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Review

Global CO_2 Emission-Related Geotechnical Engineering Hazards and the Mission for Sustainable Geotechnical Engineering

Ilhan Chang [1], Minhyeong Lee [2] and Gye-Chun Cho [2,*]

[1] School of Engineering and Information Technology (SEIT), University of New South Wales (UNSW), Canberra, ACT 2600, Australia
[2] Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Korea
[*] Correspondence: gyechun@kaist.edu; Tel.: +82-42-869-3622

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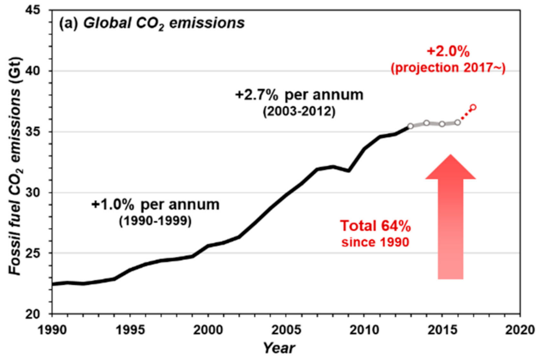
Abstract: Global warming and climate change caused by greenhouse gas (GHG) emissions have rapidly increased the occurrence of abnormal climate events, and both the scale and frequency of geotechnical engineering hazards (GEHs) accordingly. In response, geotechnical engineers have a responsibility to provide countermeasures to mitigate GEHs through various ground improvement techniques. Thus, this study provides a comprehensive review of the possible correlation between GHG emissions and GEHs using statistical data, a review of ground improvement methods that have been studied to reduce the carbon footprint of geotechnical engineering, and a discussion of the direction in which geotechnical engineering should proceed in the future.

Keywords: global warming; climate change; greenhouse gas; carbon dioxide; extreme precipitation; disaster; geotechnical engineering hazard; ground improvement; soil stabilization

1. Introduction

Greenhouse gas (GHG) emissions from human activities, especially carbon dioxide (CO_2) emissions from burning fossil fuels have continuously increased since the late 19th century and are strongly related to global economic growth and the population explosion [1]. Recent studies provide strong evidence of the progressive climate change brought about by the anthropogenic increase in GHG emissions [1]. GHGs in the Earth's atmosphere play a major role in temperature control by absorbing approximately 20% of the radiant heat emitted from the Earth's surface and then releasing it back to the surface [2,3]. Greenhouse gas emissions, and the accompanying atmospheric concentrations of CO_2, have continuously increased (Figure 1) [4,5]. The atmospheric concentration of CO_2, which was 280 ppm in 1750, has shown a 42% increase to 400 ppm in 2015 [1,3,4]. As a result, global mean temperatures are continuously rising (Figure 2) where 2015, 2016, and 2017 were recorded as the most warmest years since 1880 [5–8].

In response and as part of global efforts to reduce GHG emissions (particularly CO_2), 197 countries represented in the United Nations Framework Convention on Climate Change adopted the Paris Agreement in 2015 and committed to cutting emissions, with the aim of maintaining global mean temperatures below 2 °C [9]. However, no noticeable reduction or effort has yet been made, and average CO_2 emissions are expected to continue to rise as a result of industrial growth in developing countries and the global urbanization trend [10]. Thus, more effective action is required to maintain global mean temperatures below 2 °C [11].



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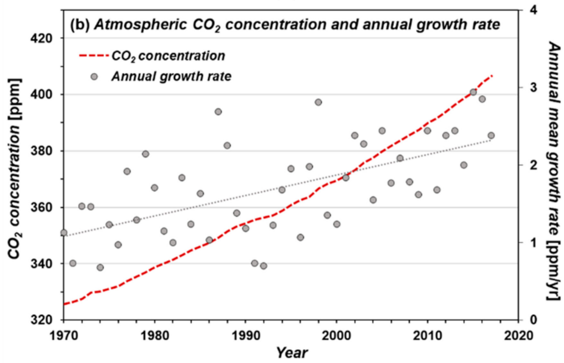

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Figure 1. Global CO_2 emission status: (**a**) Trend of global CO_2 emissions from fossil fuels. Reproduced with permission from Le Quéré et al., Global Carbon Budget 2017 in Earth System Science Data; published by Copernicus Publications, 2018 [5]; (**b**) Atmospheric CO_2 concentration and annual growth. Reproduced with permission from Ed Dlugokencky and Pieter Tans, Trends in atmospheric carbon dioxide (www.esrl.noaa.gov/gmd/ccgg/trends/); published by the National Oceanic & Atmospheric Administration (NOAA) [4].

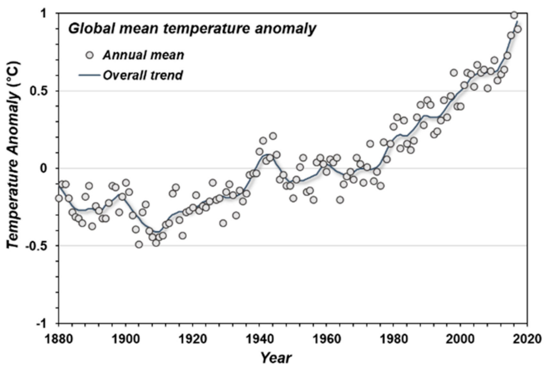
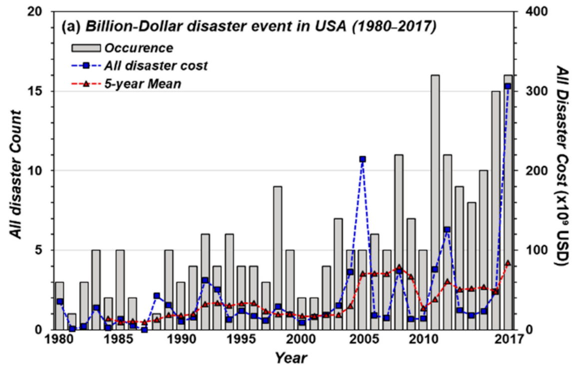


Figure 2. Global mean temperature pattern from 1880 to 2017. Reproduced with permission from the Jet Propulsion Laboratory (JPL), Global land-ocean temperature index (https://climate.nasa.gov/vital-signs/global-temperature); published by the National Aeronautics and Space Administration (NASA) [8].

