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

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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 barangay 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

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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.

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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.

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(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.

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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	IX	Most buildings in Manila, mainly made of wood and timber, were wiped
Aug		out; several persons killed/ injured.
1885	VII	Strong but no serious damage; strong sub- terranean noise observed in
Nov		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).

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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).

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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).

MMI	Description of MMI	Liquefaction Susceptibility Category						
Value	Shaking Severity	Very low	Low	Moderate	High	Very High		
Ι	-	-	-	-	-	-		
II	-	-	-	-	-	-		
III	-	-	-	-	-	-		
IV	-	-	-	-	-	-		
V	Light	-	-	-	-	-		
VI	Moderate	-	-	-	-	-		
VII	Strong	_	_	Moderately	Moderately	Moderate		
V 11	Strong			Low Hazard	Low Hazard	Hazard		
VIII	Very Strong	_	_	Moderate	Moderate	Moderate		
v III	Very Strong	-	-	Hazard	Hazard	Hazard		
IX	Violent	-	-	High Hazard	High Hazard	High Hazard		
Х	Very Violent	-	-	High Hazard	High Hazard	High Hazard		

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

(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

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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:

$$(\tau_i)_{max} = \sigma * a_{max} * r_d$$
 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".

$$(\tau_i)_u = 0.65 * (\tau_i)_{max} = 0.65 * \sigma * a_{max} * r_d$$
 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:

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

The anticipated value of MSF is restricted up to MSF=1.82 for $Mw \le 5.2$. 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 $\frac{3}{4}$ cycle.

MSF value cannot be more that of the ratio of the CSR at ³/₄ cycles divided by CSR for 15 cycles multiplied by 0.65 and can be written as:

$$MSF \le \frac{CSR \ for \frac{3}{4}Cycles}{CSR \ for \ 15 \ Cycles} * \ 065 = \frac{2.8}{1} * \ 0.65 = 1.82$$
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:

$$(\tau_i)_w = \frac{0.65(\tau_i)_{max}}{MSF} = \frac{0.65\sigma_v * a_{max} * r_d}{MSF}$$
 Equation

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.

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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).

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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.

Input	Process	Output
 Secondary Data (Metro Manila Earthquake Impact Reduction Study Report and Maps) from Philippine Institute of Volcanology and Seismology (PHIVOLCS) Secondary Data (Soil Tests Results) from Geotechnical Firms Secondary Data (Comprehensive Land 	 Assessment of Parameters through Excel Program Calculation of the Local Soil's Effective Stress Calculation of the Factor of Safety due to Liquefaction 	 Quantification of the Sites' Factor of Safety Due to Liquefaction Identification of the Location with the Greatest Potential Liquefaction Identification of Possible Mitigation Measures for the Soil and/or the Foundation

Figure 5.1 Methodological Framework

5.2 Data Analysis:

Use Plan and Maps) from Local Government Unit of Pasig City

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

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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}

$$\sigma_{TZ} = (MD_Z - MD_{Z-1}) \mathcal{Y}_{SOILZ} + \sigma_{TZ-1}$$

Equation 5-1

Equation 5-2

Equation 5-3

Equation 5-5

Equation 5-6

Equation 5-7

where:

 $MD_{z} - middepth at depth z (m)$ $MD_{Z} = \frac{DEPTH_{Z} - DEPTH_{Z-1}}{2} + DEPTH_{Z-1}$

 V_{soil} – dry unit weight of soil (kN/m³)

b. Pore Water Pressure, U_z

$$U_{Z} = IF(U1_{Z} < 0, 0, U1_{Z})$$
$$U1_{Z} = \frac{DEPTH_{Z} - DEPTH_{Z-1}}{2} DEPTH_{Z} \mathcal{Y}_{W} - (GWT \cdot \mathcal{Y}_{W})$$

where:

Vw – unit weight of water (9.81 kN/m³)

GWT – Ground Water Table (m)

C. Effective Stress, σ_{EZ}

 $\sigma_{EZ} = \sigma_{TZ} - |U_Z|$

where:

