Typically, a safety factor of 1.4 is required for the stability analyses for most levee design. However, when the acceleration coefficient increases to 0.1, the factor of safety is decreased to 1.09, and the probability of failure is increased to more than 20%, which is considered as a very high probability of failure for a levee design. The derived probability of failure from the probabilistic assessment combined with the deterministic analyses can provide valuable references for engineers to make a risk-informed decision for seismic analyses and design of the earthen levees.

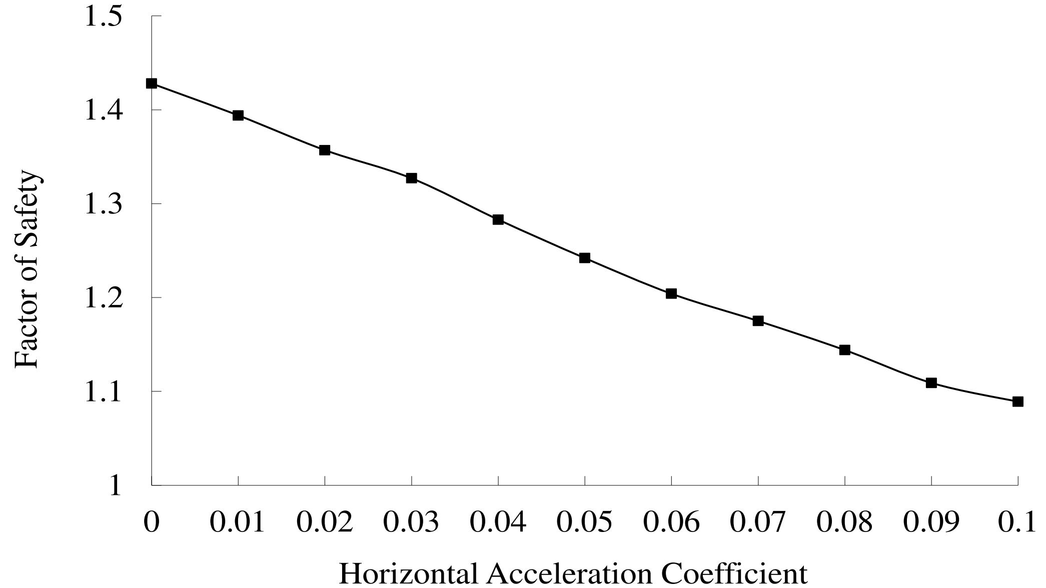

Figure 2. Resulting factor of safety with the horizontal acceleration coefficient from deterministic analyses.

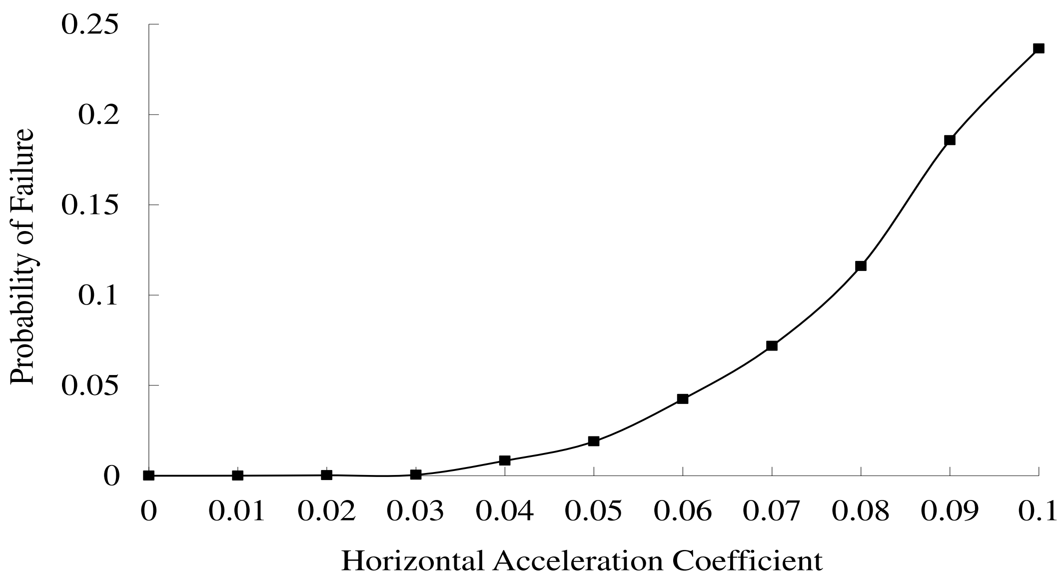

Figure 3. Resulting probability of failure with the horizontal acceleration coefficient from probabilistic analyses.

