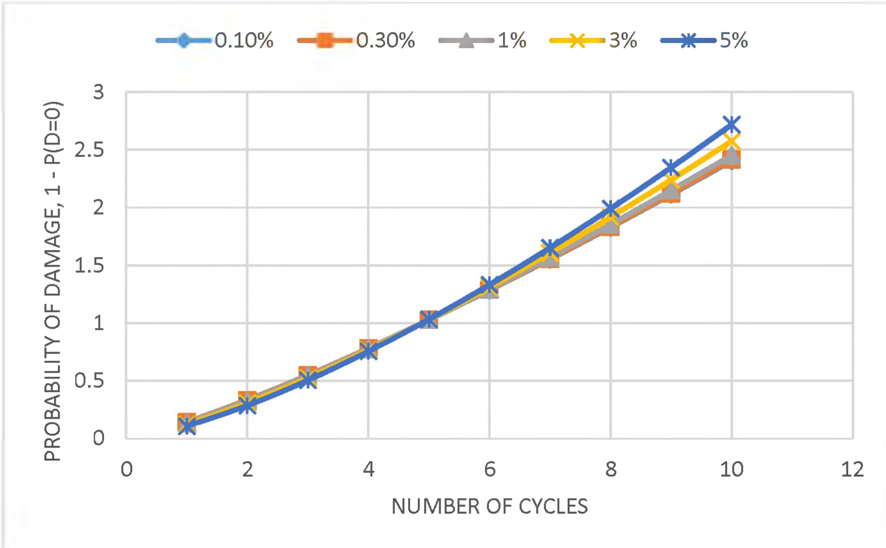


Figure 6. Damage potential from cluster events based on various threshold strains for M4.0 events

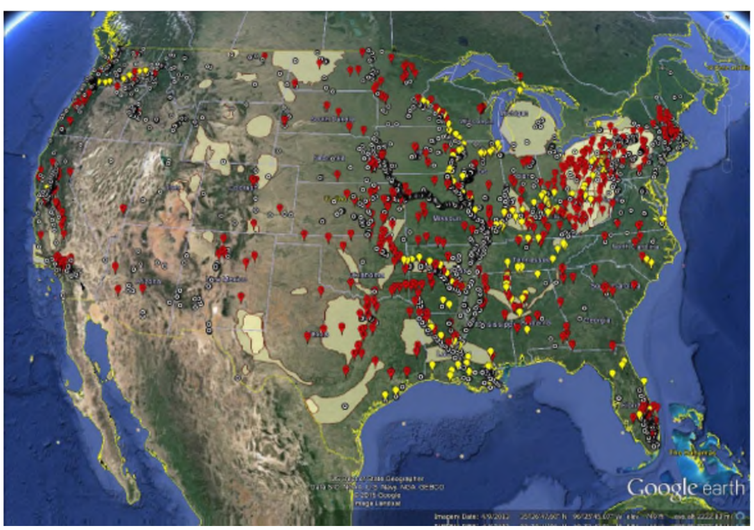


Figure 7. U.S. map of USACE facilities and shale plays (shale plays shown in tan, dams in red, navigation locks in yellow, and levees as white circles) (Chamberlayne 2015).

Table 1. Comparison of Computed Displacement Using SLAMMER Program and Bray and Travasarou (2007) Examples

						Est. disp	
System	***ky[1]***	***T_s (s)[2]***	***Site class[3]***	***Sa(1.5Ts) (g)[4]***	**M[5]**	***P(D =0)[6]***	***1- P(D =0)[7]***
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-B LF	0.35	0.45	Soft rock	0.43	2.50	0.87	0.13
Lopez Canyon C-B LF	0.35	0.45	Soft rock	0.43	3.00	0.87	0.13
Lopez Canyon C-B LF	0.35	0.45	Soft rock	0.43	3.50	0.87	0.13
Lopez Canyon C-B 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
Notes:	*[1] ky = Yield Coefficient*	*[2] T_s (s) = Degraded Period*	*[3] Site Class = Type and Properties of Soils*	*[4] Sa(1.5Ts) (g) = Spectral Acceleration*	*[5] M= Moment Magnitude*	*[6] P(D =0) = Probability of Zero Displacement*	*[7] 1- P(D=0) = 1- Probability of Zero Displacement*

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
3	8.9E-05	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
6	0.00523	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 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 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

