Effect of CO2 sequestration on soil liquefaction in geological pits

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Abstract

This paper deals with review of the previous related research on evaluation of soil liquefaction due to Carbon sequestration by various Carbon Capture Sequestration processes in geological pits. It provides critical literature recommendations on evaluation of soil liquefaction potential assessment. The detection of soil liquefaction by using seismic records has been developed by various researchers. With this information, the evaluation of soil liquefaction are well understood and this lead to a more precise and confident output. Gaining support for CCS will require engaging the interest and building the support of a variety of stakeholders, each with different perspectives and goals. Although, CCS builds upon a technology base developed over more than half a century by the oil and gas industry. In the past, the industrially released CO_2 had been introduced to ocean which was harming the aquatic animals. In view of this, the sequestration of CO_2 into ocean was internationally banned. Hence, now much of the Carbon sequestration process is done by various industries in geological pits. This creates a major threat to the earth quake problems worldwide. With the enhanced frequency of earthquakes all around the world, it is presumed by many environment scientists that the CO_2 sequestration pits leads to soil liquefaction and hence it results in more frequent earth quakes. Therefore, this paper summarises, different methods to evaluate liquefaction potential of soil by using studies from seismic waves generated in earth, it is also propose it is also explains different methodology for an eco friendly technology to reduce CO_2 from environment.

Keywords: Soil liquefaction, CO_2 Sequestration, Geological pits, CCS

Introduction

Liquefaction is a process by which sediments below the water table temporarily lose strength and behave as a viscous liquid rather than a solid. The types of sediments most susceptible are clay-free deposits of sand and silts; occasionally, gravel liquefies. The actions in the soil which produce liquefaction are as follows: seismic waves primarily shear waves, passing through saturated granular layers, distort the granular structure. Liquefaction does not occur at random, but is restricted to certain geologic and hydrologic environments, primarily recently deposited sands and silts in areas with high ground water levels. Liquefaction of soils with upto 70 % fines and clay fraction of 10% occurred during Mino-Owar, Tohankai and Fukui earthquakes (Kishida, 1970) [1]. Soils with fines up to 90% and clay content of 18 % exhibited liquefaction during Tokachi –Oki earthquake of 1968 (Tohno and Yasuda, 1981) [2]. Gold mine tailings liquefied during the Oshima- Kinkai earthquake in Japan (Ishihara, 1985) [3]. Seed et al (1983) found that some soils with fines may be susceptible to liquefaction. Such soils (based on Chinese criteria) appear to have the following characteristics; percent finer than 0.005 mm (5 microns) <15%, liquid limit <35 %, water content >90 % of liquid limit [4]. Soil liquefaction is a natural hazard that we can never ignore during a large earthquake. Many authors have studied the evaluation methods for measurement of soil liquefaction potential. This study utilized the P-wave refraction method and the Multichannel Analysis of Surface Waves (MASW) method to obtain the variation of the near surface P-wave and S-wave velocities in a particular site in southern Taiwan, where liquefaction occurred in 1946 and again in 2010 (Chen et al., 2012) [5]. This method also recognize the various propagation characteristics of the seismic wave field, (Park et al., 1999a; Xia et al., 1999; Miller et al., 1999), which employs multiple receivers equally placed along a linear survey line with seismic waves generated by an impulsive source [6-8]. Shizhou et al., 2008 studied the evaluation of soil liquefaction in terms of Surface Wave Method (SWM). This method is based on the analysis of the dispersion of surface waves. Authors estimates the dispersive characteristics of a site by means of acquisition and processing of seismic data, further inverting the data for estimate of the subsoil properties which results vertical profile of shear wave velocity [9]. Hayashi and Suzuki (2004) introduced Common Mid-Point (CMP) cross-correlation analysis of multi channel surface wave method which gave accurate phase velocity curves, and enable to reconstruct 2D (two dimensional) velocity structures with high resolution [10]. Seed 1979a; Seed and Idriss 1982 have developed the simplified procedure for the judgement of soil liquefaction potential based on the Standard Penetration Test (SPT). In this method the cyclic stress ratio (CSR) is used to represent the seismic load on the soil [11-12]. Youd and Idriss (1997); NRC 1985 reviewed the some simple methods in comparison to SPT method such as the Cone Penetration Test (CPT) and small strain shear wave velocity Vs measurement [13-14]. According to feasibility, easy and simple operation, non-destructiveness rhe liquefaction evaluation method based on Vs had been recommended by Dobry et al. 1981, Seed et al. 1983, Stoke et al. 1988, Tokimatsu and Uchida 1990 [15-18]. Global biogeochemical cycles have shaped the Earth's climate and surface environment since the earliest days of the planet. A profound case in point is the consumption of CO_2 which is generating due to rapid industrialization pollutes the environmental atmosphere. Every 0.033 MTPA of sponge iron production generates about 594-660 tonnes of CO_2 every year 46. This estimates the total CO_2 generation by the industry in India to be between 0.53-0.59 million tonnes per year. The amount of CO_2 emitted by the cement industry is nearly 900 kg of CO_2 for every 1000 kg of cement produced. In the past, the industrially released such CO_2 had been introduced to ocean which was harming the marine animals. In view of this, the pumping of CO_2 into ocean was internationally banned. Hence, the alternate approach to reduce the CO_2 from environment is to introduce it in the earth crust where the soils are resistant to liquefaction as well as seismic waves. Carbon sequestration means capturing carbon dioxide (CO_2) from the atmosphere or capturing anthropogenic (human) CO_2 from large-scale stationary sources like power plants before it is released to the atmosphere. This has the potential to significantly reduce the level of carbon that occurs in the atmosphere as CO_2 and to reduce the release of CO_2 to the atmosphere from major stationary human sources, including power plants and refineries. CO_2 sequestration is classified into two major types such as terrestrial and geologic. Terrestrial (or biologic) sequestration means using plants to capture CO_2 from the atmosphere and then storing it as carbon in the stems and roots of the plants as well as in the soil. Geologic sequestration involves underground storage of industrially emitted CO_2 into the geosphere (underground) for long-term and secure storage. It is very necessary to suppress the industrially released pollutant CO_2 to the ground without affecting the soil characteristics which causes the soil liquefaction or generate seismic waves in the earth crust.