CONCLUSION

This paper presents a simplified method for probabilistic seismic assessment of earthen levees in the face of uncertainties. Within this framework, the uncertainties are propagated by considering the uncertain geotechnical parameters as the input and the resulting factor of safety as the system response. The pseudo-static method is adopted to evaluate the stability of earthen levee under earthquake loads. The factor of safety for a given level of horizontal acceleration coefficient is determined using the strength reduction method and finite element analyses. A case study for earthen levee safety evaluation is employed to demonstrate the effectiveness and efficiency of the proposed framework. Both the deterministic and probabilistic analyses are carried out to determine the factor of safety and probability of failure at various acceleration levels. The results showed that the factor of safety decreases approximately linearly with the earthquake hazards. For the same horizontal acceleration coefficient levels, the corresponding probability of failure is also obtained, which can be used to evaluate the fragility of levee with respect to earthquake loads. The results can provide useful references that allow engineers to make more informed decisions in the face of earthquake loads.

ACKNOWLEDGEMENTS

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Slope Failures in North Dakota: Influence of Geology, Topography, and Salt Concentration in Pore Fluid

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ABSTRACT

Although located in the Great Plains, over 24,000 slope failures have been observed in North Dakota. These failures present a number of issues including blocking roads, damaging pavements, and posing numerous safety concerns. A geospatial database of these slope failures is presented in this study. The database is used to examine the geologic, topographic, and pore fluid salinity patterns at these slope failures. The majority of slope failures occur in the Sentinel Butte Formation, which primarily covers the western part of the state. McKenzie and Billings Counties contained the largest number of slope failures accounting for 21% and 14%, respectively, of the total. Approximately 6% of the slope failures have areas larger than 100,000 m^2, nearly 23% have areas between 2,100 and 6,100 m^2, and 0.1% have areas less than 100 m^2. Slope failures appear to concentrate in relatively gentle slopes with inclinations between 8° and 12°. Additionally, the majority of the failures were in soils with low salt concentrations in the pore fluid, which is notable since the presence of high salt concentrations in soils is considered nearly ubiquitous across most of North Dakota.

INTRODUCTION

Mass movements that include landslides, debris flows, rock falls, etc. are among the most devastating natural disasters. They result in billions of dollars of damage affecting millions of people each year (EMDAT 2020). For example, in 2017, 25 significant mass movements were reported around the world. Significant mass movements are those that (a) resulted in 10 or more deaths, (b) affected at least 100 people, (c) caused a declaration of a state of emergency, and/or (d) triggered a call for international assistance (EMDAT 2020). These mass movements resulted in over $6 million in damages affecting nearly 200,000 people (EMDAT 2020).

In the United States, slope failures are not usually expected in the Great Plains. However, in this study, the authors examined the landslides recorded across the State of North Dakota finding that over 24,000 slope failures had occurred. Presented within this paper are details of the landslide distribution across the state. The influence of geology, topography, soil salinity and other factors on these slope failures is also examined in this study.

STUDY AREA

The State of North Dakota is located in the Upper Midwest of the United States. As the nineteenth largest state in the country, North Dakota encompasses an area of 183,843 km^2, which was studied in its entirety as part of this investigation. The state can be divided into three regions – the western, central and eastern regions. The Great Plains and the northern part of the Badlands form the western region. The central region consists of the Drift Prairie and the Missouri Plateau. The Red River Valley primarily forms the eastern part of the state. In other words, significant hills and buttes form the topography in western North Dakota, while eastern North Dakota is one of the flattest glacial lake plains in the world. The elevation of the state ranges from approximately 230 m in the east to 1069 m in the west.

North Dakota has a continental climate that varies widely across seasons. The state experiences four distinct seasons that include cold winters and warm to hot summers. Temperatures in the winters can reach as low as -51°C, while summer temperatures can reach as high as 49°C (NOAA 2020). From 1981 to 2010, the state average annual precipitation ranged from 350 mm to 585 mm, while the average annual snowfall ranged from 45 to 51 cm (NOAA 2020).

