International Journal of Civil and Structural Engineering Research ISSN 2348-7607 (Online)
Vol. 4, Issue 1, pp: (55-69), Month: April 2016 - September 2016, Available at: www.researchpublish.com

Comparative Study of Potential Liquefaction of Three Selected Locations along the Pasig City Segment of the Valley Fault System, Philippines

Anjerick J. Topacio[1], Alyssa Erika P. Ramos[2], Jayson E. Villaester[3], Joanna Carla A. Pacamparra[4]

Abstract: **This study deals with the analysis of the potential seismic – induced liquefaction which is a complex ground failure phenomenon observed when saturated loose sand deposits loss its shear strength. It may be quantified as to the damage that it causes to the built infrastructures within the vicinity. This study was conducted to determine the potential liquefaction of three specific locations along the Pasig City segment of the Valley Fault System in Barangay Kapitolyo, Manggahan and Ugong and correlate it with their respective soil suitability. The study employed secondary data from geotechnical firms, DOST – PHIVOLCS and the local government unit of Pasig City. The results were assessed through the use of an excel program devised by the researchers based on a simplified procedure by Seed and Idriss (1997), and Das (1995). The factor of safety due to liquefaction (FS) at specific soil conditions was computed using this program and proved that the chosen location in barangay Ugong is the most susceptible to liquefaction among the three chosen locations. The mitigation measures for the soil and/or the type of foundations to be applied was considered and pile foundations are recommended in the locations in baranggay Manggahan and Ugong. Shallow foundations are, on the other hand, safe in barangay Kapitolyo.**

Keywords: **Liquefaction, Earthquake, Seismic, Valley Fault System.**

1. INTRODUCTION

1.1 Background of the study:

A seismic – induced liquefaction is a complex ground failure phenomenon observed when saturated loose sand deposits loss its shear strength. During seismic activity, the continuous cyclic loading increases the pore water pressure that causes the soil to behave like liquid. The potential soil liquefaction is primarily influenced by factors such as void ratio and relative density of soil, depth of water table, effective confining stress, coefficient of lateral earth pressure, seismic and geologic history of the site and the recorded intensity and duration of the locale (Raychowdhury & Basudhar, 2011).

The effects of liquefaction may be quantified as to the damage that it causes to the built infrastructures within the vicinity. The loss of the effective stress of the soil affects the structure's foundation through settlement. Surface rapture and structure failure are some of the detrimental effects produced by the instability of subsoil conditions. Major earthquakes that have occurred in the past years such as 1964 Alaska, 1964 Niigata, 1989 Loma- Prieta and 1995 Hyogoken- Nambu have demonstrated the damaging effects of soil liquefaction (Liyanapathirana & Poulos, 2003).

In the Philippine setting, the Valley Fault System is one of the country's active fault lines that are found in Central Luzon. It is a group of strike- slip fault extending from San Mateo to Marikina and running through the cities of Marikina, Makati, Pasig, Parañaque and Taguig. The fault is divided into two segments namely East Valley Fault and West Valley Fault. Valley Fault System or the formerly known as Marikina Valley Fault System is classified under a Seismic Source Type "A". As defined in the National Structural Code of the Philippines, it is described to be an active fault capable of producing large magnitude events with a high rate of seismic activity. The projected magnitude under Source Type "A" is greater than or equal to seven (7) which has an intensity range of "Destructive" to "Completely Devastating (DOST-PHIVOLCS, 2011).

Aside from the seismic source type, Near Source Factor is also used for designing the earthquake loading for a structure. The proximity of the location to the nearest active fault varies the factor of safety required by an infrastructure. The nearer the location to the epicenter, the greater the damage that may be expected, and it includes the higher possibility of liquefaction occurrence (Sumer et al., 2007).

The cities along the Valley Fault System are classified to be the most highly urbanized locations within Metro Manila. Large infrastructures and skyscrapers may be found to the vicinities where traces of fault are visible or approximated to lay. These are where the country's prime business districts like the Ortigas Center, which lies in the west of Pasig City, the Tiendesitas along the C-5 road, large billboards in Ugong Pasig City and other establishments are situated, thus a large portion of the economy is derived from it. Natural geological hazards like earthquake and its sub consequences may be imminent, but proper pre-assessment of the risk may eliminate its worse effects. The main objective of the study is to determine the potential liquefaction of three barangays along the Pasig City segment of the Valley Fault System which is developing in to the city's economic resources namely Barangay Kapitolyo, Barangay Manggahan and Barangay Ugong and correlate it with the land use of the specific location gathered in these barangays.

1.2 Glossary:

- **Liquefaction** - The process by which saturated, unconsolidated soil is converted into a suspension
- **Cyclic stress ratio (CSR)** - The loading induced at different depths in a soil profile during seismic activity
- **Cyclic resistance ratio (CRR)** - The amount of seismic/ cyclic load that a soil profile may resist
- **Factor of safety (FS)** - The ratio of CRR and CSR; a constant value that defines the required strength amplification to resist liquefaction
- **Standard Penetration Test (SPT)** - An in situ test conducted to measure soil density through the resistance of soil to penetration by quantifying the blow count needed in able to get through the soil layer
- **Soil Suitability** - Adequacy of the soil to support infrastructures during a large seismic event
- **Total Vertical Stress** - Overburden pressure of soil**.**
- **Pore Water Pressure** - The pressure of groundwater held within a soil or rock, in gaps between particles (pores)
- **Effective Vertical Stress** - Pore water pressure subtracted to total overburden of soil
- **Energy Correction** - Using different kinds of hammers, with different energy delivery systems which also have varying degrees of efficiency. The main reason for this variation is due to the use of different methods for raising and dropping the hammer
- **Acceleration in G** - Maximum horizontal acceleration of the ground surface in units of G from earthquake records of magnitude M
- **Deformability Reduction** - To reduce the ability to change the original state or size of a rock mass, especially by folding or faulting
- **Magnitude** - The magnitude is a number that characterizes the relative size of an earthquake

2. STATEMENT OF THE RESEARCH PROBLEM

The research sought to determine the potential liquefaction of three locations along the Pasig City segment of the Valley Fault System by evaluating different soil parameters such as unit weight of soil, depth of water table, effective stress and seismic history of the site

3. OBJECTIVES, SIGNIFICANCE, AND SCOPE OF THE RESEARCH

3.1 General Objective:

The main objective of this study is to determine the potential liquefaction of three locations along the Pasig City segment of the Valley Fault System namely Kapitolyo, Manggahan, and Ugong by evaluating the parameters such as unit weight of soil, depth of water table, effective stress and seismic history of the site obtained from secondary data.

3.2 Specific Objectives:

The study's specific objectives are: (a) To determine the potential liquefaction of the three selected areas in Pasig City in terms of factor of safety due to liquefaction. (b) To determine which of the areas has the greatest potential liquefaction. (c) To determine the mitigation measures for the soil and/or the type of foundation that can be applied to the selected areas considering their potential liquefaction.