 σ_{TZ} = total stress (kN/m²)

 U_Z = pore water pressure (kN/m²)

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

$$N_{CORZ} = \frac{9.78}{\sqrt{\sigma_{EZ}}}$$
Equation 5-4
$$N_{CORZ} = IF(N_{CORZ} > 2.2, N_{CORZ})$$

e. Energy Correction, C_{ERZ}

 $C_{ERZ} = IF(DEPTH_Z < 3, 0.75, 1.0)$

f. Corrected Blow Count, N_{CZ}

$$N_{CZ} = N_{VALUE} \cdot N_{CORZ} \cdot C_{ERZ}$$

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}

$$N_{CFZ} = \alpha_Z + \beta_Z \cdot N_{CZ}$$

where:

N_{CZ}= corrected blow count

 $\alpha_{Z} = IF(FINES\ CONTENT_{Z} < 5, \alpha 1_{Z}, IF(FINES\ CONTENT_{Z} < 35, \alpha 2_{Z}, \alpha 3_{Z}))$

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 $\beta_{Z} = IF(FINES \ CONTENT_{Z} < 5, \beta 1_{Z}, IF(FINES \ CONTENT_{Z} < 35, \beta 2_{Z}, \beta 3_{Z}))$

$$\begin{aligned} \alpha 1_{Z} &= 0 \\ \alpha 2_{Z} &= e^{1.76 - \frac{190}{(FINESCONTENT_{Z})^{2}}} \\ \alpha 3_{Z} &= 5.0 \end{aligned} \qquad \qquad \beta 1_{Z} &= 1.0 \\ \beta 2_{Z} &= 0.99 + \frac{(FINES\ CONTENT_{Z})^{1.5}}{1000} \\ \beta 3_{Z} &= 1.2 \end{aligned}$$

h. Earthquake-Induced Stress

Acceleration in g, a

where:

a = 0.4

Deformability Reduction, rd_Z

$$\begin{aligned} rd_{Z} &= IF(DEPTH_{Z} < 9.15, rd_{Z}, IF\left(DEPTH_{Z} < 23, rd_{Z}, IF(DEPTH_{Z} < 30, rd_{Z}, rd_{Z})\right)) \\ & rd_{Z} = 1 - 0.00765 \cdot DEPTH_{Z} \\ & rd_{Z} = 1.174 - 0.0267 \cdot DEPTH_{Z} \\ & rd_{Z} = 0.744 - 0.008 \cdot DEPTH_{Z} \\ & rd_{Z} = 0.5 \end{aligned}$$

Shear-Stress Average, τ_{AVEZ}

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

where:

a= peak ground acceleration

 σ_{TZ} = total stress (kN/m²)

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/m²)

i. Liquefaction Strength

Magnitude Scaling Factor, MSF

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

where:

m= magnitude of earthquake

Cyclic	Resi	stance	Rat	10, C	KKZ
0	ממי	0.0	07	(M	\1.155

$CRR_{Z} =$	$0.007 \cdot (N_{CFZ})$	1.155	
where:			

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

Factor of Safety, FS

$$FS_Z = \frac{CRR_Z}{CSR_Z} \cdot MSF$$

where:

 $\label{eq:CRR_Z} \begin{array}{l} \text{CRR}_{Z} = \text{cyclic resistance ratio} \\ \text{CSR}_{Z} = \text{cyclic stress ratio} \\ \text{MSF} = \text{magnitude scaling factor} \end{array}$

Equation 5-11

Equation 5-12

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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.