Lal, 2008 have studied the sequestration of atmospheric CO_2 in global carbon pools. The author represented that the liquefied CO_2 can be injected it into about 1000 m below the ground surface either in stable porous rocks, oil wells, coal beds, or saline aquifers. He concluded that the transfer of CO_2 into the biotic pool and soil C pool via humification which results the formation of secondary carbonates has numerous ancillary benefits through enhancement of ecosystem services [19]. Lackner, 2003 discusses the advantages and disadvantages of different methods of carbon sequestration. He strictly advises not to introduce it into oceans which may harm aquatic animals. He concluded that the better sequestration options include underground injection and (possibly underground) neutralization [20].

The focus of this paper was to review the previous related research on soil liquefaction and CO_2 sequestration which provides critical literature recommendations on liquefaction and sequestration assessment procedure. Hence, the main objective of the present study deals with the evaluation of soil liquefaction with the injection of carbon dioxide by Seismic Wave Method (SWM) into geological pits.

SOIL LIQUEFACTION

Shizhou et al., 2008 prepared geological pits to construct the shear wave velocity profile down about to 20 m below the ground surface using Multichannel Analysis of Surface Wave (MASW) method.

➢ ***Test method and procedure***

- ***Surface wave measurement***

The experimental results were acquired by MASW method. The schematic view of a surface wave method is shown in Fig. 1.

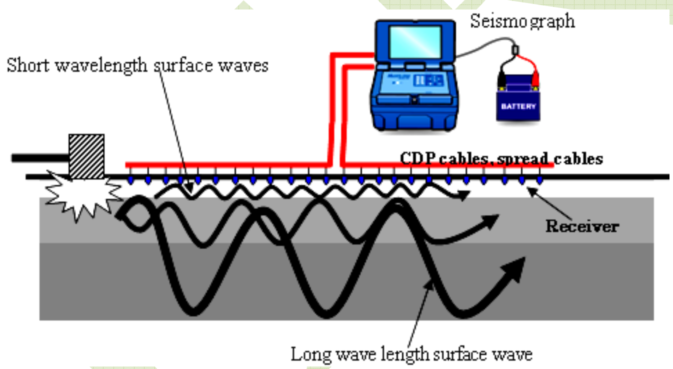

Fig. 1 Diagram of data acquisition system for MASW method (Shizhou et al., 2008)

The equipment for this survey is composed from Data logger: OYO McSEIS-SXW, Seismometers: geophones with 4.5 Hz frequency and Source: Sledgehammer. In this figure, twenty four geo-phones of 4.5 Hz resonant frequency are deployed at 1 m spacing along a survey line with receivers connected to multi-channel recording device. 10 kg sledgehammer is used as the active source placed with 1 to 2m intervals.