North Dakota has a relatively simple geology with strata that is near horizontal or at a gentle dip. Little change has resulted from metamorphism. However, the eastern border of the state has some deeply buried granite, while there have been no intrusions or extrusions of igneous materials. Rocks, including shales and sandstones, primarily from the Cretaceous and Tertiary periods underlay the state. Drift deposits from the Pleistocene era overlay these rocks (Leonard 1919).

METHODS

Maps of slope failures that occurred in North Dakota have been prepared by the North Dakota Geological Survey (NDGS 2020). The maps are prepared at a 1:24,000 scale and focus on the western part of the state, where topographical characteristics increases the likelihood of landslide occurrence. These maps do not provide a complete picture of the slope failures in the state as some regions have not been mapped yet. Particularly, mapping in the southern half of the central region and northeastern parts of the state have not, yet, been undertaken. Despite this, the database provides an accurate representation of the slope failures in North Dakota since mapping efforts have focused in areas with the greatest number of failures.

The original database was created from photos taken by low-flying aircrafts in the 1930s by the US Department of Agriculture. Digital aerial orthophotography from the USDA's National Agriculture Imagery Program was used to improve the resolution of the mapping. The most recent additions to the landslide mapping database has been made using satellite imagery from Google Earth (Moxness 2019). More detailed mapping of landslides near developed areas was undertaken by the North Dakota Geological Survey using unmanned aerial vehicles (Anderson and Maike 2017). From the North Dakota Geological Survey landslide maps, a total of 24,123 landslides were identified. The characteristics of these landslides will be provided in this paper.

LANDSLIDE DISTRIBUTIONS

Distribution across Counties: North Dakota has a total of 53 counties. Figure 1 presents a map of North Dakota showing the county boundaries and the location of each recorded slope failure examined in this study. Based on the current database, no slope failures were observed in ten of these counties. These are the Eddy, Foster, Kidder, Nelson, Pierce, Ramsey, Sargent, Sheridan, Traill, and Wells Counties. Except for Sheridan and Wells Counties, the remaining eight counties are primarily located in regions in which slope failures have not yet been mapped. The four counties with less than five slope failures included Benson (1), Bottineau (1), Towner (1) and LaMoure (2) Counties, where the numbers in parenthesis indicate the number of landslides in that county. The distribution of slope failures in the remaining counties is shown in Figure 2. From Figure 2, it can be seen that the majority of the slope failures occurred in McKenzie County with approximately 21% of the total landslides in North Dakota, followed by Billings County with approximately 14% of the failures.

Size distribution of Landslides: The distribution of slope failures with area of the landslide is shown in Figure 3. In Figure 3, the horizontal axis represents the upper bound of the bins. In other words, for the bin labeled 2100 m^2 represents the landslides with areas greater than 100 m^2 and less than or equal to 2100 m^2. The areas in this figure correspond to the area of the polygon outlining the landslide in ArcGIS. There were 25 slope failures (0.1% of the total) less than 100 m^2, which can be considered as small landslides. These landslides with areas less than 100 m^2 will not pose any threats to rivers, roads, or other infrastructure. There were nearly 1500 landslides (6% of the total) that were larger than 100,100 m^2 in area. Landslides with areas between 2100 m^2 to 6100 m^2 account for nearly 23% of the slope failures in the state. As seen from the figure, smaller landslides are more frequently observed than larger landslides.