3.3 Significance of the study:

The goal of this study is to determine the potential liquefaction of three locations along the Pasig City segment of the Valley Fault System namely Kapitolyo, Manggahan, and Ugong and to identify which of the areas has the greatest susceptibility. The local soil's unit weight, depth of water table, effective stress and seismic history of the site were used to evaluate its vulnerability to liquefaction. Through this, the study was able to determine the possible mitigation measures for the soil and/or the type of foundation that can be applied to the selected locations taking into consideration the sites' potential liquefaction.

In the Philippine setting, natural hazards like typhoons and earthquakes are common scenarios. However, the simultaneous occurrence of two natural hazards may further amplify the damage that each may cause. This study could help engineers and planners in considering the probable effects of these hazards to their design. Through this, the possible damages could be mitigated.

For civil engineering students, this study would help them to derive further studies on the branch of seismic and geotechnical engineering. This study will promote long term planning and designing of infrastructures in the micro and macro setting taking into consideration the potential liquefaction of the selected areas.

3.4 Scope and delimitation of the study:

The study focuses on the investigation of the potential liquefaction of three specific locations along the Pasig City segment of the Valley Fault System specifically on a site in barangay Kapitolyo, Manggahan, and Ugong through evaluating the parameters such as unit weight of soil, depth of water table, effective confining stress, and seismic and geologic history. The data that were used in evaluating the potential liquefaction of the vicinities were obtained from soil tests reports from geotechnical firms, secondary data from the local government unit of Pasig City and records from Department of Science and Technology- Philippine Institute of Volcanology and Seismology (DOST- PHIVOLCS). The specific locations that were evaluated are only those which are within five kilometers (5km) range of distance from the Valley Fault System to determine the maximum possible effect of a seismic activity.

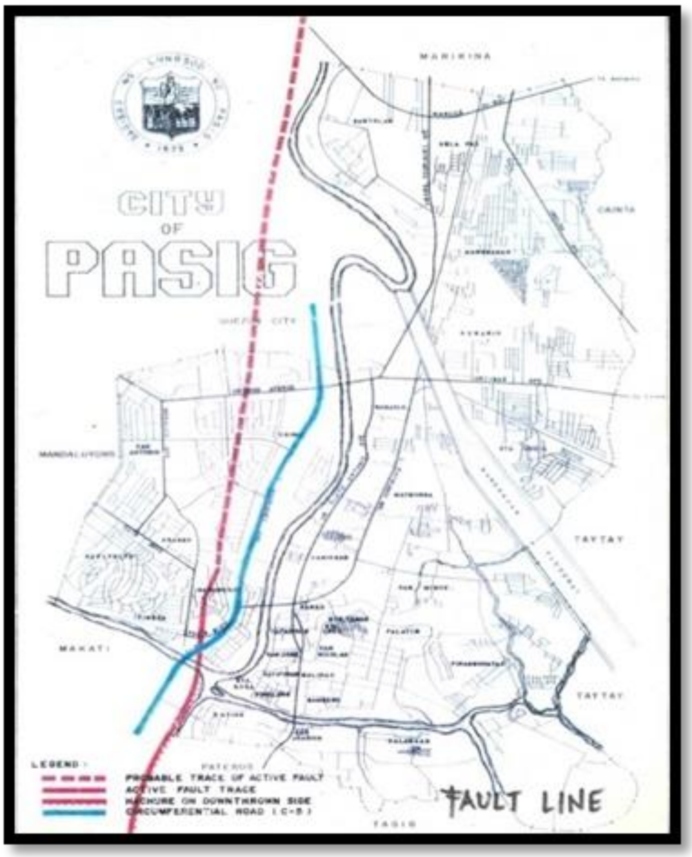
4. REVIEW OF THE LITERATURE

4.1 Earthquake:

Earthquake is a natural phenomenon caused by sudden movement of faults and trenches (tectonic) or by movement of magma beneath volcanoes (volcanic). This geologic hazard poses detrimental effects to lives and properties which are manifested either directly or indirectly. Seismic activities may cause threat to lifelines and utilities that people basically need (i.e. water supply, communication and transportation facilities, and electrical networks). The stability and the integrity of an infrastructure may also be at risk if the local soil reaches failure. The condition where the soil behaves like liquid after exposure to a devastating shaking is called liquefaction (DOST- PHIVOLCS, 2011).

In the Philippines, the seismic activities are quantified to be twenty (20) recorded earthquakes per day, two hundred (200) felt earthquakes per year and ninety (90) destructive earthquakes for the past four hundred (400) years. The seismicity of the country is directly associated with the two earthquake zone classification of the country (Zone 2 and Zone 4) and that it belongs to the "Pacific Ring of Fire" (DOST- PHIVOLCS, 2011).

One of the seismic generators in Central Luzon is the Valley Fault System and one of the cities that it traverses is Pasig City. The Pasig City segment of the Valley Fault is shown in Figure 4.1.



(Planning Department of Pasig City Hall, 2011)

Figure 4.1 Pasig City Segment of the Valley Fault System

The Valley Fault System's major historical activities are presented in Table 4.1.

Table 4.1 Major Historical Earthquakes Generated by Valley Fault System that have Affected Manila and Vicinity

Event	Intensity	Impact
1599 Jun	VIII	Violent earthquake; damaged many buildings in Manila including the Sto. Domingo Church located on bedrock (adobe); other effects include fissuring of the stone vault of the society of Jesus and other principal edifices in the city.
1601 Jan	VIII	Violent earthquake; completed destruction wrought by 1599 June earthquake; damage to the city was immense, destroying many stone houses, churches and injuring/ killing an unspecified number of people.
1658 Aug	IX	Most buildings in Manila, mainly made of wood and timber, were wiped out; several persons killed/ injured.
1885 Nov	VII	Strong but no serious damage; strong sub- terranean noise observed in Marikina and suburbs of Manila.

(PHIVOLCS Professional Paper 01, 1997)

4.2 Liquefaction:

One of the major effects of a moderate to large earthquake is the seismic induced liquefaction which is technically the generation of excess water pressure, loss of shear strength and excessive volume contraction of saturated loose soil (Raychowdhury & Basudhar, 2011). It is the transformation of the granular material from a solid to a liquefied state after the induction of cyclic loading made by a seismic excitation (Sumer et al., 2007). Liquefaction is one of the major causes of destruction whenever an earthquake occurs and it should be one of the considerations in hazard investigations for buildings, pipelines, railway, highway bridges and land use planning. Primary method used in the United States and many other countries in analyzing liquefaction hazard is the simplified procedure developed by Seed and Idriss (1971).