The increase in global atmospheric CO_2 concentration and corresponding mean temperature of the earth alters global water circulation, which is followed by unexpected weather events (e.g., heavy downpour, drought) and a rise in sea levels [1,12]. In other words, the pattern of hydrologic climate events (e.g., frequent localized heavy rain and intensive storms) is changing and induces unsuspected geotechnical engineering hazard (GEH) events (i.e., landslides, ground subsidence, levee failures, soil degradation, and coastal erosion) [13]. Thus, since the end of the 20th century, the occurrence of, and damage from, GEH events around the world has rapidly increased, along with huge social and economic losses [14–17]. For instance, in the United States, 219 natural disasters with damage exceeding $1.5 trillion occurred in 2017 alone (Figure 3a) [18,19]. The economic damage of disasters has also drastically increased in South Korea since 1990 and has become an important national issue of safety (Figure 3b) [20,21]. In response, more countries require geotechnical engineering implementation for damage recovery or disaster mitigation [22].



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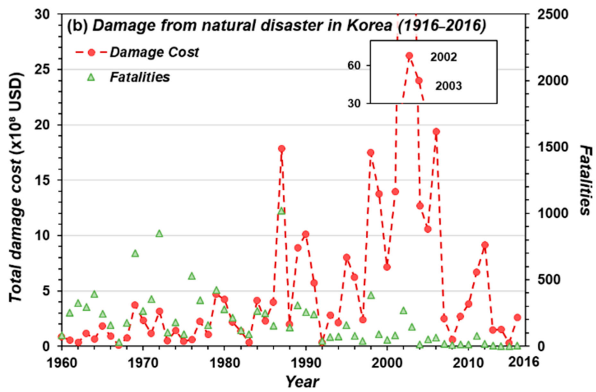

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Figure 3. Disaster occurrences, including flooding, severe storms, drought, tropical cyclones, winter storms, freezing, and wildfire, with relevant damage costs: (**a**) The U.S. billion-dollar disaster record (1980–2017). Reproduced with permission from the National Oceanic and Atmospheric Administration (NOAA) of the United States, U.S. Billion-Dollar weather and climate disasters (https://www.ncdc.noaa.gov/billions/time-series); published by National Centers for Environmental Information (NCEI) [19]; (**b**) Total disaster damage cost and fatalities in South Korea (1916–2016). Reproduced with permissions from 1) Ministry of the Interior and Safety, Annual Disaster Report 2016; published by the Ministry of the Interior and Safety of the Republic of Korea Government, 2017 [20], and 2) National Emergency Management Agency, Annual Disaster Report 2009; published by National Emergency Management Agency of the Republic of Korea Government, 2010 [21].

Therefore, a comprehensive understanding of GEHs in the context of climate change and CO_2 emissions is required. Furthermore, sustainable ground improvement methods that can respond to GEHs while reducing the CO_2 footprint should be introduced and implemented in geotechnical engineering [23]. This study aims to provide an overview on the effect of climate events on GEHs and a statistical review of the correlation between the occurrence of, and damage from, GEHs and CO_2, based on historic disaster data. The status and challenge of several ground improvement methods to replace high CO_2 emitting soil binders (e.g., cement) are also summarized, and the necessity of an environmentally friendly perspective in geotechnical engineering is addressed.

2. Relationship between Climate Change and Geotechnical Engineering Hazards

2.1. Climate Change Issues Related to Global Warming

Two major climatic issues are associated with global warming, which is accelerated by additional GHGs (Figure 4): (1) Extreme precipitation and (2) sea level rise [17,24].

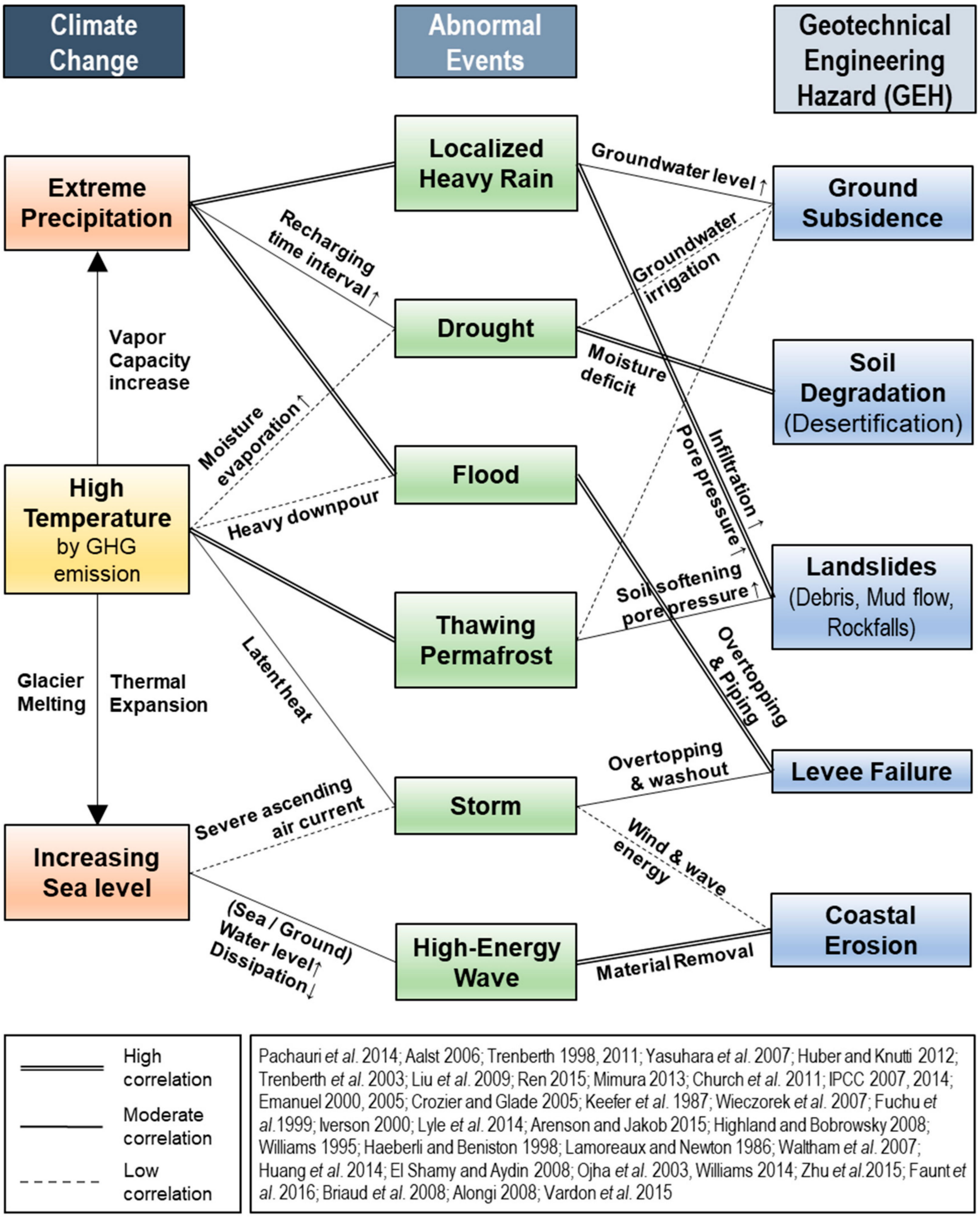


Figure 4. Geotechnical engineering hazard (GEH) events triggered by climate change [1,12,13,17,24–53].