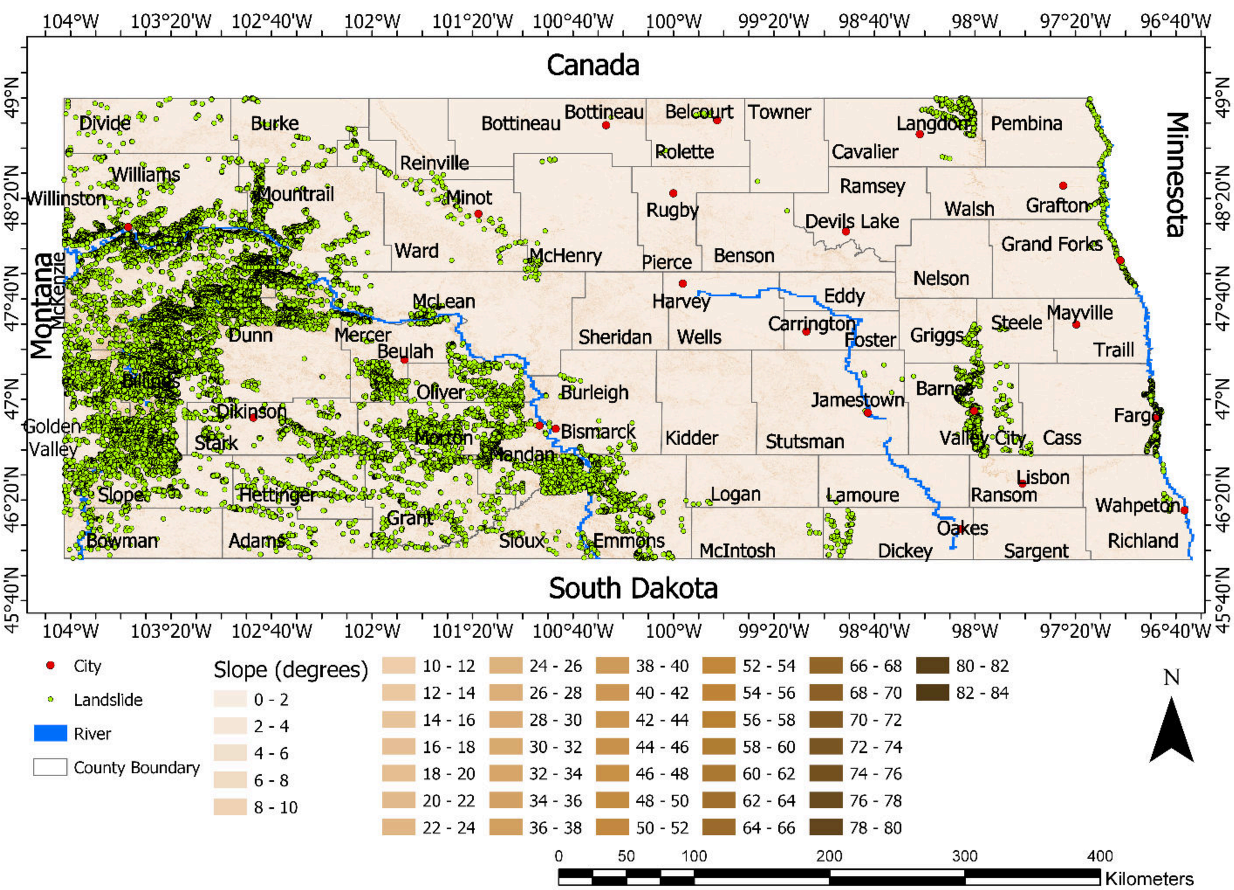

Figure 1. Slope Map of North Dakota Showing County Boundaries and Distribution of Slope Failures.