Potential liquefaction depends on the nature of ground shaking and the site's geological condition (Sumer et al., 2007). The factors that significantly affect liquefaction are the void ratio and relative density of soil, depth of water table, effective confining stress and coefficient of lateral earth pressure (Raychowdhury & Basudhar, 2011). The term liquefaction, however, varies with respect to soil classification. For loose sand, liquefaction occurs after the complete loss of strength due to the 100% build up of pore water pressure, accompanied by a softening and large deformation. For medium dense to dense sand, it is characterized by the 100% build up of pore water pressure accompanied by about 5% double amplitude axial strain but of limited deformation. The plasticity of fines to silty sands or sandy silts defines its liquefiability. Silty soils with non plastic fines make it easily liquefiable while cohesive fines increase its cyclic resistance (Sumer et al., 2007).

Such condition is catastrophic to infrastructures especially when the effective stress of the soil reaches the level that it can no longer support the building's foundation. Settlement on footings and piles may occur as the shear strength of the soil depletes. Structures built underground are also directly affected by liquefaction. Example of which are buried pipelines and storage tanks. The extent of damage may be further magnified when structures are located near the epicenter of the earthquake.

In understanding the potential liquefaction of an identified location, the locale's geologic and seismic history must be considered. This would include the recorded intensity, duration and the characteristics of the ground shaking of the specific vicinity. The study and analyses of the potential liquefaction of vicinity are strongly recommended especially when infrastructures of special purpose are to be built within the site. Locations for high risk infrastructures such as dams and nuclear power plants must be evaluated (Raychowdhury & Basudhar, 2011).

Liquefaction in Dagupan City, 1990:

Liquefaction is a major secondary effect of the July 16, 1990 Luzon earthquake with a magnitude of 7.8 in a large elongated zone of the Central Plain. Cohesionless saturated fine sandy and silty sediments near the ground surface are liable to liquefy under the effect of intense cyclic ground shaking.

Dagupan City is located on a flat terrain where extensive deposits of loose sand and gravels are present. There are numerous abandoned stream meanders and wetlands, which are prone to liquefaction (Torres et al., 2001).

The mid-Luzon tectonic depression, known as the Central Plain (about 30,000 sq. km), was filled with clastic sediments during the Tertiary and Quaternary. The uppermost part of the sequence, consisting of loose to very loose fine sand, reacted to the ground-shaking with liquefaction on a regional scale (Orense, 2011).

The earthquake was said to have been accompanied by a terrifying noise with felt aftershocks lasting until the following year (Punongbayan, 2011).

Effects of 1990 earthquake:

Close to around 500 buildings and residential houses underwent severe settlements as well as varying amounts of tilting as a result of the loss in strength of the underlying soil in Dagupan City. Except for one, no building in the affected area was supported by piles and, therefore, no resistance was possible against subsidence after liquefaction. Earthquake shaking did not destroy buildings in the area nor cause any structural damage (Orense, 2011). Also lateral spreading occurred along the banks of Pantal River of about 3 to 5 meters. The 5-storey Asia Career Building subsided by more than 1m, with minor structural damage; however, the 1-storey section adjacent to it was severely distorted. Magsaysay Bridge collapsed as a result of the lateral movement of the opposing banks of Pantal River where the bridge abutted. As a result of liquefaction of the river bank, the bridge piers sank and tilted towards the center of the river. Roads became virtually impassable because of cracks in road pavements. Several buried structures, such as gasoline tanks, septic tanks and buried pipes, were uplifted due to the buoyant force exerted by the liquefied soil. A buried water pipe along Rizal Street buckled and was thrust upward. Immediately after the earthquake, much of the town was coated in dark-grey mud and water ejected from fissures in the ground (Orense, 2011).

4.3 Liquefaction Ingredients:

Current sediments or fills of saturated, cohesionless soils located at shallow depths will be heavily prone to liquefaction during large earthquakes. Geologic history, confining pressure, density, and characteristics of the soil grain affect the liquefaction susceptibility of a specific deposit (Rauch, 2001).

The ground at the site must be "loose" – uncompacted or unconsolidated sand and silt without much clay or stuck together. The sand and silt must be "soggy" (water saturated) due to a high water table. Lastly, the site must be shaken long and hard enough by the earthquake to "trigger" liquefaction (Perkins, 2001).

Table 4.2 shows the liquefaction hazard based on combinations of Modified Mercalli Intensity (MMI) and liquefaction susceptibility (Perkins, 2001).

Table 4.2 Liquefaction Susceptibility based on Combinations of Modified Mercalli Intensity (MMI)

MMI Value	Description of MMI Shaking Severity	Liquefaction Susceptibility Category				
		Very low	Low	Moderate	High	Very High
I	-	-	-	-	-	-
II	-	-	-	-	-	-
III	-	-	-	-	-	-
IV	-	-	-	-	-	-
V	Light	-	-	-	-	-
VI	Moderate	-	-	-	-	-
VII	Strong	-	-	Moderately Low Hazard	Moderately Low Hazard	Moderate Hazard
VIII	Very Strong	-	-	Moderate Hazard	Moderate Hazard	Moderate Hazard
IX	Violent	-	-	High Hazard	High Hazard	High Hazard
X	Very Violent	-	-	High Hazard	High Hazard	High Hazard

(The Risk Plates Supplemental. Retrieved August 2011, http://www.abag.ca.gov/bayarea/eqmaps/mitigation/TheRisk-Plates-Supplemental.pdf)

4.4 Liquefaction Measurement:

If sand boils, ground cracking, lateral ground movement, settlement or transition of structures, bearing capacity failures, or uplifting of buried pipes and tanks are observed, liquefaction occurs. It is assumed that there's no liquefaction if there is no surface evidence observed. Still, deeper soils could have liquefied without producing surface indication (Rauch, 2001).

4.5 Liquefaction Resistance Assessment:

Assessing the liquefaction resistance of soil is one of the most significant measures in the engineering design of new structures and in the retrofitting of existing ones especially those earthquake prone areas. Simplified Procedure which was first introduced by Seed and Idriss is the method used in the United States and most of the countries in the world. Simplified Procedure uses the blow counts from the Standard Penetration Test (SPT) which is correlated with a parameter representing the seismic loading on the soil, called Cyclic Stress Ratio. Small-strain shear wave velocity Vs, measurements can be an alternative way to the penetration-based approach. Void ratio, state of stress, stress history and geologic stress influence both Vs and liquefaction resistance, and for that reason the use of Vs as index of liquefaction is completely supported. (Andrus & Stokoe, 2001)

Mathematically, the potential liquefaction of a location may be quantified through tests. There are two general approaches used in determining the susceptibility of the local soil to such ground condition. First is the use of laboratory testing of undisturbed samples and second is the use of empirical relationships obtained from in situ "index" test. The laboratory testing of soil samples requires a good preparation of the specimen because it strongly affects its resistance to cyclic loading. Remolded and reconstituted samples have less in situ stress history which leads to the underestimation of liquefaction. Undisturbed soil sampling techniques have been developed through the years. Examples of which are the *in situ freezing* and *frozen shelby tube samples*. Investigations were conducted and it was determined that the sampling method have lower liquefaction resistance compared with the undisturbed samples. Due to this, empirical approaches were used as a viable tool for testing. Four Empirical Liquefaction Models (ELMs) are used in assessing the potential liquefaction of a location. First is the standard penetration test (SPT), second is the cone penetration test (CPT), third is the measurement of shear wave velocity (Vs) and last is the Becker penetration test. SPT is executed to determine the stiffness of the local soil and it is done inside a borehole. The CPT, on the other hand, measures the stress, sleeve friction and the pore water pressure. The Vs measures the shear wave velocity profile of the soil. The assessment methods used in determining the susceptibility of the soil is aided with the values expressed in terms of cyclic stress ratio (CSR) and the cyclic resistance ratio (CRR). The evaluated variables dictate the factor of safety at a given depth (Sumer et al., 2007).