X	Microsoft I	Excel - PRE	SENTATIO)N																	
	A	В	С	D	E	F	G	н	1	J	К	L	M	N	0	P	Q	R	S	Т	U
1	LIQUE	FACTIC	N ANA	LYSIS																	
2																					
3	LEG	END				а	0.25		VT	1											
4	INPUT					m	7.5														
5	OUTPUT																				
6																					
7	DEPTH	N-VALUE	SOIL CLASS	ysoil	PINES CONTENT	MID DEPTH	σ	u	σ	NCOR	CER	NC	α	β	NCF	rd	Tave	CSR	MSF	CRR	FS
8	0	0		0	0	0	0	0	0	0		0				1.0000	0.0000	#DIV/0!	0.9996	0.0000	#DIV/0!
9	0.45	7	ML	16.50	92	0.2250	3.7125	0.0000	3.7125	2.0000	0.7500	10.5000	5.0000	1.2000	17.6000	0.9966	0.6012	0.1619	0.9996	0.1922	1.186
10	1.50	7	ML	16.50	95	0.9750	16.0875	0.0000	16.0875	2.0000	0.7500	10.5000	5.0000	1.2000	17.6000	0.9885	2.5842	0.1606	0.9996	0.1922	1.196
11	3.00	4		15.25	/1	2.2500	35.5313	12.2625	23.2688	2.0000	1.0000	8.0000	5.0000 E.0000	1,2000	14.6000	0.9771	5.6413 0.4E0E	0.2424	0.9996	0.00555	0.639
12	9.00	1	ML	16.00	97	5.2500	85.0313	23.2300	50,6963	13736	10000	13736	5.0000	12000	6.6483	0.3606	13 1834	0.2000	0.3336	0.0600	0.236
14	7.50	1	CL	15.25	96	6.7500	107.9063	45.3713	62.5350	1.2367	1.0000	1.2367	5.0000	1.2000	6.4841	0.9426	16.5287	0.2643	0.9996	0.0606	0.229
15	9.00	2	CL	15.25	95	8.2500	130.7813	56.4075	74.3738	1.1340	1.0000	2.2681	5.0000	1.2000	7.7217	0.9312	19.7888	0.2661	0.9996	0.0742	0.279
16	10.50	2	ML	16.50	75	9.7500	155.5313	67.4438	88.0875	1.0420	1.0000	2.0841	5.0000	1.2000	7.5009	0.8937	22.5860	0.2564	0.9996	0.0718	0.280
17	12.00	2	CL	15.25	95	11.2500	178.4063	78.4800	99.9263	0.9784	1.0000	1.9567	5.0000	1.2000	7.3481	0.8536	24.7467	0.2476	0.9996	0.0701	0.283
18	13.50	4	CL	15.25	81	12.7500	201.2813	89.5163	111.7650	0.9251	1.0000	3.7004	5.0000	1.2000	9.4405	0.8136	26.6098	0.2381	0.9996	0.0936	0.393
19	15.00	- (ML	16.50	86	14.2500	226.0313	100.5525	125.4788	0.8731	1.0000	6.1116	5.0000	1,2000	12.3339	0.7735	28.4107	0.2264	0.9996	0.1274	0.563
20	18.00	2	CH	15.00	92	17.2500	273 2813	122 6250	150,6563	0.8230	1.0000	5.5775	5.0000	12000	116931	0.7335	23.0030	0.2147	0.3336	0.0661	0.506
22	19.50	8	MH	15.50	94	18,7500	296.5313	133.6613	162.8700	0.7663	1.0000	6.1307	5.0000	1.2000	12.3568	0.6534	31.4825	0.1933	0.9996	0.1277	0.660