- ***Data Processing***

The CMP cross-correlation analysis will be applied to multichannel and multi shot surface wave data. The phase velocities of surface waves were calculated by multi channel analysis applied to the CMP cross-correlation common midpoint and by non linear least square inversion a 2D S-wave velocity profile was reconstructed (Shizhou et al., 2008).

➢ ***Calculation of liquefaction potential***

- ***Safety factor (Fs)***

The liquefaction potential based on Shear wave velocity (Vs), the safety factor against liquefaction of a soil at a particular depth in a soil deposit is defined as Eqn. 1.

$$F_s = \frac{CRR}{CSR} \quad \text{-- Eqn. 1}$$

Where, *CRR* is the resistance of the soil, which is expressed as the cyclic resistance ratio (*CRR*) and *CSR* is the loading induced by an earthquake which is expressed as the cyclic stress ratio (*CSR*). If the *Fs* are less than 1, the occurrence of liquefaction is predicted (Shizhou et al., 2008).

- ***Cyclic Stress Ratio (CSR)***

The most widely used method for evaluating liquefaction is the stress-based procedure first proposed by Seed and Idriss, 1971 [21] given by,

$$CSR = (\tau_{av} / \sigma_v') = (0.65 a_{\max} / g)(\sigma_v / \sigma_v') r_d \quad \text{--Eqn. 2}$$

Where, CSR = cyclic stress ratio representing seismic demand on soil layer;
amax = peak horizontal acceleration at the ground surface generated by the earthquake;
g= acceleration due to gravity;
σ_v and σ_v' are total and effective vertical overburden stresses respectively and
r_d = stress reduction coefficient

It is noted that conventional methods consider only peak ground acceleration (a_{max}) to reflect incident seismic motion and thus neglect the spectral characteristics of the input motion (Pathak and Dalvi, 2012) [22].

- ***Cyclic Resistance Ratio (CRR)***

The *CRR* expressed as the cyclic resistance is generally established by separating liquefied cases from non liquefied cases defined by Andrus et al. (1999) given in Eqn. 3 [23].

$$CRR = \left[a\left(\frac{V_{s1}}{100}\right)^2 + b\left(\frac{1}{c - V_{s1}}\right) - \frac{1}{c} \right] \quad \text{-- Eqn. 3}$$

Where, *a*, *b*, *c* are curse fitting parameters (*a* = 0.022, *b* = 2.8, *c* = 200 ~ 215*m)*; V_{s1} is overburden stress corrected shear wave velocity (m/s), which is defined in Eqn. 4.

$$V_{s1} = V_s \cdot \left(\frac{P_a}{\sigma_\upsilon'}\right)^{0.25} \quad \text{-- Eqn. 4}$$

Where, Vs is the measured shear wave velocity, (m/s); Pa: reference stress (100kPa); σ'_υ is initial effective overburden stress, (kPa). The parameter c in the Eqn. 3 represents the limiting upper value of V_{s1} for liquefaction.

- ***Liquefaction Index (P_L)***

The liquefaction index is calculated using Eqn. 5

$$P_L = \int_0^{20} F \cdot w(x)\, dx \quad \text{-- Eqn. 5}$$

Where, $F_L < 1.0$, $F = 1 - F_L$; $F_L \geq 1.0$, $F = 0$, $w(x)$ is weighted function value, $w(x) = 10 - 0.5x$ and x is the depth from surface (Shizhou et al., 2008).

The detection of soil liquefaction by using seismic records has been developed by various researchers such as, Trifunac (1995), Towahata et al. (1997), Kayen and Mitchell (1997) [24-26].

- ***Corrected SPT blow count and shear wave velocity***

The evaluation of soil liquefaction by SPT method depends on fines content and grain characteristics which incorporate below factors given in Eqn. 6.

$$(N_1)_{60} = N_{SPT}.C_N.C_E.C_B.C_R.C_S \quad \text{--Eqn. 6}$$

Where $(N_1)_{60}$ corrected standard penetration test blow count, N_{SPT} represents the measured standard penetration resistance, C_N is a factor to normalize, N_{SPT} represents the effective overburden stress, C_E represents the correction for hammer energy ratio (ER), C_B is the correction factor for borehole diameter, C_R is the correction factor for rod length, and C_S is the correction factor for samplers with or without liners.