Extreme precipitation takes place when warmer temperatures allow the atmosphere to hold more water vapor. The atmosphere is able to contain more water vapor because its capacity increases by 7% when the atmospheric temperature rises by 1 °C [13,25–27]. As more water evaporates into the atmosphere, clouds with heavy concentrations of water vapor can render localized and heavier downpours, while other places experience drought. Moreover, the intervals between wet periods in the water circulation process can be disturbed and generate more extreme precipitation events, as illustrated in Figure 5 [28]. Localized heavy rainfall and droughts generated by extreme precipitation can cause landslides, ground subsidence, and soil degradation. For example, successive and torrential heavy downpours in southwestern Japan in June and July of 2018 triggered landslides, mudslides, and flash flooding, causing 225 deaths [54,55].

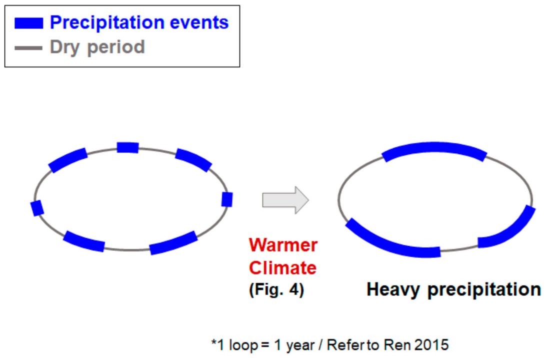


Figure 5. Illustration of extreme precipitation pattern in a warmer climate, reproduced with permission from Ren Diandong, Strom-triggered Landslides in Warmer Climates; published by Springer, 2015 [28]. Blue circles indicate precipitation events (wet days), and gray lines indicate the dry periods in between.

Meanwhile, sea level rise is mainly caused by the thermal expansion of sea water and the melting of glaciers. Latent heat is transferred from the atmosphere to the ocean as the atmospheric temperature becomes warmer due to high GHG concentrations. This increased heat capacity of the ocean, in combination with an inrush from the melting of mountain glaciers and ice sheets in Antarctica and Greenland [29], raises the average sea water level, which causes the sea level to rise [29–31]. As a result, an increased sea level creates more severe ascending air currents, helping form intensive, larger, and longer-lasting storms with heavy rains, such as hurricane Florence, which delivered nearly three feet of rain on North Carolina in 2018, causing severe damage [34,56,57]. In addition, an increased sea level strengthens waves reaching the shore by reducing the wave energy dissipation related to friction, which depends on the depth of the coastal floor [17]. The combination of high-energy storms and waves generated by sea level rise leads to severe and simultaneous erosion and flooding events that commonly cause levee failure, coastal decomposition, and ground subsidence [58].

2.2. *Effect of Abnormal Climate Events on Ground Properties and Geotechnical Engineering Hazards*

The geotechnical effect of several abnormal climate events on ground properties, and the GEHs resulting from them, are summarized in Table 1. In detail, water from localized heavy rain penetrating the ground increases the excess pore pressure of the ground in a short time (the soil suction value decreases). This reduces the effective stress between soil particles, thereby weakening the shear strength of the inclined ground and (in combination with the overburden caused by trapped rain in the active layer of the ground) leads to landslides or slope failures [32,35–38]. The reduction in ice-cementation bonds between soil particles, due to thawing in permafrost sediments as the global atmosphere gets warmer, can also assist in wet mass movement, such as debris flow [33,39–41]. Likewise, the degradation of permafrost in fractured rock mass creates concerns about rockfalls, due to long-term changes in stress distribution caused by reduced strength and increased permeability in rock masses [42].

Table 1. Overview of abnormal climate events and their effect on ground properties.

Abnormal Climate Event		Effect on Ground Properties	Related Geo-Hazard	References
Extreme Precipitation	Localized Heavy Rain	Pore pressure increase → Soil suction value decrease → Soil effective stress and shear strength reduction	Landslide	[35–38]
		Higher infiltration into surface layer → Unit weight increase above potential failure surface → Increased driving force inducing downward movement	Landslide	
		Flood → Rise of seepage line or overtopping, which increases the degree of saturation due to infiltration → Pore pressure increase → Void ratio and hydraulic conductivity increase → Effective stress decrease	Levee failure (breach, piping)	[45–47,59]
		Extreme groundwater table variation and dissolution of soluble geomaterials (e.g., $CaCO_3$)	Ground Subsidence (including sinkholes)	[43,44]
	Drought	Severe evaporation → Moisture deficit in surface soil → External soil shrinkage and internal erosion → Vegetation cover decay and soil vulnerability (erosion) increase	Soil degradation (Desertification) Ground subsidence	[48–50,53]
High Average Temperature	Thawing Permafrost	Destruction of ice-cementation bonds and unfrozen water increase in soil → Shear strength decrease	Landslide Heaving and subsidence (including thermokarst)	[33,39,41,42]
Sea Level Rise		Higher water level on coasts → Less wave energy dissipation → Higher wave energy approaching coasts → Air trapping in pore spaces and compression by waves → Weakening of soil particle interaction → Break off and coastal erosion increase	Coastal Erosion Coastal Landslide	[17,51,52]
		Latent heat energy and vapor transfer to the air → Severe and higher air ascending stream (heavy storm) → Extensive and frequent inundation by storm surges in coastal regions → Overtopping and washing out → Erosion and failure	Coastal Erosion Levee Failure	

However, downpours in certain areas can lead to a dramatic change in the groundwater level. For instance, in karst terrain, the limestone geologic compositions can be easily dissolved by water, and calcium carbonate ($CaCO_3$) dissolution can accelerate sudden ground subsidence events, such as sinkholes. These events can also occur in urban areas. For example, a groundwater change can lead to the loss of soil near water pipelines with leaks [43,44].

Rainfall intensity increase due to changes in precipitation patterns can lead to frequent flooding and other GEHs, such as failures of levees and erosion in riverine areas. In drastic riverine flooding caused by heavy rain, the water level exceeds the allowable design capacity of levees or embankments, which generally results in overtopping, whereby overflow water erodes the end of a slope, leading to failure [45]. In addition, internal erosion in a levee and an excessive flow rate of water with a tractive force eroding away the bottom and lateral surfaces can contribute to severe earthen levee failures [46,47].