23	21.00	50	SM	19.75	49	20.2500	326.1563	144.6975	181.4588	0.7260	1.0000	36.3011	5.0000	1.2000	48.5613	0.6133	32.5051	0.1791	0.9996	0.6205	3.463
24	22.50	50	SM	19.75	49	21.7500	355.7813	155.7338	200.0475	0.6915	1.0000	34.5734	5.0000	1.2000	46.4881	0.5733	33.1421	0.1657	0.9996	0.5900	3.560
25															r						
						_															
26		SOIL IN	DEX PRO	PERTIES				CORRE	CTIONS				E	ARTHQUA	Ke- Induc	CED STRES	S		R OF SAF	ETY DUE T	O LIQUEF/
26 27	- DEPTH ,	SOIL IN	DEX PRO	Perties		SPT COR	RECTION (CORRE 0.4 9, 1995)	CTIONS			DEFORM/	EABILITY RE	ARTHQUA DUCTION,	Ke- Induc	ED STRES	5 5		R OF SAF	ety due t	O LIQUEF/
26 27 28 29	- DEPTH .	SOIL IN MD ₂ EPTH ₂ - DEP	DEX PRO	PERTIES		SPT CORI	RECTION (1	CORRE 004921995)	<u>CTIONS</u>			DEFORM/ rd1z = 1 ·	EABILITY RE	ARTHQUA DUCTION,	<mark>ke- induc</mark>	CED STRES	<u>S</u>		IR OF SAF	ETY DUE T $\delta_z = \frac{CRR_z}{CSR_z} \cdot M$	O LIQUEFA
26 27 28 29 30	- DEPTH . $MD_z = \frac{D_z}{dt}$	SOIL IN MD ₂ EPTH ₂ - DEP 2	DEX PRO	PERTIES		SPT CORI	$\frac{9.78}{\sqrt{\sigma_{E2}}}$	CORRE 004941995)	CTIONS			$\frac{\text{DEFORM}}{rd1_Z = 1}$ $\frac{rd1_Z = 1}{rd2_Z = 1.3}$	EABILITY RE - 0.00765 - DE 174 - 0.0267 -	ARTHQUA DECTION,	<mark>ke- Induc</mark>	CED STRES	<u>55</u>		IR OF SAF	ETY DUE T $S_{Z} = \frac{CRR_{Z}}{CSR_{Z}} \cdot M$	O LIQUEF#
26 27 28 29 30 31	- DEPTH . <i>MDz</i> = <u></u>	SOIL IN MD ₂ EPTH ₂ - DEP 2	TH _{Z=1} + DEP	PERTIES		SPT CORI N _{corz} N _{corz}	RECTION () = $\frac{9.78}{\sqrt{\sigma_{EZ}}}$ = $IF(N_{CORZ} >$	CORRE DØ ₁ 9 ₈₂ 1995) 2.2. N _{conz}	<u>Ctions</u>			DEFORM/ rd1z = 1 rd2z = 1.1 rd3z = 0.7	EABILITY RE - 0.00765 - D2 174 - 0.0267 - 44 - 0.008 - 2	ARTHQUA DECTION, IPTH ₂ DEPTH ₂ DEPTH ₂	<mark>ke- Induc</mark>	CED STRES	is I		IR OF SAF	ETY DUE T $5_z = \frac{CRR_z}{CSR_z} \cdot M$	O LIQUEF <i>I</i> ISF
26 27 28 29 30 31 32	- DEPTH . MD ₂ = ^D TOTAL ST	SOIL IN MD ₂ EPTH ₂ - DEP 2 FB5 ₇ §S.	DEX PRO	PERTIES		SPT CORI N _{CORZ} N _{CORZ}	RECTION () = $\frac{9.78}{\sqrt{\sigma_{EZ}}}$ = $IF(N_{CORZ} >$	CORRE Diggaz1995) 2.2. N _{conz}	CTIONS			DEFORMA $rd1_{z} = 1$ $rd2_{z} = 1.1$ $rd3_{z} = 0.7$ $rd4_{z} = 0.3$ $rd4_{z} = 0.5$	E6 ABILITY RE - 0.00765 - D1 174 - 0.0267 - 144 - 0.008 - 1 5 DEPTH- < 91	ARTHQUA DOCTION, IPTH ₂ DEPTH ₂ DEPTH ₂	KE- INDUC		8 5	rd4-)))	IR OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z} \cdot M$	<mark>O LIQUEF</mark> A