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III. UNDERSTANDING THE MULTIPLE SMALL MAGNITUDE INDUCED SEISMIC SOIL FATIGUE POTENTIAL ON HAZARD ASSESSMENTS

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ABSTRACT

The potential damage from human-induced seismic activity is becoming more urgent as the increase in seismic events occur. There are several new studies that focus on shallow induced seismic activity and the effects on infrastructure including innovative ways to quantify that damage. However, these studies neglect to incorporate damage potential from spacio-temporally ed events. Through the comparison of three varying soil profiles and a modified induced seismic fatigue equation, damage potential on infrastructure is identified from these events. This resulting data shows a need to establish new criteria to evaluate infrastructure in proximity to shallow low impact spacio-temporally clustered events.

1. INTRODUCTION

The increase in human-induced seismic activity in the central United States has increased damage potential for buildings, critical infrastructure and can even affect non-structural components of buildings such as chimneys (Liu, T et al 2019, Khosravikia et al. 2018, and Khosravikia et al. 2020). Seismic activity in the central United States, between 1973 and 2008, averaged 25 seismic events that registered at a moment magnitude (Mw) of M3 or larger (Peterson, et al 2016, Ellsworth, 2013, Taylor et al. 2015 a, b; McGarr 2014). After 2008, the number of seismic events increased to 362 per year and then peaked in 2015 at 1,010. These events have slowly declined from 2015, however the number of seismic events with an Mw ranging from M3-M4 are still around 364 (USGS 2018).

As the amount of seismic events is on the rise, so is the need to study impacts on infrastructure in these locations is becoming more prevalent. There are several studies that are ongoing to determine impacts to infrastructure from shallow low impact seismic loads in areas of increased seismic activity (Liu, T et al. 2019, Khosravikia et al. 2018, Khosravikia et al. 2020, Frohlich et al. 2014, Atkinson et al.). There are also a few damage models used for larger events to show potential damage from geo-induced seismic activity. Allotey and Nagger (2007) use a generalized consistent soil fatigue formulation of soils under cyclic loading. In addition to the Allotey and Nagger model, the Seismic Landslide Movement Modeled (SLAMMER) is used to perform a number of sliding-block analyses to identify seismic slope performance. SLAMMER includes various programs for displacement predictions (Jibson et al.). The data used from

SLAMMER in this paper focuses on the Bray and Travasarou simplified method that is based on a fully coupled, equivalent-linear sliding block analysis undergoing ground motions. However, these studies still neglect to account for shallow low impact seismic loads as cluster events.

Soil fatigue is defined as the magnitude of strain that a material can endure for a given number of cycles until point of maximum strain where the soil doesn't function as intended. Similar to fatigue for other engineering structures bridges, roads, etc., it is further defined as losing strength over time without failure which can ultimately lead to a catastrophic failure if left unchecked. This is an important element of engineering because soil fatigue will continue to grow as the amount of applied impact load increases which ultimately leads to failure however is not widely studied. Critical infrastructure life of fatigue prediction is an important element that should be identified and defined prior to failure of the system to ensure the safety of those in its vicinity.

To date, the study of impacts from induced seismicity has been rare with indeterminate conclusions. There are several studies that focus on single seismic event loading (Seed and Idriss 1970; Idriss and Boulanger 2008), in addition to the behavior of partially saturated soils under cyclic loading (Okamura and Soga 2006; Eseller-Bayat et al. 2013). However, there is a lack of definitive data showing the effects on geotechnical structures based on the performance of soil under impulse loading. To better understand the impacts of those small magnitude cluster events to critical infrastructure, an induced seismic fatigue equation is used to identify potential damage associated with these events. Existing risk assessment practices show only larger tectonic events as an adequate representation for smaller human induced engineered seismic events even though there are several differences in shaking durations, frequencies, amplitudes, and focal depths (Frohlich et al. 2011; Atkinson 2015; Green and Terri 2005; Seed and Idriss 1970). Moreover, human induced engineered events occur at rates far in excess of equivalent tectonic counterparts (Taylor O.D.S 2011; Taylor et al. 2015 a,b; Atkinson 2015). These differences show that spacio-temporally clustered induced seismic events have the potential to cause soil fatigue but not ultimate failure which results in unexpected degradation of critical infrastructure.