Meanwhile, drought caused by an extended dry period with limited precipitation results in a moisture deficit in the surface layer of soil. Surface desiccation and soil shrinkage decreasing surface vegetation cover make the land more vulnerable to soil erosion, leading to soil degradation and desertification [48,53]. Some recent studies have also reported that irregular groundwater irrigation due to water shortages can render ground subsidence [49,50].

In coastal areas, unprecedented strong storms due to sea level rise and warmer temperatures can weaken the ground strength and escalate surface erosion [51]. In particular, high-energy waves accelerate coastal erosion and can also result in damage to shore structures through a decrease in load-bearing capacity [17]. In addition, sea level rise and warming sea waters are speeding up coastal erosion by destroying coastal ecosystems (e.g., mangroves and reefs) that attenuate waves and prevent the washing away of particles in coastal areas [52].

3. Statistical Trends of CO_2 (Climate Change) Emission and Geotechnical Engineering Hazards

3.1. Status of Geotechnical Engineering Hazards

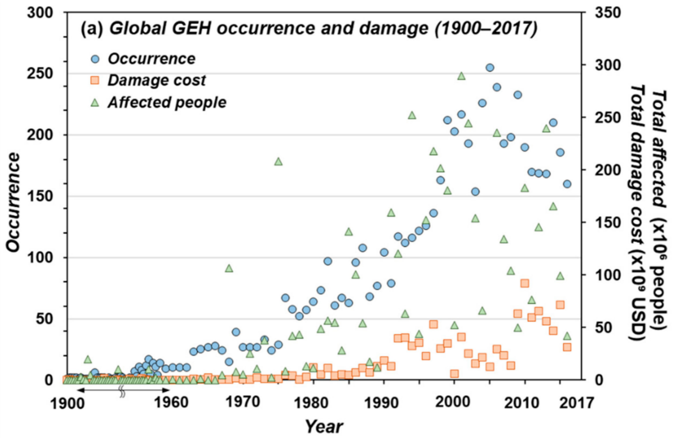
The Emergency Events Database (EM-DAT) provided by the Centre for Research on the Epidemiology of Disasters (CFRD) is among several widely used international disaster databases. EM-DAT was created in 1988 with support from the World Health Organization and the Belgian government, which provides overall disaster data from United Nations agencies, U.S. government agencies, research centers, and the press every year [60]. As EM-DAT is publicly available and has been used in a number of scientific studies, it is used in this study for statistical review [61–64]. The database in EM-DAT is mainly classified by biological, geophysical, climatic, hydrologic, meteorological, and extraterrestrial groups, including several subgroups in each main group [60]. This study focused on the data for landslides (wet mass movements), floods, wave action, and droughts (excluding dry mass movement or ground subsidence by earthquake) to analyze the statistics of GEHs from the perspective of climate change and geotechnical engineering.

The EM-DAT database provides global disaster data from 1900 to the present. However, the old data may not be reliable, due to the inadequate standardization of the data collection and analyzing methods up to the middle of the 20th century. Thus, the authors decided to focus on the occurrence and damage data of GEHs since the 1960s.

3.2. Relationship between CO_2 Emissions and Geotechnical Engineering Hazards

The damage scale of disasters may be attributed to multiple factors, including anthropogenic influences on global warming and climate change, as well as socioeconomic conditions, such as infrastructure development level and readiness of national or local disaster confrontation systems [65]. Still, there is no doubt that climate change strongly correlates to the frequency increase of severe GEH events, and the simultaneous global population growth during the past century must be considered when interpreting damage scale and socioeconomic impacts (e.g., damage cost, casualties, and affected populations) of GEHs [66].

Figure 6a shows the overall incidence, damage, and affected populations of global GEHs from 1900 to 2017 [67]. All indices in Figure 6a show significant increases since the 1960s. Meanwhile, damage scales (cost and affected people) adjusted for the global population in each year (in cost or people per million people) are plotted in Figure 6b, demonstrating climate change's effects on the significant rise in GEH-related damage. The occurrence of GEHs among different continents is shown in Figure 7. All continents show a simultaneous and continuous increase in GEHs occurrences since the 1960s. In particular, occurrences in Asia grew most rapidly among the continents, indicating that the monsoon region is affected by frequent floods and landslides caused by recent climate change [68]. If the frequency and damage of GEHs were similar to levels prior to the damage, indices may have either been reduced or remained steady due to the social economic growth and technology development [69–72]. However, as most disasters are unpredictable, the positive increase in the data indices could mean that the magnitude and intensity of each unforeseen GEH has become much stronger. In other words, these results show that abnormal climate phenomena of severe magnitudes have increased, and that climate change is a direct cause of GEHs.



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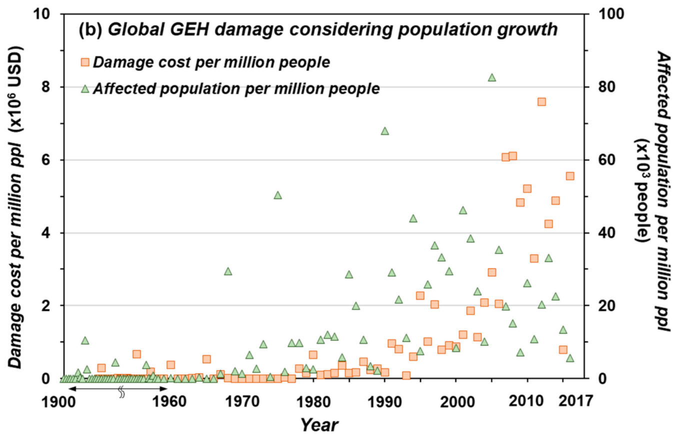

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Figure 6. Global geotechnical engineering hazard status (1900–2017): (**a**) Occurrence and total damage indices; (**b**) Damage cost and affected population per million people. Reproduced with permission from the Centre for Research on the Epidemiology of Disasters (CRED), Emergency Events Database (EM-DAT); published by the Université catholique de Louvain (UCL) [67].