26 27 28 29 30 31 32 33 34	- DEPTH , $MD_2 = \frac{D}{T}$ TOTAL ST $\sigma_{TT} = (MD)$	SOIL IN MD ₂ EPTH ₂ - DEP 2 Fa5 ₇ §S. Ar - MDra1W	DEX PRO	PERTIES		SPT CORI N _{CORZ} N _{CORZ}	$\frac{9.78}{\sqrt{\sigma_{EZ}}} = IF(N_{CORZ} > CORRECTION)$	CORRE DØ ₂ 9 ₈₂ 1995) 2.2. N _{corz} DN,	<u>ctions</u>			$\begin{array}{c} \textbf{DEFORM/}\\ rd1_{Z} = 1 \\ rd2_{Z} = 1.1 \\ rd3_{Z} = 0.7 \\ rd4_{Z} = 0.3 \\ rd_{Z} = IF(\end{array}$	E ABILITY RE - 0.00765 - DE 174 - 0.0267 - 144 - 0.008 - E 5 DEPTH _Z < 9.1	ARTHQUA DBCTION, DEPTH ₂ DEPTH ₂ DEPTH ₂ 15, rd1 ₂ , IF (D	KE- INDUC	CED STRES	9 5 4 ₂ < 30.rd3 ₂ ,	rd4z)))	IR OF SAF	$\mathbf{ETY DUE T}$ $S_Z = \frac{CRR_Z}{CSR_Z} \cdot M$	O LIQUEFA
26 27 28 29 30 31 32 33 34 35	- DEPTH , $MD_Z = \frac{D}{T}$ TOTAL ST $\sigma_{TZ} = (MD)$	$\frac{\text{SOIL IN}}{MD_2}$ $\frac{BPTH_2 - DEP}{2}$ $\frac{1}{100} \frac{1}{2} \frac{1}{100} \frac{1}{2} \frac{1}{100} \frac{1}{$	DEX PROI	PERTIES		SPT CORI Ncorz Ncorz ENERGY (Czrz =	RECTION (I = $\frac{9.78}{\sqrt{\sigma_{E2}}}$ = $IF(N_{CORE} >$ CORRECTION = $IF(DEPTH_2)$	CORRE Diggaz 1995) 2.2, N _{CORZ} DN. c 3. 0.75.1.0)	<u>CTIONS</u>			DEFORM/ rd1z = 1 rd2z = 1.: rd3z = 0.7 rd4z = 0.; rdz = IF(SHEAR- S	E. ABILITY RE - 0.00765 - DL 174 - 0.0267 - 44 - 0.008 - L 5 DEPTH ₂ < 9.1 TRESS AV	ARTHQUA DECTION, DEPTH2 DEPTH2 DEPTH2 15.rd12,IF(D EDAGE,	K <mark>E- INDUC</mark> EPTH ₂ < 23, r	CED STRES	3 5 1 ₂ < 30.rd3 ₂ ,	rd4z)))	IR OF SAF	ETY DUE T $\delta_Z = \frac{GRR_Z}{CSR_Z} \cdot M$	O LIQUEF#
26 27 28 29 30 31 32 33 34 35 36	- DEPTH , $MD_{Z} = \frac{D}{T}$ TOTAL ST $\sigma_{TZ} = (MD$ PORE VA	SOIL IN MD ₂ EPTH ₂ - DEP 2 F65 ₂ S. y ₂ - MD ₂₋₁)y ₃ TER PRBS	DEX PROP $TH_{Z-1} + DEP$ souz + σ_{7Z-1} SURE,	PERTIES		SPT CORI Nosaz Nosaz ENERGY (CERZ =	RECTION () $= \frac{9.78}{\sqrt{\sigma_{E2}}}$ $= IF(N_{CORE} > 1)$ CORRECTION = IF(DEPTH ₂)	CORRE D ² 49821995) 2.2. N _{COR2} DN. c 3. 