The simplified methods in potential liquefaction assessment are very useful in creating preliminary designs. The loading parameters that are often used in testing are represented by either the generated cyclic shear stress due to earthquake or by the amount of energy released (Liyanapathirana & Poulos, 2003). The relationship between the values of CSR and CRR derives the factor of safety for liquefaction that may be used in structural analysis.

The most comprehensive liquefaction data catalogues are based on Standard penetration Test (SPT) blowcounts (N_{SPT}). Starting in 1970's, H. B. Seed and his colleagues worked to develop a reliable method for assessing liquefaction potential based on SPT data. Their framework for SPT-based assessment of liquefaction potentials was developed in a series of papers that includes Seed and Idriss (1971), Seed et al (1977), Seed (1979), Seed and Idriss (1981; 1982), and Seed et al (1983) (Rauch A. F., 2001).

The simplified procedure formulated by Seed and Idriss in evaluating potential liquefaction is dicussed below.

Induced Shear Stress, τ_i can be computed using the Seed-Idriss Simplified Liquefaction Evaluation Procedure. The maximum shear stress induced at depth z is given by:

$$(\tau_i)_{max} = \sigma * a_{max} * r_d \qquad \text{Equation 4-1}$$

where:

σ_v is the total vertical stress

a_{max} is the peak horizontal acceleration at the ground surface

r_d is the stress reduction coefficient at depth z.

For the period of ground shaking, at least a maximum shear stress is induced.

Seed and Idriss (1967) used a 0.65 coefficient to be multiplied to $(\tau_i)_{max}$ to characterize an "equivalent uniform shear stress".

$$(\tau_i)_u = 0.65 * (\tau_i)_{max} = 0.65 * \sigma * a_{max} * r_d \qquad \text{Equation 4-2}$$

The values of the magnitude scaling factor (MSF) consider that MSF=1 for M_w=7.5.The value of the MSF can be computed using the equation:

$$MSF = 6.9 \exp\left(-\frac{M}{4}\right) - 0.06 \qquad \text{Equation 4-3}$$

The anticipated value of MSF is restricted up to MSF=1.82 for Mw $\leq$ 5.2. The controlled value is because of the fact that the equivalent uniform induced stress is measured to be equivalent to 0.65 of the maximum induced stress. The maximum stress must be at least more than half to one cycle. It can be practical to consider that the peak shear stress would work at about ¾ cycle.

MSF value cannot be more that of the ratio of the CSR at ¾ cycles divided by CSR for 15 cycles multiplied by 0.65 and can be written as:

$$\text{MSF} \leq \frac{CSR\ for \frac{3}{4} Cycles}{CSR\ for\ 15\ Cycles} * 065 = \frac{2.8}{1} * 0.65 = 1.82 \qquad \text{Equation 4-4}$$

The equivalent uniform induced stress at a certain depth z with regards to ground motions produced by an earthquake with a magnitude Mw can be written as:

$$(\tau_i)_w = \frac{0.65(\tau_i)_{max}}{MSF} = \frac{0.65\sigma_v * a_{max} * r_d}{MSF} \qquad \text{Equation 4-5}$$

The stress reduction coefficient, r_d was originally formulated by Seed and Idriss (1971) and was given in chart form with an average value ranging from 1 at the ground surface to about 0.85 at depth of 40 ft (-12.2m), while the complete range of the parameter r_d was from a range of magnitudes of earthquakes. Recent studies of Golesorkhi (1989) under the supervision of the late H.B. Seed show the variations of r_d with earthquake magnitude.

The induced shear stress at depth z is proportional to the ratio (r_d/MSF). If r_d has no connection with magnitude, then it is essential to adjust MSF to reflect the potential reduction r_d with decreasing value of magnitude.

The effect of magnitude on r_d at shallow depths is not as important as it is at greater depths. Consequently, it is necessary that the two parameters be determined separately and properly include in assessing the liquefaction potential at a site (Idriss, 1999).

The liquefaction potential index may be introduced to the analysis to determine the severity of the possible liquefaction at a given depth of soil sample. LPI exhibits the probability of surface manifestation of liquefaction. It may be assumed that the severity of liquefaction is proportional to the thickness of the liquefied layer, proximity of the affected layer to surface and to the factor of safety amounting to less than 1 (Toprak & Holzer, 2003).

4.6 Liquefaction Modeling:

Through the continuous search for the quantification of the liquefaction vulnerability of soil, numerous modeling were derived in order to get the most precise values that may be used in the engineering practice. The common means of measurement in the field are the penetration tests (standard penetration test (SPT) and cone penetration test (CPT)) that are used in determining the soil density and stress of soil. These in situ tests are said to produce volumetric stresses in soil; thus, pore water pressure induced by the shear is not directly measured. In order to mitigate the discrepancies produced by the method and to better understand the basic mechanisms, liquefaction modeling like torsional shear test, centrifuge model, and constitutive model were then developed.

Torsional shear test may be done through laboratory experiments or field tests. Laboratory set up intends to identify the distinct pattern between the torsional moment and the rotation angle of cylinder for dilative behavior of sample. The field test, however, is executed by slightly modifying the standard penetration test (Dehghani et al., 2001). Centrifuge earthquake modeling is intended to produce an artificial gravitational field higher than that of the earth's gravitational field. The prototype simulates the soil structure system and the response of the system to dynamic loading (Dobry & Liu, 2002). Lastly, the constitutive model is focused on the deviatoric stress- strain response mechanism of soil. Cyclic laboratory tests are included in this model to produce salient relations of deformations to the cycle of applied load (Elgamal et al., 2002).

4.7 Effects of Liquefaction: Ground Failure and Settlement:

When ground liquefies and "fails," it may cause damage to built environment. These failures take the form of flows, lateral spreads, ground oscillations (or movement of the surface layer of ground separately from the underlying liquefied layers), loss of bearing strength (to hold up buildings or hold tanks and pipes underground); and settlement and differential settlement (Perkins, 2001).