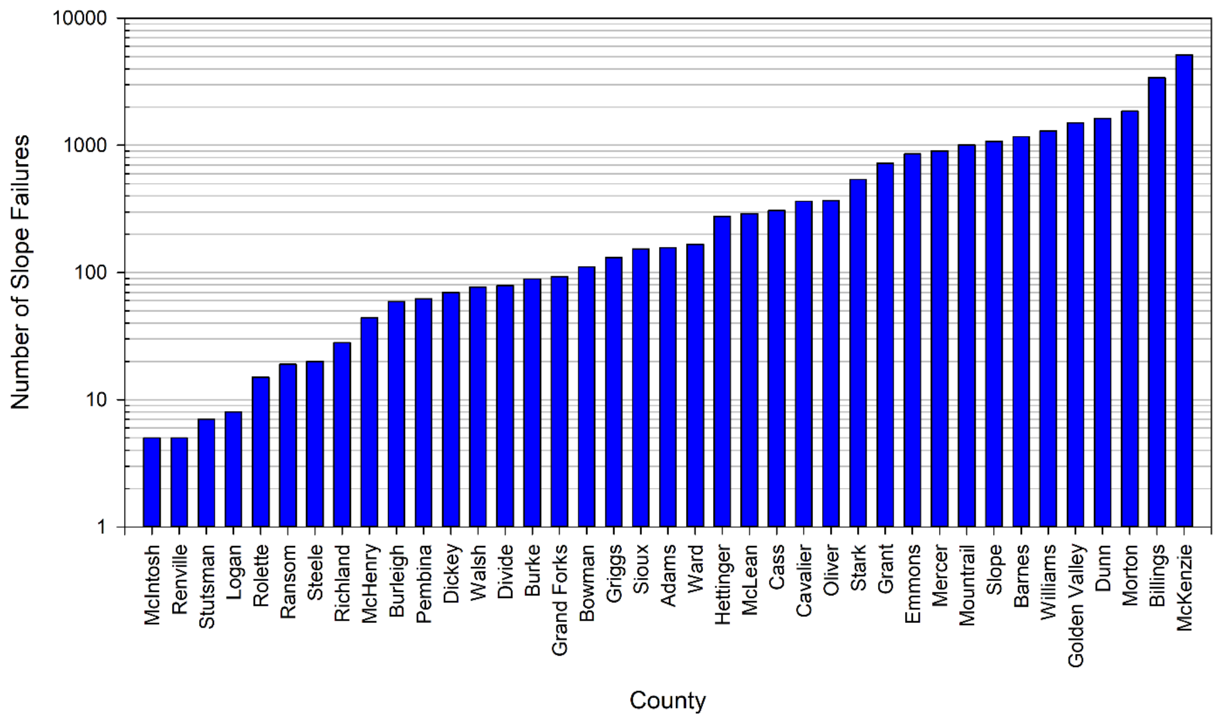

Figure 2. Distribution of Slope Failures in North Dakota Counties.

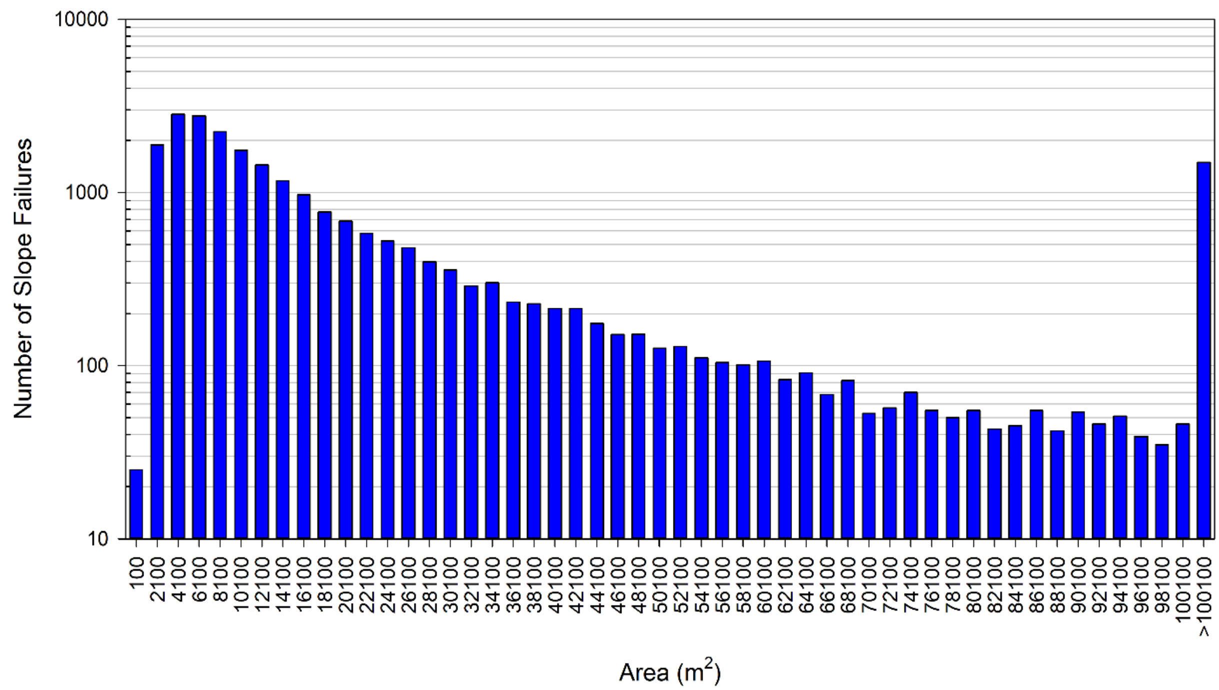

Figure 3. Distribution of Slope Failures with Area. Horizontal axis represents the upper bound value of the bin.