Shear wave velocity should be corrected to overburden stress is given in Eqn. 7.

$$V_{S1} = V_S(\frac{P_a}{\sigma_V'})^{0.25}.(\frac{0.5}{K_0'})^{0.125} \quad \text{--Eqn. 7}$$

Where Vs is the shear wave velocity (m/s), V_{s1} is the stress-corrected shear wave velocity (m/s), Pa is the atmosphere pressure equal to 100kPa, σ'_V, shows the effective overburden stress and K'_o is the coefficient of effective earth pressure (in this study assumed equal to 0.5).

Notash et al., 2012 have studied the soil liquefaction potential by comparing of two Vs and SPT method of South Tehran by using above five empirical relations. He observed that the relationships between Standard Penetration Test and shear wave velocity are not appropriate because the empirical relations dependent on soil type, fines content (clay and silt), type of tests and their accuracy [27].

Chern and Chang, 1995 developed a mathematical model for the evaluation soil liquefaction characteristics subjected to earthquake loading. Based on the proposed mathematical model soil's physical properties such as cyclic shear strength, the number of cycles required to cause liquefaction or failure condition and the generation of excess pore water pressure can be evaluated [28].

Andrus and Stokoe, 2000 [29] outlines the procedure for evaluating the liquefaction resistance of soils using shear wave velocity. The traditional method of estimating the shear velocity of soil uses an instrumented borehole or penetrometer to measure the travel time of shear wave to various depths. Dual and multiple borehole studies have been used to measure the horizontal and vertical shear wave velocities of the ground. These methods indirectly estimate the soil shear velocity for soil liquefaction assessment through an inversion of the surface wave dispersion characteristics of the ground (Stokoe et al., 1994) [30].

METHODOLOGY OF CO2 SEQUESTRATION

From past several years atmospheric CO_2 concentrations have steadily increased and have now risen to over 370 ppm from the pre-industrial level of 280 ppm. The release of CO_2 to the atmosphere mainly due to burning of coal, oil and natural gas for electrical generation, transportation, industrial and domestic uses. Today, globally, over 20 billion tons of CO_2 are emitted into the atmosphere and of that, 5.5 billion tons are from the U.S. alone. The increase of CO_2 concentration in atmosphere will disrupt the earth's climate, cause sea level to rise enough to flood many low-lying coastal regions, and damage sensitive ecosystems. In view of this several authors have done research to avoid significant disruption of the climate system and ecosystems, due to which CO_2 concentration must be stabilized within the next several decades. At today's emission rates, atmospheric CO_2 concentrations will continue to grow rapidly and, within 50 years, may exceed the levels needed to protect sensitive ecosystems. Benson and Cole, 2008 reported that the Carbon dioxide capture and sequestration (CCS) in deep geological formations has recently emerged as an important option for reducing greenhouse emissions. Hence, Benson made an approach to decrease CO_2 emissions by Carbon Dioxide Capture method and storage in underground geologic formations. CCS in underground geologic formations is unique among the options for reducing CO_2 emissions. The main purpose behind CCS is that CO_2 is captured before it is emitted into the atmosphere and then injected deep underground where it would remain for thousands of years or longer without affecting the soil characteristics which causes soil liquefaction [31].

In recent days, researchers have found evidence that underground carbon dioxide injection in oil and gas fields may cause earthquakes, which arises carbon sequestration leads due to soil liquefaction. Researchers reported that injecting CO_2 gas into underground could cause seismic activity. Now days, Carbon sequestration process is done by various industries in geological pits. This creates a major threat to the earth quake problems worldwide.

- ***CO_2 Capture and Storage Technology***

CCS is a four-step process where at first, a pure or nearly pure stream of CO_2 is captured from process stream; next it is compressed to about 100 atmospheres; it is then transported to the injection site; and finally, it is injected deep underground into a geological formation such as an oil and gas reservoir where it can be safely stored for thousands of years or longer (Fig. 2).

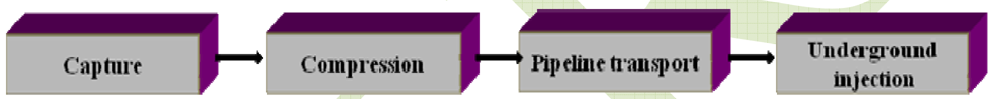

Fig. 2 Schematic presentation showing the major steps in the Carbon Capture and Storage Process

Burruss (2004) focused on the potential for physically trapping of carbon dioxide in deep geologic formations. Long-term storage is even more secure when the CO2 dissolves in water or is converted to minerals such as calcium carbonate. From 10 to 30% of the injected CO2 will usually dissolve into the formation water shortly after it is injected. The CO2 dissolves in the liquid, some fraction of that will be converted to minerals that will remain trapped over geologic time scales of millions of years [32].