0.75.1.0)	<u>CTIONS</u>			DEFORM/ rd1z = 1 · rd2z = 1.: rd3z = 0.7 rd4z = 0.3 rdz = IF(SHEAR- S	EABILITY RE = 0.00765 · DI 174 = 0.0267 · 174 = 0.008 · I 5 DEPTH ₂ < 9: TRESS AW	ARTHQUA DUCTION, DEPTH ₂ DEPTH ₂ DEPTH ₂ 15.rd1 ₂ .IF (D: EBAGE,	KE- INDUC IPTH _Z < 23, r	CED STRES	9 5 H ₂ < 30.rd3 ₂ ,	rd4z)))	IR OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z} \cdot M$	O LIQUEF <i>I</i>
26 27 28 30 31 32 33 34 35 36 37	- DEPTH , $MD_{Z} = \frac{D}{T}$ TOTAL ST $\sigma_{TZ} = (MD$ PORE VA	SOIL IN MD_2 $EPTH_2 - DEP$ 2 Rispes. $M_2 - MD_{2-1}(Y_1)$ TER PRESE $PTH_2 = DEPT$	DEX PROP $TH_{Z=1} + DEP$ sourt + $\sigma_{TZ=1}$ SURE,	PERTIES		SPT CORI Neonz Neonz ENERGY (Canz = CORRECT	RECTION () = $\frac{9.78}{\sqrt{\sigma_{ZZ}}}$ = $IF(N_{cosz} > CORRECT)$ = $IF(DEPTH_Z$ TED BLOV:	CORRE D ² 4982(1995) 2.2. N _{COR2} DN. c 3. 0.75.1.0) COUNT.	<u>CTIONS</u>			DEFORM $rd1_{z} = 1 \cdot rd2_{z} = 1.1$ $rd3_{z} = 0.7$ $rd4_{z} = 0.3$ $rd_{z} = IF($ SHEAR- S $\tau_{avzz} = 0$	E: ABILITY RE = 0.00765 · DI 174 - 0.0267 · 144 - 0.008 · I 5 DEPTH ₂ < 9: TRESS AW 0.65 · $a \cdot \sigma_{72}$ ·	ARTHQUA DUCTION, DEPTH ₂ DEPTH ₂ DEPTH ₂ IS. rd1 ₂ . /F (D: EPAGE, rd ₂	KE- INDUC PTH ₂ < 23, r	A22,1F(DEPT1	9 5 4 ₂ < 30.rd3 ₂ .	rd4z)))	IR OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z} \cdot M$	O LIQUEF#
26 27 28 30 31 32 33 34 35 36 37 38 38	- DEPTH , $MD_2 = \frac{D}{T}$ TOTAL ST $\sigma_{TZ} = (MD$ PORE VA $U1_Z = \frac{DE_1}{T}$	SOIL IN MD_2 $EPTH_2 - DEP$ 2 P_2	$\frac{DEX PROP}{TH_{Z=1}} + DEP$ soltz + $\sigma_{TZ=1}$ SURE, $\frac{H_{Z=1}}{DEPTH_Z}$	PERTIES TH_{2+1} $Y_{W} = (GWT \cdot Y_{W})$	ş _{ir})	SPT CORI Neonz Neonz ENERGY (Canz = CORRECT Nez (RECTION () $= \frac{9.78}{\sqrt{\sigma_{22}}}$ $= IF(N_{CORE} > CORRECTION)$ $= IF(DEPTH_2)$ TED BLOV() $= N_{TAUSE} \cdot N_{COE}$	CORRE D ⁰ k9a21995) 2.2. N _{CORE} DN. C 3. 0.75.1.0) COUNT. No. C CRE	<u>CTIONS</u>			DEFORM $rd1_{2} = 1$ $rd2_{2} = 1.1$ $rd3_{2} = 0.3$ $rd4_{2} = 0.3$ $rd4_{2} = 0.3$ $rd_{3} = IF($ SHEAR-S $\tau_{AVZZ} = 0$	Ei ABILITY RE - 0.00765 · D2 174 - 0.0267 · 5 DEPTH ₂ < 9.1 TRESS AX 0.65 · a · σ_{72} · 1 TRESS FA	ARTHQUA IPTH ₂ DEPTH ₂ DEPTH ₂ SEPTH ₂ IS.rd1 ₂ .IF(D: EPAGE. rd ₂ TIO	KE- INDUC	d2 ₂ ,IF(DEPTI	35 4 ₂ < 30.rd3 ₂ ,	rd4z)))	IR OF SAF	ETY DUE T $S_Z = \frac{GRR_Z}{GSR_Z} \cdot M$	O LIQUEF#