Geological Distribution: Figure 4 contains a geological map of North Dakota. Included in the figure are the locations of the landslides that were studied in this paper. Shown in Figure 5 is the distribution of the number of slope failures relative to the geological formation. As seen, from Figure 5, the majority of the slope failures, specifically 51%, occur in the Sentinel Butte Formation. Figure 4 reveals that the Sentinel Butte Formation is widely found in the western North Dakota, which corresponds to locations of the majority of slope failures observed. The second largest number of slope failures occur in the Bullion Creek Formation. Approximately an additional 24% of the slope failures are in this formation, which is also widely distributed in the western part of the state.

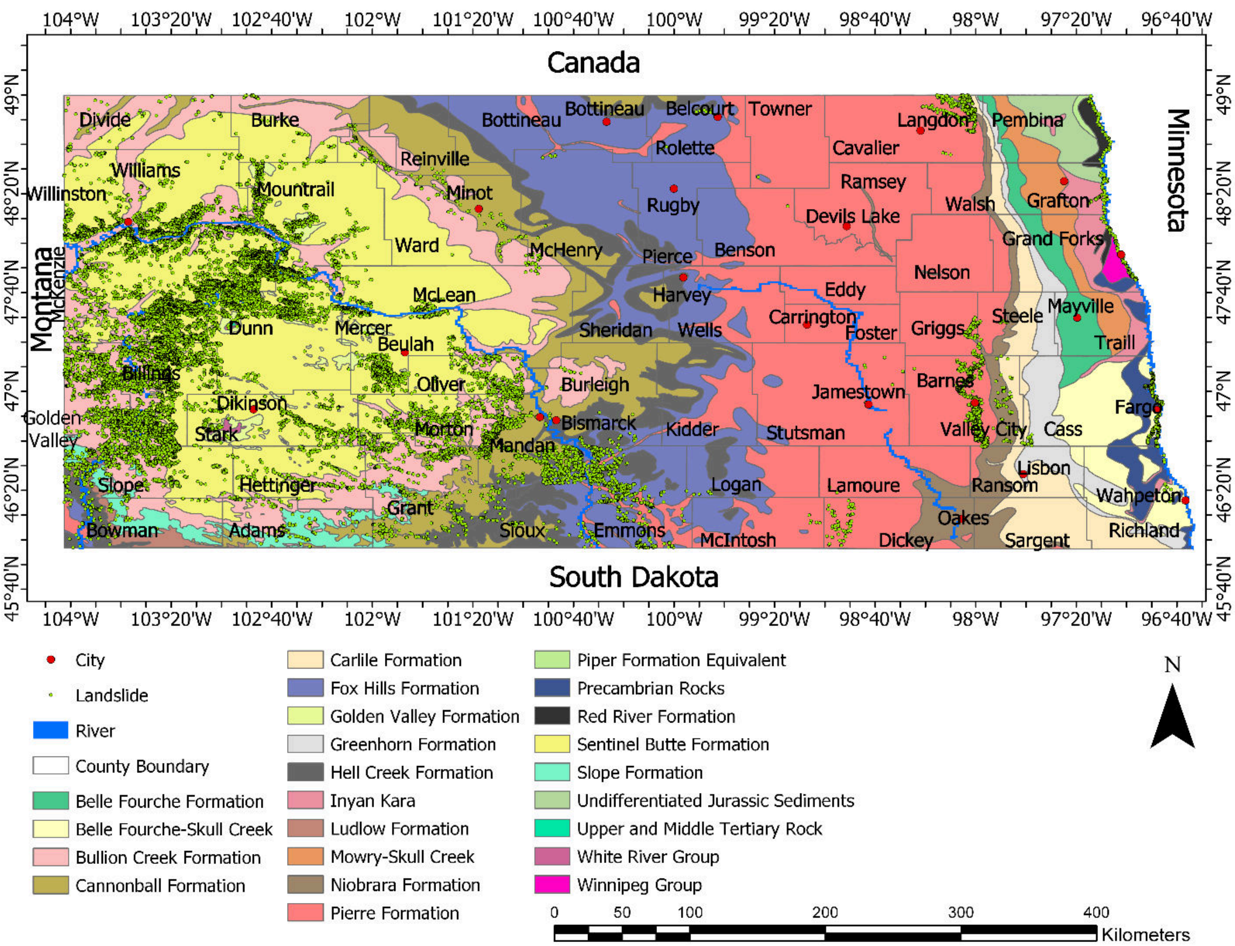

Figure 4. Geological Map of North Dakota with the Locations of the Slope Failures. Geological base map was obtained from USGS (2020).