The United States Army Corps of Engineers (USACE) is responsible for maintaining and operating a large number of dams and levees. It oversees about 14,000 miles of federal levees and about 162 dams in the seismic zone (Quinn & and Taylor, 2014). Figure 5 depicts the location of USACE facilities in seismic zones (Chamberlayne, 2015). Many of these structures are in need of constant repair and is calculated that over 50% of these facilities have exceeded their 50-year service life (Chamberlayne, 2015). The relevance of these critical infrastructure is the intent of existence which is to provide public safety across the nation and any failure could be catastrophic. Current USACE guidance requires critical infrastructure to be at least 3,000 feet from human induced seismic activity to mitigate potential damage (Chamberlayne, 2015). However, these guidelines do not include spacio-temporally clustered induced seismic events that could potentially cause more damage than studies that focus on a single seismic event.

This paper will focus on evaluating small magnitude events based on magnitude and impact to the near surface foundations through the evaluation of three varying soil profiles using a modified fatigue analysis to identify the minimum number of clustered events to exceed a damage threshold for each profile at different magnitudes and fatigue threshold strains. This is to show the potential impacts that could cause fatigue failure in addition to the number of clustered small magnitude events that are required to impact the operational performance of each profile. The goal of this study is to identify critical infrastructure that are most vulnerable to the impact of small clustered events that have the potential to cause fatigue damage although a single event would be of sufficient magnitude to cause a determinate amount of damage. (Taylor et al. 2018).

2. MATERIALS AND METHODS

To investigate the issue of potential damage from cluster events, we looked at idealized structures base on soil profiles from Idriss and Boulanger (2007) and Seismic Landslide Movement Modeled using Earthquake Records (SLAMMER) created for the USGS (Jibson et al. 2014). The results of the SLAMMER program show that the system is not sensitive enough to register varying degrees of damage for low magnitude events such as the M4.0, used in this analysis. Due to the limited sensitivity of SLAMMER at these low magnitudes, a simplified analysis by Idriss and Boulanger (2007) was used to show the damage potential from a single event at M4 and M6.9. M4 is a representation of the smaller magnitudes that could potentially cause damage and M6.9 is the actual loading that was identified during the 1989 earthquake in Loma Prieta. Both of these events were used to ensure consistency in the presented equations. Soil consists of varying degrees of classifications based on locations and were all pulled from the Loma Prieta area with a focus on the earthquake event from 1989. The soil profiles used in this study are listed in Table 1. Soil Classifications are: A – Hard Rock representing a Dam, D – Stiff Soil representing a Levee and E – Soft Clay representing a Fire Station (Idriss and Boulanger, 2007). Most of the same design parameters were used, see Table 1, except earthquake event magnitudes were evaluated at M4.0 and M6.9. These parameters were incorporated into the SLAMMER program, with data pulled from Idriss and Boulanger Liquefaction Triggering Procedures report (2007) as well as into the modified damage potential equation derived from Allotey and Naggar (2007).

To this extent the damage potential equation, Eq. 1, from Allotey and Naggar (2007) was investigated.

$$D = [Ng_1(S)]^{\Theta} \quad (1)$$

where the cyclic stress ratio, S, is the applied cyclic shear stress divided by the initial mean effective confining stress and N is the number of elapsed cycles at this stress ratio. Eq. 1 is stress-dependent only by-way of the g_1 function and Θ is a stress-independent variable (see Allotey and Naggar 2007 for full details). The damage rate shows similar changes each stress level so the Palmgren-Miner rule of superposition (Palmgren 1924; Miner 1945) is assumed logical. Allotey and Naggar (2007) propose a stress-dependent formulation of Eq. 1 that assumes the damage rate changes at different stress levels:

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

Equation 2 would be considered true of induced seismicity where single events of the same magnitude yield different ground-motion characteristics due in part to the spacio-temporal variance generating source compared with tectonic events where the Palmgren-Miner rule is valid (Taylor et al. 2015 a,b). It was further adjusted to include spacio-temporally clustered events:

$$D = \sum_{i=0}^{n} \left[N_{fn}(S_n)\right]^{\Gamma_n} \tag{3}$$

where N_{fn} is number of simultaneous impulsive events at the cyclic stress ratio S. In addition, a variable stress-dependent function,Γ, was incorporated to account for the spacio-temporal cyclic stress ratio along with felt intensity variability of clustered induced seismic events that have similar magnitudes. Newmark (1964) alludes to transitory forces in a series of displacement pulses in lieu of slope failure where it is necessary to identify a seismic coefficient that is a fraction of the largest seismic demand. For this effort, that reduction that is applied to the event magnitude, is found to be $M - \frac{\varepsilon_{lim}}{0.1}$ this is to 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 $\varepsilon_{da} = 5\%$ to $\varepsilon_{da} = 1\%$, 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 Naggar equation, Eq. 3, can be reduced to:

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

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

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 exceedance strain for the structure under consideration for a single event, the cyclic stress ratio, S, is the applied cyclic shear stress divided by the initial mean effective confining stress and N is the number of elapsed cycles at this stress ratio and 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. 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.

3. RESULTS

Based on the results presented in Table 2 and Figure 1, which depict damage potential for stiff soil representing a levee at M4 show the initiation of a linear increase in D, which is defined when the change in rate of D is shown as constant with follow on events, occurs for Ne = 4 suggesting that this is a critical swarm event number for the modeled levee where the soil resistance has reached a critical state or fatigue failure condition. Moreover site specific analysis, Table 3 and Figure 2 representing M4 for Hard Rock with an Earthen Dam identifies that it would yield damage at around Ne = 5. Table 4 and Figure 3, representing M4 event loading on soft clay with the fire station show the potential for damage to be reached at Ne = 7. This data indicates that the cluster events have the potential for damage potential as based on the threshold strain.

The threshold strain is effectively dependent of the interactions between soil and structure. The soil type is as a general screening tool that uses a threshold value of 0.3% to show significant limiting strain at the beginning of movement from seismic activity. This is to say that the structure is contained in the threshold value. So a structure such as the fire station example would not yield significant damage potential in the early stages of cluster events however based on Table 4 it does eventually yield in later cluster events. Also, the earthen dam shows a higher threshold value than the levee and contains a higher number cluster events needed to exceed the damage threshold. Whereas a weaker structure, such as the levee shows damage at a much lower number due to the less stable structure.

4. DISCUSSION

The displacement identified in the Bray and Travasarou (2007) examples and Idriss and Boulanger (2007) are known to be under cyclic loading and therefore would eventually regain stability from the displacement as pore pressures dissipate and the soil stiffens. For this effort, the assumption is that there would be minimal pore pressure dissipation occurs and that characteristics that are similar so that the first order variable is the number of clustered events then followed by the Γ that is based on the magnitude of the event. So, using the hazard screening tool, one would calculate the number of events Ne required for D to exceed unification. When using the Bray and Travasarou (2007) method in SLAMMER to determine damage based on their criteria at M4, Treasure Island on Table 1 has the lowest probability of zero displacement, or damage, at 0 and shows damage potential of up to 6". However when incorporated into the simplified method by Idriss and Boulanger (2007), the potential for damage is less than 1 at 0.6". The earthen dam and levee examples do not render any amount of damage from either from Bray and Travasarou (2007) or Idriss and Boulanger (2007), see Table 1. When the same data is incorporated into Eq. 4 and 5, it shows the potential for damage and settlement from earthquake swarms, Figures 1-3. The data generated in Tables 2-4, the first few clustered events did not yield a significant damage potential at any εda, however the damage quotient continued to increase as the number of clustered events and magnitude increased. For events at M4, the damage quotient exceeds unity for all threshold strains, but it is observed that if εlim is 5%, the results illustrate because the structure has a high strain fatigue tolerance the damage quotient is lower than more sensitive εlim structures. This is what was predicted and provides a logical check for the damage prediction from Eq. 4. The threshold strain is basically dependent of the soil-structure interactions within the screening analysis and the determination of the threshold strain is not trivial.

The soil type is as a general screening tool with the use of a 0.3% threshold value is used to identify significant limiting strain at the beginning of any 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. A shown in Figures 1 and 2, 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 Ne = 4, this would indicate that this is a critical swarm event number for the modeled levee where the soil resistance has reached a critical state or fatigue failure conditions. Through the use of Eq. 4 and 5, a screening measure emplaced to identify the number of spacio-temporally clustered events that can be expected prior to the initiation of fatigue that is within the structure so that fatigue can be identified when the event threshold (Ne) is exceeded. Based on this information, there is a potential for damage to occur on critical infrastructure that are near event epicenters, typically around > 5km. Considering infrastructure in areas with low natural frequencies, a single high frequency peak acceleration would not affect the structure nor would an impulse load. However, when considering impulse forces to induced events, the main effort regarding the potential of damage would come from subsurface yield and not from frequency or cyclic effects (Taylor, et al. 2018). The structure of dams and levees can be compromised as they were built seismic standards that did not consider induced seismic events if induced events cause soil fatigue (Chamberlayne, 2015). This data provided in this paper illustrates the importance of standoff distances in terms of Corps own critical infrastructure.