26 27 28 30 31 32 33 34 35 36 37 38 39 40	- DEPTH, $MD_2 = \frac{D}{T}$ TOTAL ST $\sigma_{T2} = (MD$ PORE VA $U1_2 = \frac{DE1}{T}$	SOIL IN MD_2 $EPTH_2 - DEP$ 2 $PE5_2S.$ $D_2 - MD_{2-1})Y_1$ TER PRESS $PTH_2 - DEPT$ 2	$\frac{DEX PRO}{TH_{2-1}} + DEP$ soll2 + σ_{72-1} SURE, $\frac{H_{2-1}}{DEPTH_2}$	PERTIES TH_{T-1} $Y_W = (GWT + Y)$	Şw)	SPT CORI Neorez Neorez ENERGY (Cent = CORRECT Net (RECTION () $= \frac{9.78}{\sqrt{\sigma_{22}}}$ $= IF(N_{CORE} > CORRECTION)$ $= IF(DEPTH_2 + IF(DEPTH_2 + N_{CORE} + N_{CORE} + N_{CORE})$	CORRE D ⁰ k9a21995) 2.2. Neonz DN, c 3. 0.75.1.0) CQUNT, az: Cenz	<u>CTIONS</u>			DEFORM/ $rd1_{z} = 1 \cdot rd2_{z} = 1.1$ $rd3_{z} = 0.3$ $rd_{z} = 0.3$ $rd_{z} = 0.1$ $rd_{z} = 1.F($ SHEAR- S $\tau_{avzz} = 0$ CYCLIC S	Ei ABILITY RE - 0.00765 · D2 174 - 0.0267 · 5 DEPTH ₂ < 9.0 TRESS AM 0.65 · a · σ_{72} · : TRESS FIA	ARTHQUA DUCTION, DEPTH: DEPTH: DEPTH: S.rdl:,IF(D: EPAGE, rd: TIO,	XE- INDUC 2PTH ₂ < 23, r	CED STRES	35 4 ₂ < 30.rd3 ₂ ,	rd4z)))	IR OF SAF	ETY DUE T $5_Z = \frac{GRR_Z}{GSR_Z} \cdot N$	O LIQUEF <i>I</i>
26 27 28 30 31 32 33 34 35 36 37 38 39 40 41	- DEPTH . $MD_2 = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (MD$ PORE VA $U1_Z = \frac{DE}{2}$ $U_Z = IF(U$	SOIL IN MD_z $EPTH_z - DEP$ 2 $PTH_z - DEP$ $PTH_z - DEPT$ 2 $PTH_z - DEPT$ 2 $1_z < 0.0.01_z$	$\frac{TH_{2-1}}{TH_{2-1}} + DEP$ soll2 + σ_{72-1} SURE, $\frac{H_{2-1}}{DEPTH_2}$	PERTIES TH_{T-1} $X_W = (GWT \cdot)$	Sw)	SPT CORI Neosz Neosz ENERGY (Casa = CORRECT Nez : FINES CO	RECTION () $= \frac{9.78}{\sqrt{\sigma_{22}}}$ $= IF(N_{CORE} > 1)$ CORRECT: $= IF(DEPTH_2 + 1)$ TED BLOV; $= N_{VALUZ} \cdot N_{CO}$ NTENT CO	CORRE Digge 1995) 2.2. N ₂₀₈₂ DN. c 3. 0.75.1.0) COUNT. nz [.] Cenz FRECTION	<u>CTIONS</u>			DEFORM/ $rd1_{Z} = 1$ $rd2_{Z} = 1.1$ $rd3_{Z} = 0.7$ $rd_{Z} = 0.7$ $rd_{Z} = 0.7$ $rd_{Z} = 1F($ SHEAR-S $\tau_{AVZZ} = 0$ CYCLIC S CYCLIC S	E ABILITY RE = 0.00765 - DI 174 = 0.0267 - 144 = 0.008 - I 5 DEPTH ₂ < 9.1 TRESS AX 0.65 - a - σ_{72} -: TRESS INA AVE2 σ_{72}	ARTHQUA DUCTION, DEPTH ₂ DEPTH ₂ 15, rd1 ₂ , IF (D: EPAGE, rd ₂ TIO,	<mark>E- INDUC</mark> PTH ₂ < 23, r	A22,1F(DEPT)	6 5 4 ₂ < 30.rd3 ₂ .	rd4z)))	IR OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z} \cdot M$	O LIQUEF <i>I</i>