Distribution with Slope Inclination: A slope map showing the recorded landslides is provided in Figure 1. The distribution of the landslides with slope inclination is shown in Figure 6. As seen from Figure 6, approximately 13.4% of the landslides occur in regions with slope inclinations between 8° and 10°. Slopes with inclinations between 10° and 12° contain the second largest number of failures accounting for approximately 13.3% of the landslides. An understanding of the mechanisms and causes for these failures on such shallow slopes is beyond the scope of this paper.

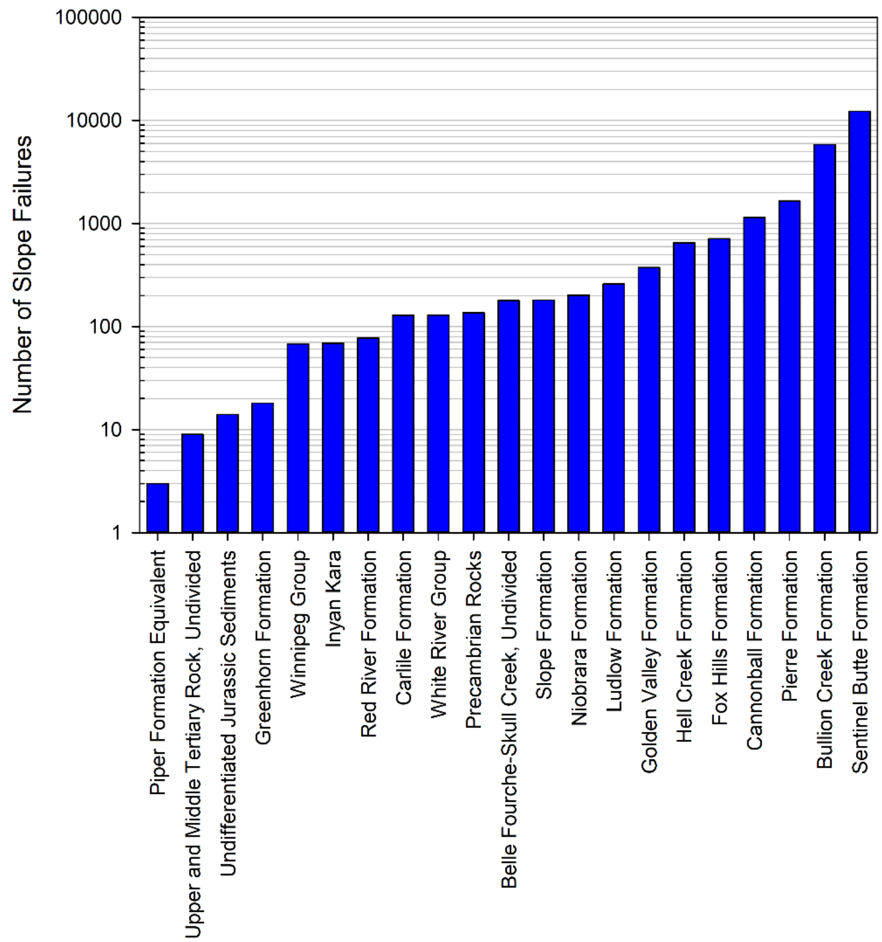

Figure 5. Distribution of Landslides in Geological Formations.

Landslide Distribution based Concentration of Pore Fluid Salinity: Natural soil salinity levels in North Dakota soils are known to range from 2 mmolc/L to 260 mmolc/L. However, for most soils the salinity will range from 2 mmolc/L to 80 mmolc/L. Average values cannot be reasonably provided as the salinity levels will fluctuate with annual weather variations. The soil salinity is also a function of the geological formations, particularly those with shales or layers that are underlain by shales. The salinity in ND is derived from the geologic formations and not from other sources such as oceanic spray (e.g., Australia). However, subsurface water flows are well known to transport salts along the interface of geologic beds to form saline seeps where those beds are dissected by the surface. Therefore, salinity may be present for a particular formation or if water flows have translocated salts via seeps and underground flow paths.