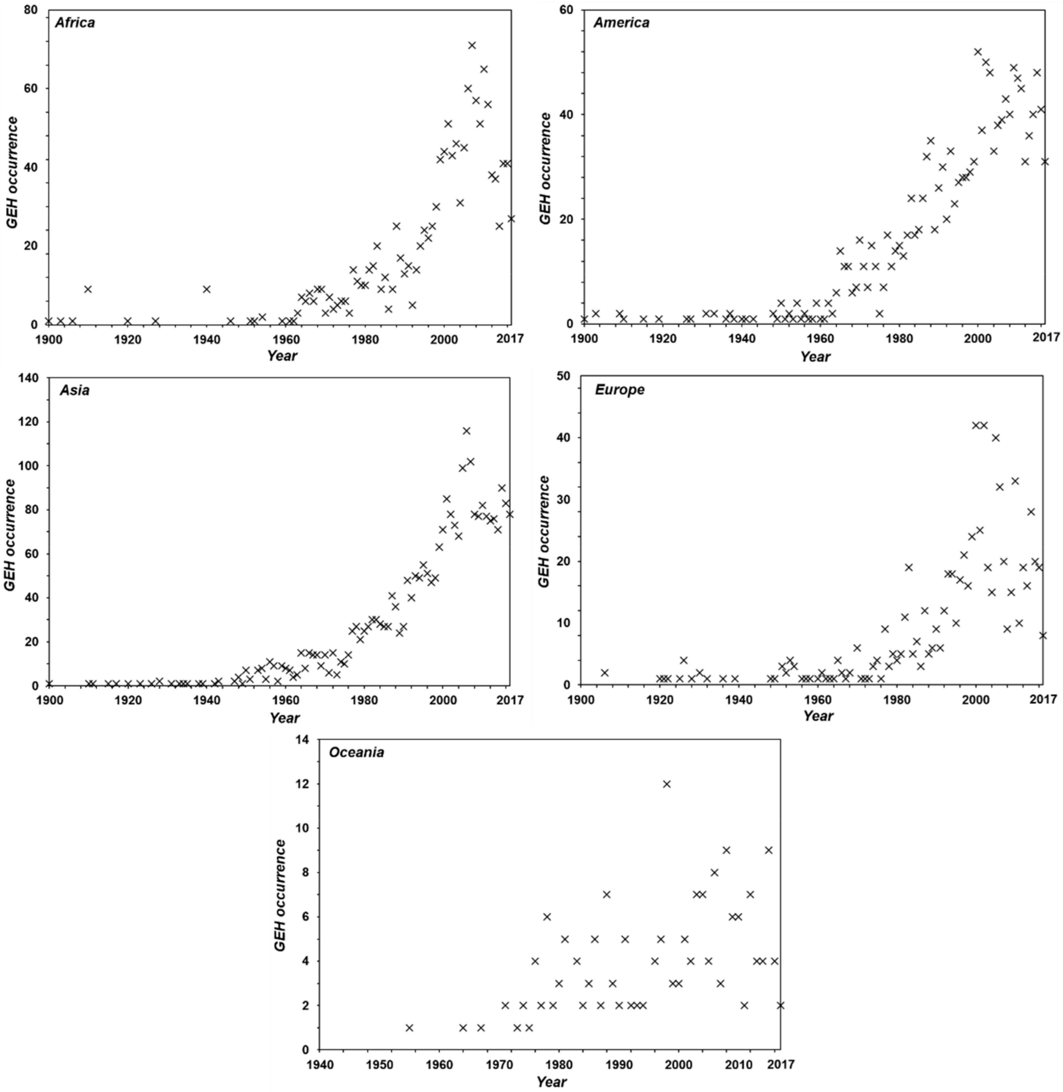

Figure 7. Geotechnical engineering hazard occurrence by continent from 1900–2017. Reproduced with permission from the Centre for Research on the Epidemiology of Disasters (CRED), Emergency Events Database (EM-DAT); published by the Université catholique de Louvain (UCL) [67].

As mentioned above, CO_2 emissions from human activity, especially the burning of fossil fuels, are one of the main contributors to global warming and climate change [1]. The recent rapid increase of atmospheric CO_2 concentration—324 ppm in 1970 to 406 ppm in 2017, representing a 25% rise—is known to induce climatic events of greater abnormality and severity [73], in line with data scattering associated with higher CO_2 concentration in Figure 8. Most emitted GHG, including CO_2, exist in the atmosphere for several decades [3]. Furthermore, since global CO_2 emissions have been continuously increasing and are unlikely to be flat in the near term, the climate change phenomenon that has been recently observed is regarded as the beginning [1] Therefore, the reduction of CO_2 emissions is an essential way to mitigate GEH damage to human civilization, from a geotechnical engineering aspect.

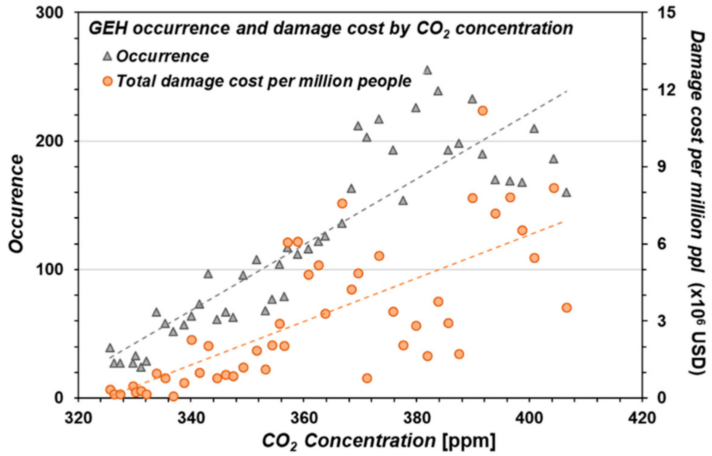

Figure 8. Correlation between CO_2 concentration and geotechnical engineering hazards, in terms of occurrence and total damage per million people. Reproduced with permission from the Centre for Research on the Epidemiology of Disasters (CRED), Emergency Events Database (EM-DAT); published by the Université catholique de Louvain (UCL) [67] and permission from Ed Dlugokencky and Pieter Tans, Trends in atmospheric carbon dioxide (www.esrl.noaa.gov/gmd/ccgg/trends/); published by the National Oceanic & Atmospheric Administration (NOAA) [4].

4. The Response to Geotechnical Engineering Hazards and the Necessity of an Environmentally Friendly Method

4.1. Contribution from Geotechnical Engineering to Reduction of CO_2 in the Earth

Over the last three decades, much geotechnical engineering research has been conducted to mitigate CO_2 emissions from fossil fuels [74].

One representative approach to directly reduce already-emitted atmospheric CO_2 is carbon capture and storage (CCS), including geological CO_2 storage (GCS). GCS aims to inject captured atmospheric CO_2 into underground geological media, such as oil and gas fields, coal layers, deep saline aquifers, and hydrate bearing sediments [74,75]. Compared to the other CCS techniques, GCS has the advantage of large capacity and additional merit in enhancing oil recovery. However, GCS poses challenges, including high cost, long-term leakage, and the possibility of rendering subsea GEHs [75].

CCS and GCS technologies are the predominant tactics in reducing the present atmospheric CO_2, with less effect on mitigating GEHs triggered by CO_2 emission-related climate change. Thus, this section will focus on current attempts in ground improvement by not using high CO_2 emitting cement in geotechnical engineering practices.