5. CONCLUSIONS

In recent years, there has been an increase in induced seismicity or induced earthquakes which creates a need to determine if these loads can cause damage especially to critical infrastructure. There are several studies that focus on shallow low impact seismic loads and how they affect infrastructure, however they neglect to incorporate a study that focuses specifically on cluster events. They are also not focused on critical infrastructure such as dams and levees that if damaged can potentially catastrophically fail. These two components need to be studied to ensure these entities are functioning as intended.

The lack of information regarding hazardous effects of short-term impact loads leaves critical infrastructure vulnerable to failure. Damage to critical infrastructure such as dams and levees can lead to larger issues if and when they fail due to the mission these structures support to maintain the safety of those around it. To understand the limits of failure will enable us to verify the level of protection the structure can adequately maintain. The existing process to access damage to dams and levees from induced seismicity is not adequate as it requires a better understanding of the failure modes and threshold limits within the Seismic Hazard and vulnerabilities structures that are not well equipped to survive seismic loading. Moreover, the difficulty in quantifying the Seismic Hazard for induced event continues as the hazard is not completely understood and changes in geo-engineered locations, activities and technologies are constant. As mentioned earlier, the aging dams and levees maintained by USACE lower the exceedance threshold and further complicate the process of defining the vulnerability of the structure. Once the exceedance is lowered within the Seismic Hazard, the increase in fragility within the vulnerability creates a greater Seismic Risk for smaller seismic events. This makes it very difficult to try and define whether a single or multiple induced seismic events cause damage to dams and levees and should be further studies. Recent studies show that geo-engineered induced events do cause damaging degradation to the subsurface and should not be overlooked. (Taylor, Lester, & McKenna, 2018)

Date presented in this study show potential damage on three varying soil types and structures from spacio-temporally clustered small magnitude events. The damage may not be seen initially however can lead to catastrophic failure if left unchecked. It further illustrates that spacio-temporally clustered small magnitude events create a need to establish new guidelines for evaluation of structures under seismic loading. Furthermore, the need to establish guidelines defining the proximity of induced events to critical infrastructure. This lack of oversight lends to additional seismicity or the creation of seismicity in areas that did not exist. As these events increase the life span of critical infrastructure in these areas can decrease and potentially fail over time. Existing evaluations to not incorporate damage potential on the subsurface from induced seismic events which can compromise the foundation of critical infrastructure from settlement and lead to catastrophic failure.

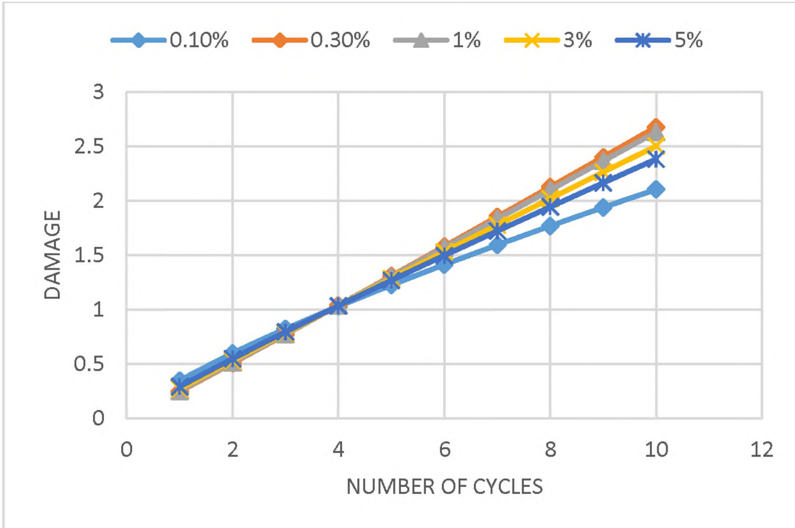

Figure 1. Damage Potential from Cluster Events Based on Various Threshold Strains for M=4 Seismic Events – Levee