Typically, "flows" failure occurs on slopes of more than 3 degrees, while "spreads" failure are on less steep slopes (EERI, 1994). A lateral spread failure is a failure where a layer of ground at the surface is carried on an underlying layer of liquefied material over a nearly flat surface toward a river channel or other bank (Perkins, 2001). Also, when soil liquefies, it becomes "weaker." It may lose its capacity to support buildings, particularly large buildings with poorly designed foundations. In addition, underground tanks and pipelines can "float" upwards, sometimes all the way to the surface. Another common problem is settlement as soil compacts and consolidates after the ground stops shaking.

Settlement can range from 1% - 5% of the liquefiable layer. In very loose sands, it can be as large as 10% of the thickness of the saturated loose materials that liquefy (Tokimatsu & Seed, 1984). Although small uniform changes are typically not damaging, the soil can settle unevenly. This problem, called differential settlement, occurs when the layers that liquefy are not of a uniform thickness, a common problem when the liquefaction occurs in artificial fills, particularly fills that have been placed during different times and using different techniques. Thus, using the 10% settlement estimate for loose materials, if the liquefying layers are 10 feet different in thickness, differential settlement of a foot can be achieved (Perkins, 2001).

4.8 Soil Improvement: Soil Grouting:

Grouting is a widely used method for strengthening and sealing rock, soil and concrete. The possibilities for sealing structures are of great importance from both an economic and environmental point of view. The primary purpose of any grouting project is to alter, to a desired degree, the properties of an existing medium by the most economical means. Different grouting types that can be used include:

Portland-cement grout is a mixture of portland cement, water, and, frequently, chemical and mineral additives (Guyer, 2009).

Soils used as the primary grout ingredient can be divided into two classifications. One includes the natural soils found at or near the project with little or no modification required. The second includes commercially processed clay such as bentonite (Guyer, 2009).

In 1957 there had been some 87 patents issued for processes related to chemical grouting. Since then, there undoubtedly have been more. These processes cover the use of many different chemicals and injection processes. The primary advantages of chemical grouts are their low viscosity and good control of setting time. Disadvantages are the possible toxic nature of some chemicals and the relatively high cost (Guyer, 2009).

5. METHODS

The study employed secondary data from geotechnical firms, Department of Science and Technology- Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS) and the local government unit of Pasig City in determining the potential liquefaction of selected locations in three different barangays namely Barangay Kapitolyo, Barangay Manggahan and Barangay Ugong along the Pasig City segment of the Valley Fault System. The process, as shown in figure 2, was followed.

5.1 Data Gathering:

The data used in this study such as surface geology maps were obtained from Department of Science and Technology- Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS). The quantities were utilized as a secondary data in assessing the liquefaction susceptibility of a selected location in three different barangays namely Barangay Kapitolyo, Barangay Manggahan and Barangay Ugong along the Pasig City segment of the Valley Fault System. The researchers also coordinated with geotechnical engineering professionals in determining the soil properties of the selected locations through soil test results. Also, the researchers secured the local fault line map of the selected locations from the local government of Pasig City. The figure below shows the flow of the study. The inputs and the corresponding outputs are stated. Different methods were used to yield these results.

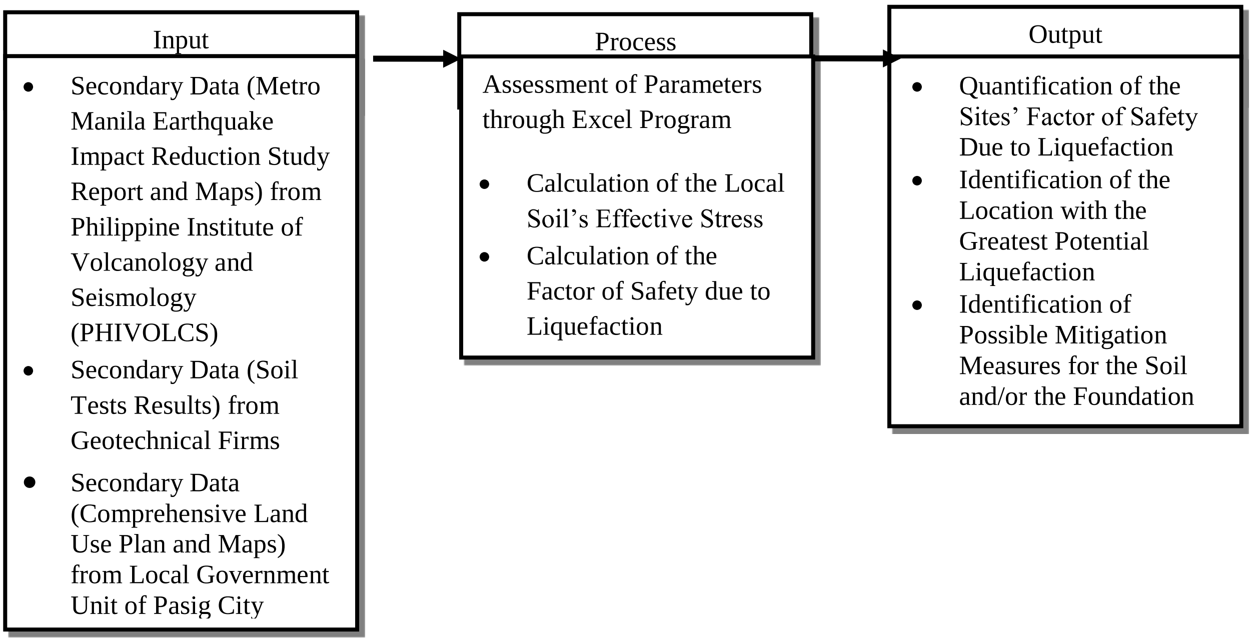


Figure 5.1 Methodological Framework

5.2 Data Analysis:

The specific test locations were derived from the Active Fault Map, Geological Surface Map, and Valley Fault System Map that were obtained from the Department of Science and Technology- Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS); and from the Pasig City segment of the Valley Fault System Map that was obtained from the local government unit of Pasig City.

The gathered quantified subsurface parameters (void ratio, ground water level, relative density of soil, and effective confining stress) of the selected locations were assessed through the use of an excel program based on a simplified procedure by Seed and Idriss (1997), and Das (1995) for SPT correction. The input values were obtained from the geotechnical tests results. The assessment aimed to determine the factor of safety due to liquefaction (FS) at specific soil conditions. The FS values were derived from the Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) by following the simplified procedure formulated by Seed and Idriss (1997). The corresponding results from the test locations were compared to identify which has the greatest liquefaction susceptibility. The equations used to determine the Factor of Safety (FS) are mathematically written as:

a. Total Vertical Stress, σ_{TZ}

$$\sigma_{TZ} = (MD_Z - MD_{Z-1})\gamma_{SOILZ} + \sigma_{TZ-1} \qquad \text{Equation 5-1}$$

where:

MD_z – middepth at depth z (m)

$$MD_Z = \frac{DEPTH_Z - DEPTH_{Z-1}}{2} + DEPTH_{Z-1}$$

γ_{soil} – dry unit weight of soil (kN/m^3)

b. Pore Water Pressure, U_z

$$U_Z = IF(U1_Z < 0, 0, U1_Z)$$

$$U1_Z = \frac{DEPTH_Z - DEPTH_{Z-1}}{2} DEPTH_Z \gamma_W - (GWT \cdot \gamma_W) \qquad \text{Equation 5-2}$$

where:

γw – unit weight of water (9.81 kN/m^3)

GWT – Ground Water Table (m)

c. Effective Stress, σ_{EZ}

$$\sigma_{EZ} = \sigma_{TZ} - |U_Z| \qquad \text{Equation 5-3}$$

where:

σ_{TZ}= total stress (kN/m^2)

U_Z= pore water pressure (kN/m^2)

d. SPT Correction (Das, 1995), N_{CORZ}

$$N_{CORZ} = \frac{9.78}{\sqrt{\sigma_{EZ}}} \qquad \text{Equation 5-4}$$

$$N_{CORZ} = IF(N_{CORZ} > 2.2, N_{CORZ})$$

e. Energy Correction, C_{ERZ}

$$C_{ERZ} = IF(DEPTH_Z < 3, 0.75, 1.0) \qquad \text{Equation 5-5}$$

f. Corrected Blow Count, N_{CZ}

$$N_{CZ} = N_{VALUE} \cdot N_{CORZ} \cdot C_{ERZ} \qquad \text{Equation 5-6}$$

where:

N_{VALUE}= field blow count

N_{CORZ}= SPT correction

C_{ERZ}= energy correction

g. Fines Content Correction of SPT-N (Seed and Idris, 1997), N_{CFZ}

$$N_{CFZ} = \alpha_Z + \beta_Z \cdot N_{CZ} \qquad \text{Equation 5-7}$$

where:

N_{CZ}= corrected blow count

$$\alpha_Z = IF(FINES\ CONTENT_Z < 5, \alpha 1_Z, IF(FINES\ CONTENT_Z < 35, \alpha 2_Z, \alpha 3_Z))$$

$$\beta_Z = IF\left(FINES\ CONTENT_Z < 5, \beta 1_Z, IF(FINES\ CONTENT_Z < 35, \beta 2_Z, \beta 3_Z)\right)$$

$\alpha 1_Z = 0$ $\beta 1_Z = 1.0$

$\alpha 2_Z = e^{1.76-\frac{190}{(FINESCONTENT_Z)^2}}$ $\beta 2_Z = 0.99 + \frac{(FINES\ CONTENT_Z)^{1.5}}{1000}$

$\alpha 3_Z = 5.0$ $\beta 3_Z = 1.2$

h. Earthquake-Induced Stress

Acceleration in g, a

where:

$a = 0.4$

Deformability Reduction, rd_Z

$$rd_Z = IF(DEPTH_Z < 9.15, rd1_Z, IF\left(DEPTH_Z < 23, rd2_Z, IF(DEPTH_Z < 30, rd3_Z, rd4_Z)\right))$$

$$rd1_Z = 1 - 0.00765 \cdot DEPTH_Z$$
$$rd2_Z = 1.174 - 0.0267 \cdot DEPTH_Z$$
$$rd3_Z = 0.744 - 0.008 \cdot DEPTH_Z$$
$$rd4_Z = 0.5$$

Shear-Stress Average, τ_{AVEZ}

$\tau_{AVEZ} = 0.65 \cdot a \cdot \sigma_{TZ} \cdot rd_Z$ Equation 5-8

where:

a= peak ground acceleration

σ_{TZ}= total stress (kN/m^2)

rd_Z= deformability reduction factor

Cyclic Stress Ratio, CSR_Z

$CSR_Z = \frac{\tau_{AVEZ}}{\sigma_{EZ}}$ Equation 5-9

where:

τ_{AVEZ}= shear- stress average

σ_E= effective stress (kN/m^2)

i. Liquefaction Strength

Magnitude Scaling Factor, MSF

$MSF = \frac{10^{2.24}}{m^{2.56}}$ Equation 5-10

where:

m= magnitude of earthquake

Cyclic Resistance Ratio, CRR_Z

$CRR_Z = 0.007 \cdot (N_{CFZ})^{1.155}$ Equation 5-11

where:

N_{CFZ}= fines content correction of SPT-N

Factor of Safety, FS

$FS_Z = \frac{CRR_Z}{CSR_Z} \cdot MSF$ Equation 5-12

where:

CRR_Z= cyclic resistance ratio

CSR_Z= cyclic stress ratio

MSF= magnitude scaling factor

Figure 5.2 shows the sample user interface of the Excel based program devised by the researchers in calculating the selected locations' potential liquefaction. The program includes input cells that can be filled up using the Standard Penetration Test results specifically the depth of soil layer, blow count value, soil class, magnitude, and depth of ground of water table. The output includes the parameters defined in the Seed and Idriss Simplified Liquefaction Evaluation Procedure. Through the program, the factor of safety due to liquefaction is determined.