The salinity was estimated from the electrical conductivity of the pore fluid and sodium adsorption ratio at the location of the slope failures. Maps from the Soil Survey Geographic Database (SSURGO) containing each of these parameters prepared by the National Cooperative Soil Survey were used in this study. The electrical conductivity was converted to a measure of the total dissolved salt concentration in the pore fluid. This combined with the sodium adsorption ratio can provide an estimate of the salinity in terms of the sodium, calcium, and magnesium cations and their associated sulfate anion concentrations dissociated in the pore fluid.

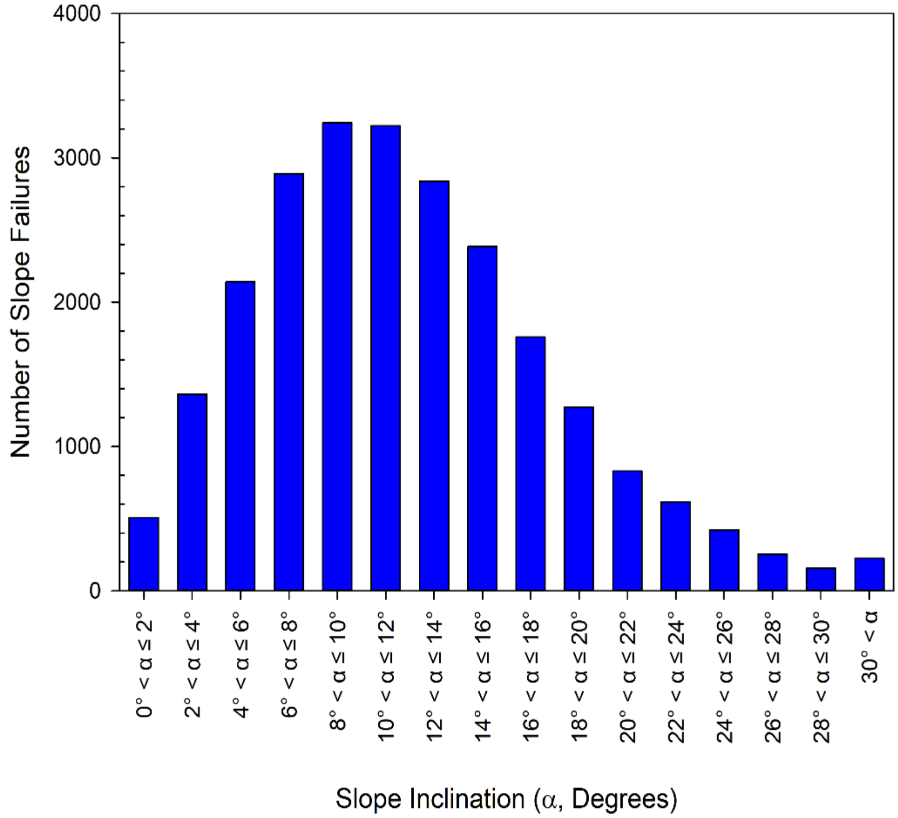

Figure 6. Distribution of Landslides with Slope Inclination.

The distribution of slope failures based on the pore fluid salinity is summarized in Figure 7. It can be seen that the greatest number of landslides occur when the sodium cation concentration in the pore fluid is larger than 0 mmolc/L, but less than or equal to 2 mmolc/L with the second higher number of landslides occurring in regions with the concentrations between 2 mmolc/L and 4 mmolc/L. For both calcium and magnesium cations in the pore fluid, the largest number of failures occurred when the concentration was between 4 mmolc/L and 6 mmolc/L. The second highest number of failures occurred when the calcium cation concentration was between 2 mmolc/L and 4 mmolc/L or when the magnesium cation concentration was between 6 mmolc/L and 8 mmolc/L.

Figure 7 illustrates that the majority of the slope failures occur in regions that have low pore fluid salinities. This may be a result of the fact that soils with high pore fluid salinities tend to have higher strengths than soils with distilled water in their pore fluids (Tiwari and Ajmera, 2015). However, the detailed investigation of the influence of pore fluid salinity in changing the shear strength of the soils encountered in these slope regions was beyond the scope of this study and will be performed in future work by the authors.