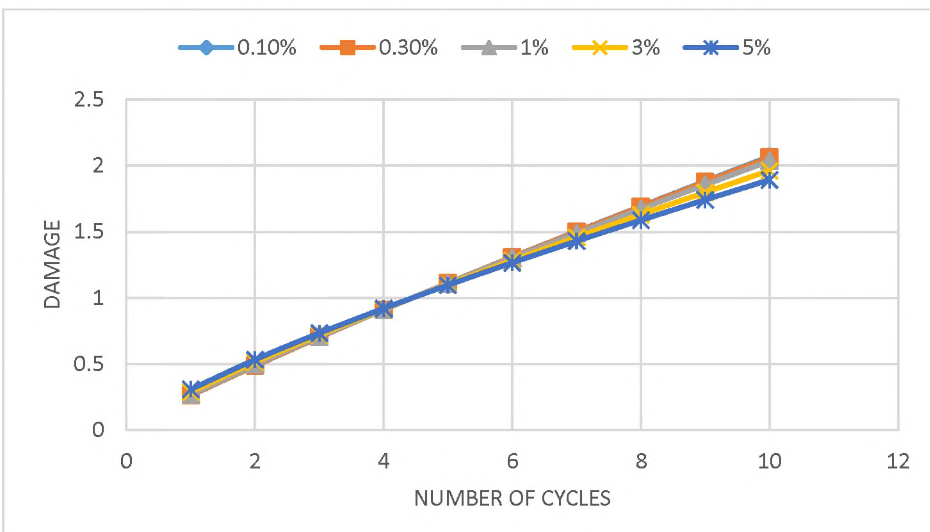

Figure 2. Damage Potential from Cluster Events Based on Various Threshold Strains for M=4 Seismic Events – Earthen Dam

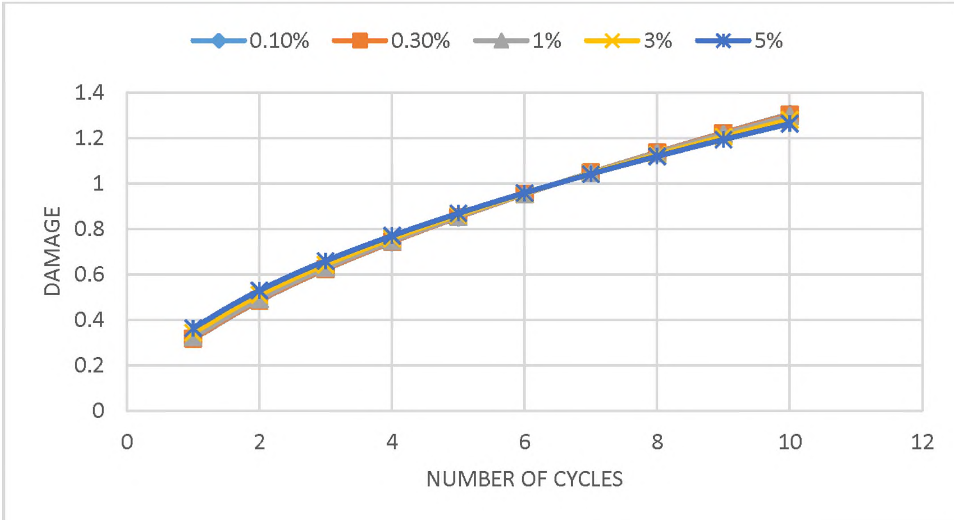

Figure 3. Damage Potential from Cluster Events Based on Various Threshold Strains for M=4 Seismic Events – Fire Station

Table 1. Deterministic Liquefaction Triggering using Boulanger & Idriss (2008)/SLAMMER