4.2. Ground Improvement and CO_2 Emissions Related to Cement

Since most GEHs are related to soil strength reduction due to changes associated with water, geotechnical engineers have been studying various methods of ground improvement, to increase the strength of the ground. For instance, retaining walls [76], geosynthetic products [77], and anchors with grout (called soil nailing) [78,79] are installed to increase the stability of slopes. Also, the strength of soft, clayey soils has been improved through electrokinetic stabilization with chemical grouting to prevent slope failures (e.g., landslides) [80].

To prevent levee failures, concrete pilings or geosynthetic products are constructed to strengthen the levee structure and resist against overtopping or internal erosion [81]. Ground subsidence, which is mainly affected by changes in the groundwater level, can be mitigated via cement or lime based deep mixing or grouting practices [82], while chemical binders (including cement and polyurethane) are commonly used to prevent erosion and cliff failure in coastal regions [83]. Thus, it should be noted that cement and chemical binders are mostly used for geotechnical ground improvement, to respond to GEHs. Cement has various advantages in terms strengthening, durability, and economic aspects, thus it holds a dominant position among other construction materials in civil and construction engineering practices. However, questions have recently been posed about the long-term environmental impact of cement, despite its many advantages.

Cement production emits CO_2 through two main processes: the kiln calcination ($CaCO_3$ + heat → $CaO + CO_2$) and the combustion of fossil fuels for heating. Generally, about one ton of CO_2 is generated to produce a single ton of cement [84]. According to data from the U.S. Geological Survey, 4.2 gigatons of cement are produced worldwide per annum, and the percentage of cement-related CO_2 emissions in total CO_2 emissions has reached almost 10%, more than doubling from 4% in 1970 (Figure 9) [85]. In geotechnical engineering practices, ground improvement processes such as mixing and grouting are reported to contribute about 0.2% of entire global CO_2 emissions [23]. Although global efforts to reduce CO_2 emissions were initiated after The Paris Agreement in 2015, cement production is expected to grow, due to the huge demand for traditional civil engineering materials, particularly in China, India, and large parts of the developing world, given the global urbanization trend [84]. In geotechnical engineering perspectives, ironically, cement that releases CO_2 in its production is used to prevent and recover from GEHs related to climate change caused by CO_2. Moreover, other environmental problems, including alkalization of the soil (affecting ecosystems, urban runoff, and vegetation levels), demonstrate the need for environmentally friendly and sustainable alternatives to cement to reduce the CO_2 footprint. In response, various geotechnical approaches for alternatives to cement, such as chemical mixtures, geopolymers, geosynthetics, microbial organisms, and biopolymers, have recently been investigated.

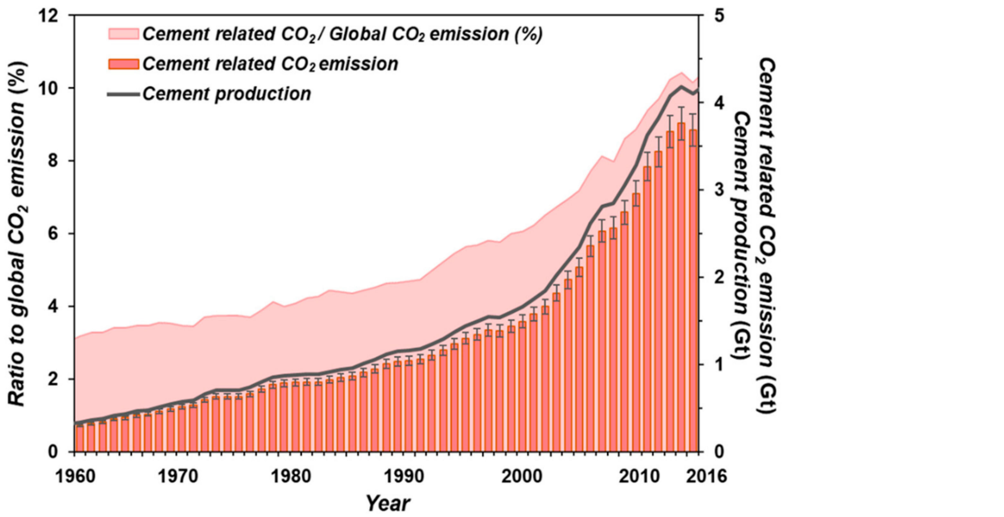

Figure 9. CO_2 emissions related to the production of cement and its ratio to total CO_2 emissions. Reproduced with permission from Thomas D. Kelly and Grecia R. Matos, Historical statistics for mineral and material commodities in the U.S.; published by the United States Geological Survey (USGS), 2015 [85].

4.3. Recent Research on Environmentally Friendly Ground Treatment Methods

Various geotechnical approaches for replacing cement are listed in Table 2.

Table 2. State-of-the-art attempts to reduce cement usage in geotechnical engineering.

Properties	Chemical Stabilizer	Geopolymer	Geosynthetics	Microbiologically Induced Calcite Precipitation	Biopolymer
Methodology	Injection or spraying and mixing before compaction	Mixing, injecting, or spraying of alkali activated pozzolans	In situ installation of synthetic materials	Injecting bacteria and nutrient solution into the ground	Direct mixing, injecting, or spraying of biopolymers
Materials and Mechanism	Chemically synthesized polymers (i.e., acrylamide-based anionic polyelectrolytes) Ionic bonding with soil particles or interparticle cementation	Alumina-silicate (i.e., pozzolanic materials) and alkali or alkali earth substance Alkali silicate activation (polycondensation)	Synthetized polymer products Tensile strength enhancement and fluid flow control in soil	Microbial (bacterial) and urease enzyme Biologically driven $CaCO_3$ precipitation (cementation, pore-clogging)	Dry (powder type) of hydrogel (solution) biopolymers Particle aggregation of inter-particle bonding through hydrogen and ionic bonding
Geotechnical Effects	-Strength improvement and density increase -Reduced sensitivity to water (plasticity)	Void ratio reduction by geopolymerized gel filling and increased bulk density	-Separation, filtration, and drainage of water in soil -Tensile strengthening -Impeding flow of liquid or gas	-Improvement in soil matrix stiffness and initial shear strength -Hydraulic conductivity control	-Cohesion and strength increase (biopolymer–soil matrix formation) -Permeability reduction
Advantages	-Prevention of detachment by erosion and runoff -Encouraged seed germination -Flocculants for wastewater treatment -Increased sweep efficiency in oil recovery	-Lower CO_2 emissions than cement -Resistance to acid, sulfate, and freeze–thaw attack -Usage of industrial by-products (fly and bottom ashes)	-High durability -Easy transportation and site installation -High tensile strength, flexibility, and imperviousness -Various ranges of applications	-Low energy consumption, with a low carbon footprint -Flexible implementation in soil due to easy control of the treatment process, using bacteria -Chemical characteristic of soil grains do not alter	-Low carbon footprint and biodegradability -Low binder quantity -Sufficient quality control -Erosion reduction and vegetation improvement
Limitations and Challenges	-Contamination concerns into soil and ground water -High material cost -Infeasible for deep/thick ground treatment	-Lack of standards for tests and production -Lack of geotechnical applications -Needs heat process (about 60 °C) in the field	-Material-dependent strength -Non-biodegradable -Inappropriate for significant depths in the ground	-Inappropriate for fine - soils-Consistent quality control -Weakness against low pH -Ammonia as a byproduct -Few field applications	-Low economic feasibility -High sensitivity to water -Severe hydrogel swelling -Concerns on long-term durability
Related Recent Research	-Monitoring of long-term effectiveness by measuring metal bioavailability and soil quality improvement -Biomass silica stabilizer from agricultural waste -Calcium carbide residue from acetylene production	-Attempt to use lime sludge from paper industry waste for paving blocks -Soft marine clay stabilization by fly ash and calcium carbide residue-based geopolymer	-Nano clay combined geotextile for removing heavy metal or toxic manners -Hybrid combined geosynthetics -Sensor-embedded geosynthetics	-Field-scale test focused on surface applications for erosion and dust control -Use of seawater as a calcium source (feasibility for marine applications)	-Casein from dairy waste as a new binder -Inter-particle interaction characterization using microscopic devices -Strength enhancement in wet conditions using crosslinking -Economic feasibility improve
Reference	[86–92]	[93–101]	[102–108]	[109–117]	[23,118–127]