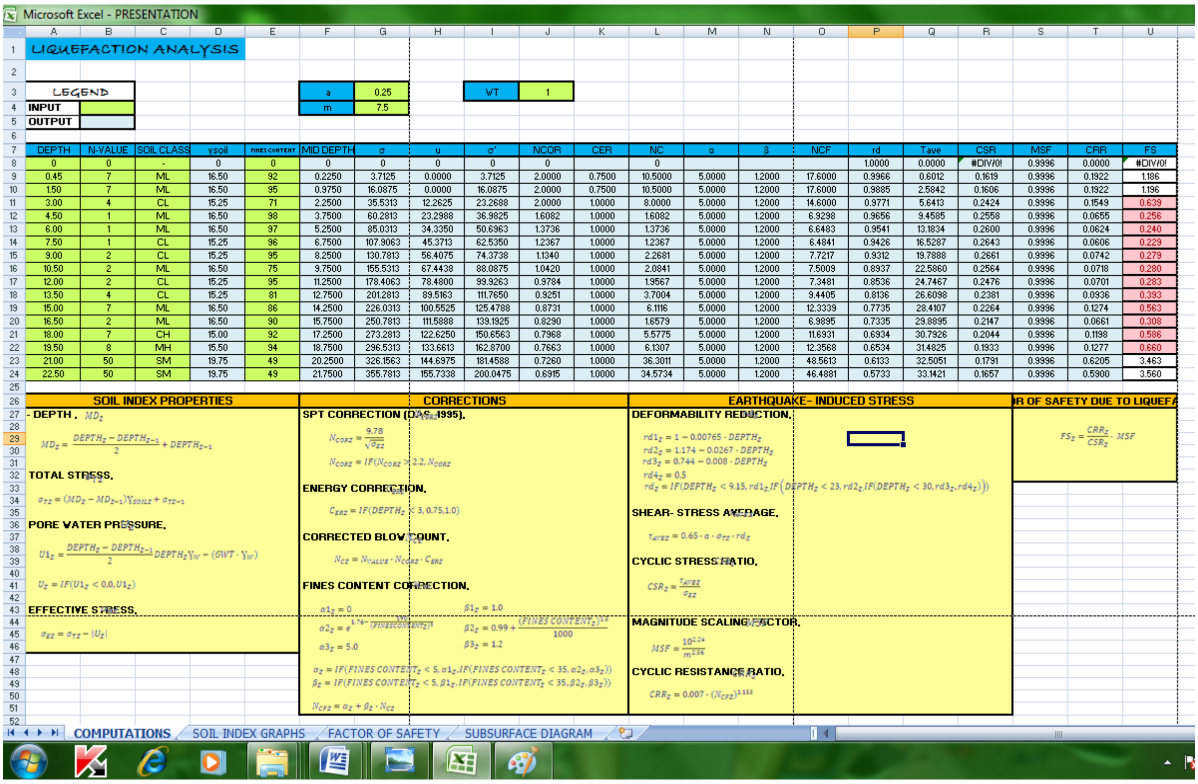


Figure 5.2 Sample User Interface of the Potential Liquefaction Program

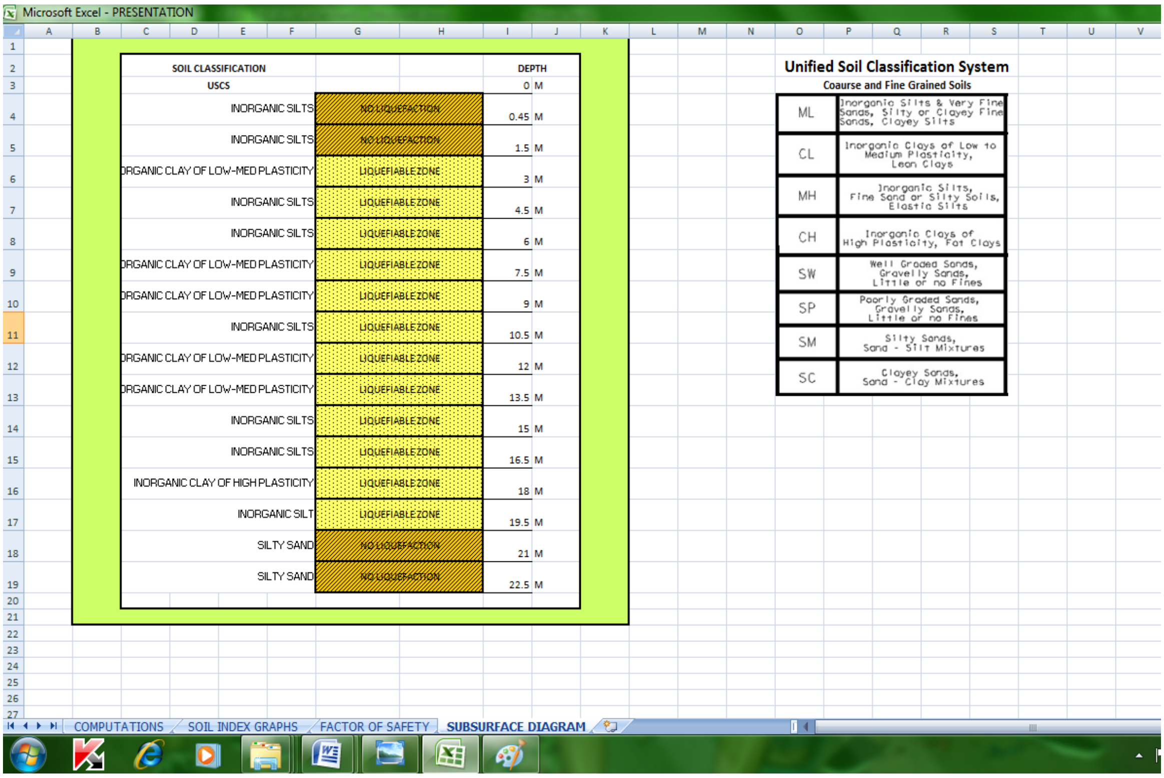


Figure 5.3 Sample User Interface of the Liquefiable Zone Diagram

Figure 5.3 shows the sample user interface of the liquefiable zone diagram included in the Excel based program devised by the researchers. The diagram presents the soil classification and the probability of liquefaction occurrence of the soil layer at a given depth. The plots that the figure exhibits are based from the input values entered at the user interface of the potential liquefaction program.

6. RESULTS AND DISCUSSION

The data obtained from soil test results were processed through the use of an excel program devised by the researchers. The program followed the simplified method of analysis formulated by Seed and Idriss (1997) and Das (1995) for the SPT correction. The peak ground acceleration value that was used in determining the earthquake induced stress is equal to 0.4g, the value assigned to Pasig City by Philippine Institute of Volcanology and Seismology (PHIVOLCS) based on its proximity to a seismic generator.

The factor of safety due to liquefaction calculated through the simplified procedure formulated by Seed and Idriss shows that the behaviour of soil varies with classification, depth of water table and magnitude. It may be monitored from the presented tables of the preceding chapter that the blow count values and undrained shear strength may project the factor of safety due to liquefaction.

Table 6.1 Summary of Liquefaction Susceptibility of the Selected Locations

Magnitude	Ugong	Manggahan	Kapitolyo
5.00	0.12	1.06	2.81
5.50	0.10	0.83	2.20
6.00	0.08	0.67	1.76
6.50	0.06	0.54	1.44
7.00	0.05	0.45	1.19
7.50	0.04	0.38	1.00
8.00	0.04	0.32	0.84
8.50	0.03	0.27	0.72
9.00	0.03	0.24	0.62

Table 6.1 shows the susceptibility of the locations to liquefaction. It may be observed that Barangay Ugong and Manggahan exhibit vulnerability since the yielded factor of safety is less than 1at any given magnitude. However, Barangay Kapitolyo shows partial susceptibility. Liquefaction occurrence starts at magnitude 7.5 while the factor of safety exceeds the critical value of 1 at lower magnitudes.

By comparing the selected sites' potential liquefaction, it was identified that Borehole 2 in Barangay Ugong at depth 6m has the greatest vulnerability. It was determined through its value of factor of safety due to liquefaction that the induced lateral force of a seismic event overcomes most layer of the soil's lateral force, thus posting an FS value less than 1. Results show that magnitudes 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, and 9 yielded factor of safety values of 0.12, 0.10, 0.08, 0.06, 0.05, 0.004, 0.004, 0.003 and 0.003 respectively.

The probable foundation or mitigation used for the safety of the future establishments that may be developed on the specific locations was considered in the study. For the specific location in barangay Manggahan and Ugong, liquefaction will occur at a magnitude 7.5 earthquake, in which the Valley Fault System is capable of producing; thus, settlement will occur and pile/deep foundations are recommended in these locations. The data for the specific location in barangay Kapitolyo show that shallow foundations can be safe from liquefaction up until a magnitude 9 earthquake; thus, only soil improvement is recommended.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions:

The figure below shows the vulnerability of the three selected locations along the Pasig city segment of the Valley Fault System. This presents the most vulnerable area among the three locations which is the site in Barangay Ugong. This is followed by barangay Manggahan. And among the three locations, Barangay Kapitolyo shows greatest resistance against liquefaction occurrence.