System	k_y	T_s(s)	Site class	Sa(1.5 Ts) (g)	σ_{vc}	σ'_{vc}	a_{max}	rd	(N1)60	CSR	K	CRR	PGA	Bray and Travasarou M6.9	Bray and Travasarou M4	Idriss and Boulanger M6.9	Idriss and Boulanger M4
Anderson Dam Loma Prieta	0.20	0.64	Rock	0.21	129.00	112.00	0.33	0.91	6.9	0.225	0.99	0.097569901	0.077	0.3	0	0.417050367	0.173184726
Hollister City Hall Loma Prieta	0.26	0.59	Stiff Soil	0.36	204.00	120.00	0.28	0.84	9.1	0.26	0.98	0.111888829	0.21	0.6	0.3	0.422363888	0.175391224
Treasure Island Fire Station	0.14	0.33	Soft Clay	0.94	93.00	59.00	0.16	0.94	6.4	0.155	1.05	0.094473853	0.159	13.4	6	0.52110697	0.216395369

Table 2. Changes in D for various threshold strains as a function of clustered events for M=4 seismic events – Levee

Number of cluster events	Damage Quotient, D, for Levee for various threshold strains as a function of clustered events (M4) [Eq. 1]				
	0.10%	0.30%	1%	3%	5%
1	0.34972	0.249	0.25518	0.27369	0.29355
2	0.60039	0.50909	0.51519	0.53301	0.55145
3	0.82363	0.77354	0.77705	0.78717	0.79742
4	1.03073	1.04087	1.04013	1.03804	1.03594
5	1.22661	1.31035	1.30412	1.28648	1.26908
6	1.41397	1.58155	1.56882	1.53301	1.49801
7	1.59455	1.85421	1.83413	1.77796	1.7235
8	1.76952	2.12811	2.09996	2.02156	1.94609
9	1.93971	2.40311	2.36624	2.264	2.16618
10	2.10579	2.67908	2.63293	2.5054	2.38406

Table 3. Changes in D for various threshold strains as a function of clustered events for M=4 seismic events – Earthen Dam

Number of cluster events	Damage Quotient, D, for Earthen Dam for various threshold strains as a function of clustered events (M4) [Eq. 1]				
	0.10%	0.30%	1%	3%	5%
1	0.26216	0.26129	0.2702	0.28896	0.30901
2	0.48821	0.48734	0.49617	0.51433	0.53315
3	0.70238	0.70176	0.708	0.72065	0.73352
4	0.90917	0.90896	0.91113	0.91549	0.91987
5	1.11065	1.11095	1.10803	1.10222	1.09643
6	1.308	1.30888	1.3001	1.28272	1.26557
7	1.50197	1.50351	1.48826	1.45822	1.42878
8	1.6931	1.69534	1.67311	1.62953	1.58708
9	1.88178	1.88477	1.85514	1.79727	1.74121
10	2.06831	2.07208	2.03468	1.9619	1.89172

Table 4. Changes in D for various threshold strains as a function of clustered events for M=4 seismic events - Fire Station

Number of cluster events	Damage Quotient, D, for a Fire Station for various threshold strains as a function of clustered events (M4)[Eq. 1]				
	0.10%	0.30%	1%	3%	5%
1	0.31668	0.31851	0.325	0.34428	0.36471
2	0.48496	0.48672	0.49294	0.51115	0.53003
3	0.62226	0.62374	0.62896	0.64409	0.65959
4	0.74266	0.74377	0.74766	0.7589	0.7703
5	0.85188	0.85256	0.85496	0.86186	0.86881
6	0.95293	0.95316	0.95397	0.95627	0.95859
7	1.04766	1.04742	1.04656	1.04413	1.04169
8	1.13731	1.13658	1.13401	1.12672	1.11948
9	1.22273	1.22149	1.21719	1.20499	1.1929
10	1.30456	1.30282	1.29676	1.27959	1.26265

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SECTION

3. CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

As human-induced seismic events increase, the need to study the potential for damage on infrastructure increases. Current studies are emerging that are now focusing their efforts on shallow low impact seismic events. However, this paper explains that it should be taken a step further so as to investigate these seismic events as small magnitude cluster events.