4.3.1. Chemical Stabilizers

After the 1950s, research commenced on nontraditional soil stabilization additives consisting of multiple chemical agents as a means of replacing traditional binding materials (i.e., cement and lime) in geotechnical engineering. One of these agents was lignosulfonate, a chemical stabilizer containing Na-, Ca-, and NH_3-lignosulfonate, which are synthetic materials from lignin used as cellulose fibers. When this material meets soil, it coats the soil particles with a thin adhesive film and bonds them together. In addition to its primary cementing effect, lignosulfonate forms ionic bonds with clay particles having electrically charged surfaces rendering a strengthening effect [86]. In other words, soil strength is enhanced and shrinkage–swelling is reduced. This approach is particularly effective in coarse and granular soils [87].

Other types of chemical stabilizers are anionic acrylamide-based polyelectrolytes, and the most common type is polyacrylamide (PAM). PAM establishes an effective interaction among soil particles through charge neutralization, bridging, and adsorption, using negative charges. Thus, PAM has been applied to multiple geotechnical engineering practices, such as flocculants, shale stabilizers, and thickening and binding agents. PAMs are especially used to reduce runoff, erosion, and soil sealing [88].

Salt stabilizers, including calcium and magnesium chloride compounds, and other polymer stabilizers, such as vinyl acetates, have been shown to improve strength, stabilize volume, and enhance waterproofing with sandy or clayey soils [86].

Chemical stabilizers are generally implemented by injecting them into or spraying them on the soil and mixing before compaction. However, they have the potential to contaminate the surrounding geo-environment and nearby groundwater, resulting in limited usage near drinking water sources, despite their merits [92]. Therefore, although recent studies have been conducted on applying sustainable and nontoxic chemicals, such as biomass silica and calcium carbide [89,90], to soil, the economic limitations of applying deep injections to a large-scale site, and the necessity of establishing criteria for the laboratory scale to predict effective in situ performance, should be further researched [91].

4.3.2. Geosynthetics

Geosynthetics are synthetized polymeric products used with soil, rock, or other earth material to solve geotechnical engineering problems [103]. They are generally classified into eight main product types: Geotextile, geogrid, geomembrane, geocomposite, geosynthetic clay liner, geonet, geofoam, and geocells [23]. Geosynthetics are generally prefabricated and transported to a site in the form of a roll package and installed directly in the ground. The biggest advantage of geosynthetics is their multiple functions. In detail, geosynthetics are installed in the transition zone of intermixed ground to serve a separation function, prevent intrusion between aggregates with different sizes, or increase the stability of soil–geosynthetics composites by applying tensile strength. They are also used to provide filtration and drainage by adjusting the fluid flow path, to address soil erosion and other geosynthetics (i.e., geomembrane) that are relatively weak against external damage, through stress relief [102]. The production of geosynthetics grew after 1970 due to their advantages of easy installation, transport, and handling, and because of their ability to reduce construction time and cost [102,104]. Also, some geosynthetics (e.g., polypropylene, polyester, polyethylene, and polyamide) are highly applicable to various geotechnical problems and have excellent biological and chemical resistance. Therefore, the geosynthetics market has steadily grown, and in 2017 the demand for these materials was approximately 5200 mm^2 worldwide [76].

Recently, studies have been conducted on multipurpose hybrid geosynthetics that combine two or more types of geosynthetics to improve their applicability. Sensor-embedded geosynthetics have also been investigated for long-term site monitoring [107,108]. However, geosynthetics have some limitations and challenges. The strength of soil geosynthetics mainly relies on that of the synthetized material itself, and they are applicable at shallow depths but are not appropriate at significant depths [23]. Although their durability is as good as a plastic material, their sustainability needs to be further discussed and verified, due to their ecotoxic effect on the environment from the leakage of additives and residual product from degradation of polymeric or metallic materials into the ground [104–106].

4.3.3. Geopolymers

Geopolymers, a substitute for Portland cement, are alkali-activated, cementitious binder materials produced by a reaction called geopolymerization that occurs between aluminosilicate materials containing high levels of silicon and aluminum oxides (i.e., slag, fly ash, and metakaolin) and alkali-activating agents (i.e., alkali hydroxides) [93,98]. Alkali-activated geopolymers consist of three-dimensional structures of sodium aluminosilicate hydrate (N-A-S-H) gel along with calcium-silicate-hydrate (C-S-H) gel, which make up the Portland cement [94]. These geopolymerized gel binders, formed through a polycondensation process, fill the pores between soil particles to reduce the void ratio and increase bulk density, resulting in enhanced strength. Geopolymers have an environmental advantage because industrial wastes, such as fly ash or blast furnace slag, are used as the raw materials [95] and because the consumption of heat energy is smaller than conventional Portland cement, thereby reducing CO_2 emissions [99].