Simbeck (2004) calculates that CO_2 capture (separation and compression) alone will increase the cost of electricity from $43 per MWh to $61-$78 per MWh for new power plants and from $17 per MWh to $58-$67 per MWh for existing coal plants that have already been paid off. Separation and compression typically account for over 75% of the costs of CCS, with the remaining costs attributed to transportation and underground storage [33].

Zweigel et al., 2001 studied on the seismic imaging of the plume of CO_2 injection into a deep geologic formation below the sea floor in the North Sea. He indentified that electromagnetic and gravitational measurements have lower sensitivity and resolution, but may be used in combination with seismic techniques to fine-tune the interpretation of the data or in the interim between seismic measurements [34].

Orcutt, 2013 suggested that storing of carbon dioxide in one particular type of underground rock could significantly reduce the risk by forming minerals. *Geophysical Research Letters* suggests that storing carbon dioxide underground in a type of volcanic rock called reactive mafic rock could potentially present little seismic risk, because the surface of mafic rock reacts with carbon dioxide to form a solid mineral *Geophysical Research Letters* suggests that storing carbon dioxide underground in a type of volcanic rock called reactive mafic rock could potentially present little seismic risk, because the surface of mafic rock reacts with carbon dioxide to form a solid mineral [35].

Compressed CO_2 can be injected into porous rock formations below the Earth's surface using many of the same methods already used by the oil and gas industry. The three main types of geological storage are oil and gas reservoirs, deep saline formations, and un-minable coal beds. CO_2 can for instance be physically trapped under a well-sealed rock layer or in the pore spaces within the rock. It can also be chemically trapped by dissolving in water and reacting with the surrounding rocks. The risk of leakage from these reservoirs is rather small. It is technically feasible to use captured CO_2 in industries manufacturing products such as fertilisers. In the UK, all carbon dioxide storage sites will be located offshore (under the seabed) and therefore any minor seismic event/earthquake would not be felt by the public. If any major event was to occur offshore, this would be detected by onshore seismic measurement technologies. A recent report by the US Department of Energy's National Energy Technology Laboratory found that no earthquakes have been associated with any of the global carbon dioxide injection tests, or any of the many projects using carbon dioxide for Enhanced Oil Recovery. Managing carbon dioxide injection is an ongoing process and in a very small number of cases where a risk of induced seismicity may be found, action will be taken to reduce this risk such as shot down of injection wells.

CONCLUSION AND RECOMMENDATION

This paper had outlined the different methods of evaluating soil liquefaction and CO_2 sequestration in last few years. The controversy and confusion of the fines grained soils behaviour after disturbed by cyclic load is complex. Hence, review on fine grained soils which vulnerable to liquefaction must be study and more related research on this was warranted. More recent, researchers tentatively consider the liquefaction index as controlling variable in their study on liquefaction susceptibility. Given the current literature reviews, it is believed that different empirical equations evaluate soil liquefaction potential. The detection of soil liquefaction by using seismic records has been developed by various researchers. With this information, the evaluation of soil liquefaction are well understood and this lead to a more precise and confident output.

Gaining support for CCS will require engaging the interest and building the support of a variety of stakeholders, each with different perspectives and goals. Although CCS builds upon a technology base developed over more than half a century by the oil and gas industry. In the past, the industrially released CO_2 had been introduced to ocean which was harming the aquatic animals. In view of this, the sequestration of CO_2 into ocean was internationally banned. Hence, now a day's much of the Carbon sequestration process is done by various industries in geological pits. This creates a major threat to the earth quake problems worldwide. With the enhanced frequency of earthquakes all around the world, it is presumed by many environment scientists that the CO_2 sequestration pits leads to soil liquefaction and hence it results in more frequent earth quakes. Therefore, this paper summarises, different methods to evaluate liquefaction potential of soil by using studies from seismic waves generated in earth, it is also explains different methodology for an eco friendly technology to reduce CO_2 from environment.

Acknowledgements

One of the authors would like to thank the Sophitorium Engineering College, Bhubaneswar, Odisha, India for the financial support.

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