Paper I discusses soil fatigue from human-induced seismic activity and the need to study these events as small cluster events. The effects on civil engineering systems from induced seismicity is not well known, specifically soil fatigue. Soil fatigue is of concern in that natural conditions of the subsurface in addition to operational parameters under small impact loads are not well known. As human-induced seismic activity increases the need to reassess foundations that are affected by the increased seismic loading becomes more prevalent, especially in aseismic zones. The lack of specific data focused on these areas puts the reliability of the civil engineering system at risk of failure. Therefore, I created a new damage equation from the Allotey and Naggar (2007) model. It was modified to observe impulse loads vs cyclic loads as well as included a nonlinear function with loading cycles with a stress dependent variable for confining and applies stress. This modified equation provides a better understanding of potential damage from soils at near surface that are under impulse loading. Paper II focuses on establishing a new hazard screening tool to determine potential damage from cluster events. Although new studies focus on human-induced seismic activity, they are only looking at damage from a single induced seismic event. The amplitude and duration of a single induced seismic event would not be significant enough to cause damage as displacement under cyclic loading would eventually regain stability as the soil stiffens and pore pressure dissipates. However, the potential of spacio-temporally clustered small magnitude events to cause damage on infrastructure exists as determined in presented modified induced seismic fatigue equation (Paper II, Eq. 4 and 5). In contrast to a single induced seismic event, cluster events would not allow for the soil to rest long enough to regain the original strength and could potentially lead to failure. This tool it will allow for an additional assessment of seismicity of short duration swarm events that have the potential of causing fatigue damage to critical infrastructure. Paper III discusses the potential damage on three varying soil types and structures from spacio-temporally clustered small magnitude events. The soil data was placed into the modified induced seismic fatigue equation (Paper II, Eq. 4 and 5) showed the potential for damage on infrastructure from spacio-temporally clustered small magnitude events. The damage may not initially be seen but can lead to catastrophic failure if not assessed properly.

3.2 RECOMMENDATIONS

The increase in human-induced seismic activity is creating a push for studies that focus on short duration impulse loads. However, these studies neglect to include potential effects on civil engineering systems. One potential damaging effect is soil fatigue which is the gradual weakening of material due to external sources of the system that act upon the reliability of the system. As determine in the reformulation of the equation, a better depiction of potential damage effects to soils near the surface under impulse loading can be generated. Current evaluation standards and assessments should include a determination of damage from impulse loading at shallow depths to identify potential damage of the foundation prior to failure. Furthermore, the limitation of the Allotey and Naggar (2007) model to identify soil degradation from induced events based on cyclic loading needs to be addressed.

As identified in this paper, spacio-temporally clustered small magnitude events still have the potential to cause fatigue although single events at the same magnitude would not register damage. The presented modified induced seismic fatigue equation (Paper II, Eq. 4 and 5) allows for additional assessments of seismicity of short duration swarm events. Damage to critical infrastructure have the potential of leading to larger issues. In an effort better assess critical infrastructure, the use of the modified induced seismic fatigue equation will allow for a better understanding of the limits of failure to ensure the level of protection the structure can actively provide. Further studies are needed on this topic to ensure these structures function as designed.

The data presented in this paper regarding spacio-temporally clustered small magnitude events show a need to establish new guidelines to evaluate structures that are under seismic loading. In addition, there is a need to establish guidelines that clearly defines the proximity of induced events to critical infrastructure. Due to the lack oversight, the creation of seismicity in aseismic zones is increasing as well as potential damage that could decrease the life span of critical infrastructure

VITA

Merissa Zuzulock was an Army Engineer Officer serving in Afghanistan when she started her Master's Degree in Engineering of Geotechnics at Missouri University of Science and Technology. In 2011, she received her Technical or Occupational Certificate in Geological Engineering followed by her Masters of Engineering in Geotechnical Engineering in 2012. In 2015, she enrolled as a doctoral student at Missouri University of Science and Technology.

After leaving the U.S. Army, Merissa worked as a Project Engineer with the U.S. Army Corps of Engineers (USACE). Through the support by the Engineering Research and Design Center, USACE, she was able to begin research on the effects of short duration impulse loads on federal infrastructure. In 2019, she co-authored her first published article directly associated with lab work conducted in the soils laboratory that focused on the soil fatigue, titled "Dynamic failure Potential of Partially Saturated Sand under Ultra-Low Confining Pressures". In 2020, she co-authored her second article which was accepted to be published from the Journal of Advances in Civil Engineering titled, "Soil Fatigue from Induced Seismicity". Her second co-authored article is under review at the Journal of SN Applied Sciences, titled "Hazard screening analyses of induced seismicity as multiple impulsive loads versus single events with respect to damage potential". A third co-authored article titled, "Understanding the Multiple Small Magnitude Induced Seismic Soil Fatigue Potential on Hazard Assessments", has been submitted for publication. In August 2020, she received her PhD degree in Geological Engineering from Missouri University of Science and Technology.