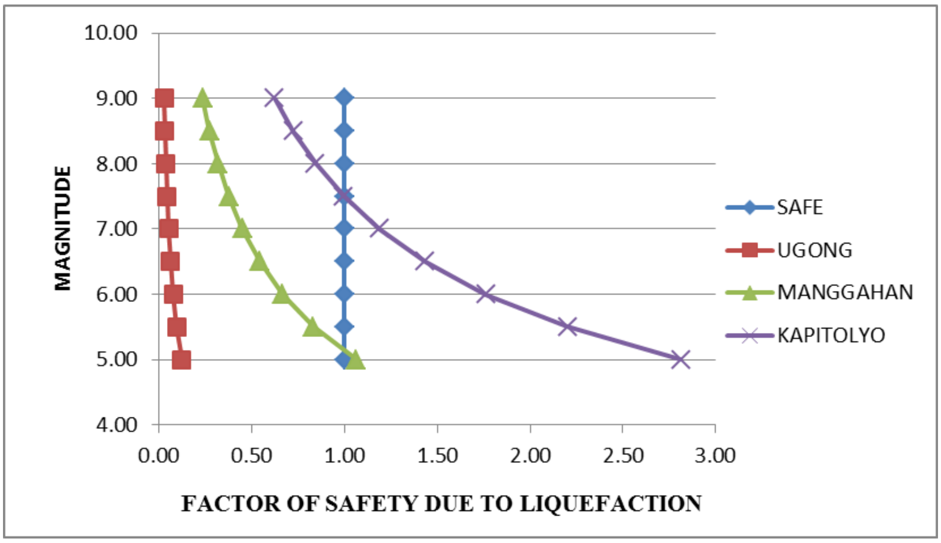


Figure 7.1 Summary of Liquefaction Susceptibility of the Selected Locations

Based on the blow count values (N-Field) and undrained shear strength of each layer of soil considered in this study, the factor of safety due to liquefaction values was grouped into their respective soil profile type. The individual values of factor of safety classified for each soil type were used to provide the range of the probable factor of safety for each profile.

Table 7.1 Augmented Table of Soil Profile Types

Soil Profile Type	Soil Profile Name/ Generic Description	Average Soil Properties for Top 30m of Soil Profile			
		Shear Wave Velocity, V_s (m/s)	SPT, *N* (blows/300 mm)	Undrained Shear Strength, S_U (kPa)	Factor of Safety Due to Liquefaction, FS (at Magnitude 7.5)
S_A	Hard Rock	>1500			-
S_B	Rock	760 to 1500			-
S_C	Very Dense Soil and Soft Rock	360 to 760	>50	>100	>2
S_D	Stiff Soil Profile	180 to 360	15 to 50	50 to 100	>1 but ≤2
S_E[1]	Soft Soil Profile	<180	<15	<50	≤1
S_F	Soil Requiring Site-specific Evaluation				

(National Structural Code of the Philippines, 2010)

Table 7.1 shows the average properties of soil for top 30m of soil profile. The original table obtained from the National Structural Code of the Philippines 2010 was augmented based from the results yielded by the researchers. In determining the range of factor of safety due to liquefaction for each soil type, blow count values and undrained shear strength were considered. It may be synthesized from the results that Soft Soil Profile (S_E) is vulnerable to liquefaction since the expected factor of safety due to liquefaction is less than or equal to the critical value of FS which is 1. On the other hand, Stiff Soil Profile (S_D) has an FS range of greater than 1 but less than or equal to 2 and Very Dense Soil, and Soft Rock (S_C) has an FS value of greater than 2 which can be considered as non liquefiable stratum.

Potential liquefaction in the selected locations is considered in determining the probable mitigation measures for the soil and/ or the type of foundation that can be applied to the selected areas. The summation of the liquefiable depths is referred as the possible settlement of the soil. At a given magnitude, the soil may liquefy and the affected soil will act as liquid; thus, the tough layers in between the liquefiable zones will settle up to the depth of the deepest liquefiable stratum. This data can then be considered for soil improvement or pile foundation.

7.2 Recommendations:

Through the yielded values of factor of safety due to liquefaction, the extent of mitigation can now be determined. The measures that will be applied will depend on the severity of the site's vulnerability to liquefaction. In the case of the site in Barangay Ugong, where most of its layers are comprised of soft soils and the factor of safety is below the critical value of 1, soil improvement must be considered on the soils where light structures like residential houses are to be built. On the other hand, pile foundations must be considered if heavy structures like high rise building are to be built in the selected site.

The augmented soil profile type table may provide the probable values of factor of safety at specific soil classification. The table will enable the people concerned to determine the probable mitigation measures that the location requires, given the extent of the site's susceptibility to liquefaction.

Further studies may be conducted in determining the potential liquefaction of other locations within the selected baranggays. The quantification of their susceptibility to such condition will enable future researchers to create a model that could generalize the susceptibility of each baranggay to liquefaction. It can also provide precision to the range of values of factor of safety due to liquefaction in the augmented soil profile type table.

REFERENCES

[1] Arab, A., Shahrour, I., & Lancelot, L. (2010). A Laboratory Study of Liquefaction of Partially Saturated Sand. *Journal of Iberian Geology*, 37(1), 29-36. Retrieved July 2011, doi: 10.5209/rev_JIGE.2011.v37.n1.2

[2] Gordon A. Fenton, G.M. Paice, & D. V. Griffiths (1978). *Probabilistic Analysis of Foundation Settlement*

[3] Guyer, J. P.,P.E., R.A., Fellow ASCE, Fellow AEI. (2009), *An Introduction to Soil Grouting*

[4] Ozcep, F. & Zarif H. (2009). Variations Of Soil Liquefaction Safety Factors Depending On Several Design Earthquakes In The City Of Yalova. *Scientific Research and Essay*, 4(6), 594-604.

[5] Perkins (2001). The REAL Dirt on Liquefaction. *Earthquake Program Manager, Association of Bay Area Governments*

[6] Poulos (2000). *Foundation Settlement Analysis – Practice versus Research (The Eight Spencer J. Buchanan Lecture)*. TX 77840: College Station Hilton 810 University Drive East College Station.

[7] Raychowdhury, P. & Basudharz P.K. (2011). Liquefaction Characteristics Evaluation Through Different Stress-Based Models. *A Comparative Study. Journal of Engineering Research and Studies*. 2(2), 131-142.

[8] Sumer, B., Ansal A., & Cetin, K. (2007). Earthquake Induced Liquefaction around Marine Structures. *Journal of Waterway, Port, Coastal, and Ocean Engineering*. Retrieved July 2011, doi: 10.1061/_ASCE_0733-950X_2007_ 133:1_55.