According to recent studies, however, one of the typical geopolymers based on fly ash has lower initial strength characteristics compared to Portland cement, due to its slow and time-dependent strength gain rate [97,101], so heat-curing treatments to increase strength lead to in situ geotechnical limitations [96]. Despite a numbers of studies having been conducted to verify the strengthening efficiency of geopolymers compared to cement-based methodologies, further research about standards for testing and production, including the generalization of the water/geopolymer ratio, the Si/Al and Na/Al ratios, and the bond between reinforcement and geopolymer paste, are required for reliable in situ applications [100].

Although ground improvement using geopolymerized binders and chemical additives, through jet grouting or spraying, aid in enhancing shear strength, their lack of feasibility in large-scale applications, due to potential contamination of the surrounding environment (including the effect on the pH of soil and groundwater) [109], has led to the development of new, alternative approaches. For example, biological soil stabilization methods relying on microbial-induced calcite precipitation (MICP) and biopolymers have recently been developed to achieve environmental sustainability.

4.3.4. Microbiologically Induced Calcite Precipitation

Microbiologically induced calcite precipitation (MICP) is one of the most recognized biological ground treatments and uses biologically induced $CaCO_3$ precipitation with urea hydrolysis through the metabolism of bacteria such as *Bacillus pasteurii* and *Sporosarcina pasteurii* [23]. Carbonate crystals produced by urea hydrolysis and precipitated near particles act as cementitious inter-particle bonding agents, strengthening the stiffness and shear strength of the soil matrix by blocking the pores and, furthermore, reducing hydraulic conductivity. Through these mechanisms, called bio-cementation and bio-clogging, MICP can be flexibly implemented to solve geotechnical problems [113]. Also, MICP involves less energy consumption, which results in a low carbon footprint compared to traditional ground improvement methods [113]. Recent studies have used an enzymatic reaction with calcium chloride instead of a direct injection of grown bacteria in an attempt to enhance the production rate of carbonate [111,112]. Other research has involved the removal of heavy metals [114], surficial application of MICP for erosion and dust control [115], and usage of seawater as a nutrient source to attain higher carbonate precipitation [116]. However, most MICP research so far has been conducted on the laboratory scale using coarse-grained soils in which the pores are relatively large, and shows applicability limitation for clayey soils [110]. Also, the non-uniform distribution of precipitated $CaCO_3$ in field conditions and the emission of ammonia as an end product are future challenges for MICP. The relatively high price of bacterial nutrients is another issue. Therefore, further research should be conducted to resolve these limitations and to scale up to in situ and industrial-level production studies [109,117].

4.3.5. Biopolymers

Another biological soil treatment method involves excretory products from living organisms, called biopolymers, which have recently begun to gain attention for their soil-stabilization potential in the geotechnical engineering field [23]. Biopolymers, which are widely used in the food and pharmaceutical industries, are defined as an assembly of monopolymers produced from biological organisms. Polysaccharides, such as cellulose, starch, Xanthan, β-glucan, and gellan gum, are among several types of biopolymers that have been recently examined in the geotechnical engineering field with the purpose of soil strengthening and hydraulic conductivity control [119–121,128]. In previous studies, biopolymers increased the compressive and shear strength of soil through hydrogen-based chemical bonding between the biopolymers and soil particles. Bonding by electrostatic attraction between biopolymers and clay particles generates a noticeable strengthening effect [121,124]. For instance, a gellan gum and soil mixture (kaolinite clay) showed greater strength than a 10% cement mixture, in spite of the small content of biopolymers (under 2%) [121]. Furthermore, biopolymers are hydrophilic, and they absorb water to form a water zone in wet conditions, resulting in a reduction in permeability by filling the pores in soil with an expanded biopolymer gel [124]. Therefore, biopolymers have the potential to prevent desertification by increasing soil strength, reducing particle erosion, and assisting plant growth with their high water-retention capabilities [123].

From an environmental perspective, biopolymers produce few CO_2 emissions and can be naturally decomposed (biodegradable) with no harmful effect on the geo-environment or groundwater to which they are applied, so biopolymers are a promising option as environmentally favorable and sustainable materials for the future [23]. The biggest distinction from traditional Portland cement and the other alternatives to cement is that biopolymers can provide higher strength for smaller binder content [23]. According to previous research, the strength of biopolymer-treated soil with a biopolymer to soil content in mass of ~0.5–1% can be similar to, or stronger than, Portland cement and geopolymer cement, which must make up at least 10% of the content in soil-improvement applications [120]. Also, unlike MICP, biopolymers can be externally cultivated, enabling efficient mass production with high quality. They can also be applied using multiple methods, including injection, spraying, and mixing, which means they have the potential to be applied in various geotechnical field applications (e.g., for deep mixing, slope reinforcement, quick blockage of water inflow, and vegetation improvement). However, biopolymers are less economically feasible, due to their expensive global market price compared to cement. They are being used in other industries (e.g., food, pharmaceuticals, and cosmetics) that require pure and good-quality biopolymers, but they are not common in the geotechnical engineering field, so production costs are high. According to a recent survey, the unit costs of some biopolymers are declining with the growth of the biopolymer market [122], and biopolymers that have a relatively rough quality may be suitable for geotechnical engineering, so they are likely to be more competitive in the future [129]. However, the challenges are that not enough research has been conducted to provide specific guidelines for field applications and that biopolymers have a durability problem, due to strength reduction in wet conditions, that needs to be resolved [125]. In response to these issues, recent research has attempted to maintain soil strength by using thermo-gelation biopolymers [121,125], water-familiar, protein-based biopolymers (i.e., casein) [126], and cross-linking biopolymers [130].

5. Conclusions

This study provides a statistical review of the increase in GEHs resulting from CO_2 emissions from a geotechnical engineering perspective. Global warming, accelerated by increases in CO_2 emissions, creates abnormal climate events around the world that change the properties of soil over the short and long term, resulting in GEHs such as landslides, ground subsidence, levee failures, soil degradation, and coastal erosion. The occurrence and damage costs of GEHs have increased because of climate change, and these patterns are positively correlated with the increase in atmospheric CO_2 concentration. Meanwhile, cement has been the most widely used material as a ground improvement method in geotechnical engineering in response to GEHs. Cement accounts for 10% of global CO_2 emissions, so the geotechnical engineering field in the 21st century faces the ironic situation of simultaneously using CO_2-emitting materials to prevent the increase of GEHs related to CO_2 emission increase. Therefore, ground improvement methods implementing alternatives to cement, such as chemical additives, geosynthetics, geopolymers, MICP, and biopolymers, to reduce the global carbon footprint have been examined for sustainable geotechnical engineering. These attempts to find suitable alternatives are not yet fully satisfying, in terms of strength, economic feasibility, and field applications, and each method has its own limitations and challenges. Consequently, geotechnical engineering research should be more actively advanced in the direction of environmentally friendly and sustainable geotechnical materials that can contribute to reducing CO_2 emissions and relevant threats of GEHs.

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