26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42	- DEPTH. $MD_2 = \frac{D}{T}$ TOTAL ST $\sigma_{TZ} = (MD$ PORE VA $U1_Z = \frac{DEI}{U_Z}$ $U_Z = IF(U)$	SOIL IN MDz EPTHz - DEP 2 R552S. (z - MDz-1)V; TER PR82 PTHz - DEPT 2 1z < 0.0.01z; E - DEPC	$\frac{TH_{2-1}}{SOHZ} + DEP$ $\frac{TH_{2-1}}{SOHZ} + \sigma_{72-1}$ $\frac{SURE}{H_{2-1}} DEPTH_2$	PERTIES TH ₂₊₁ -Y _W - (GWT - Y	lur)	SPT COR Nesse ENERGY (Cese = CORRECT Nes (FINES CO	RECTION (I $= \frac{9.78}{\sqrt{\sigma_{E2}}}$ $= IF(N_{CORE} > 1)$ CORRECTION $= IF(DEPTH_2 + 1)$ TED BLOV() $= N_{VALUZ} + N_{CO}$ NTENT CO	CORRE D ² 1982[1995] 2.2. N _{CORZ} DN, c 3. 0.75,1.0) DN, c 9 C	CTIONS			DEFORMA $rd1_{x} = 1$ · $rd2_{x} = 1.1$ $rd3_{x} = 0.7$ $rd_{x} = 0.1$ $rd_{x} = IF($ SHEAR- S $\tau_{AVZZ} = 0$ CYCLIC S $cSR_{z} = \frac{1}{2}$	E: ABILITY PE - 0.00765 - DI 174 - 0.0267 444 - 0.008 - E 5 DEPTH ₂ < 9: TRESS AX 0.65+ $a + d_{T2} + 1$ TRESS FIX AVE2 FIX	ARTHQUA E9CTION, IPTH ₂ DEPTH ₂ DEPTH ₂ IS.rdl ₂ .IF(D) EDAGE, rd ₂ TIO,	<mark>KE- INDUC</mark>	ED STRES	3 5 } } } }	rd42)))	IR OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z}$, N	O LIQUEF <i>I</i>
26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 41 42 43 44	- DEPTH, $MD_z = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (MD)$ PORE VA $U1_Z = \frac{DE}{2}$ $U_Z = IF(U)$ EFFECTIV	SOIL IN MD_2 $EPTH_2 - DEP 2 F652S. i_2 - MD_{2-1})V_1TER PR62PTH_2 - DEPT 2 1_2 < 0.0.01_2E STRESS$	DEX PRO TH ₂₋₁ + DEP soltz + 972-1 SURE, H ₂₋₁ DEPTH ₂	PERTIES TH_{t+1} $Y_{W} = (GWT \cdot 1)$	ใน)	SPT CORI Neonz ENERGY (Correct Nex * FINES CO a1z = 0	RECTION (I) $= \frac{9.78}{\sqrt{\pi_{E2}}}$ $= IF(N_{cost} > CORRECT)$ $\approx IF(DEPTH_2 = N_{Cost} > N_{Cos$	CORRE D/19821995) 2.2. Neonz DN. < 3. 0.75.1.0) COUNT. NR ⁺ CENZ FREECTION	CTIONS	FINES CONT	ENTERIA	DEFORM $rd1_2 = 1$ $rd2_2 = 1.1$ $rd3_2 = 0.0$ $rd4_2 = 0.0$ $rd4_2 = 0.0$ SHEAR-S $\tau_{argz} = IF$ SHEAR-S $\tau_{argz} = C$ CYCLIC S $CSR_2 = \frac{1}{2}$	E ABILITY RE = 0.0765 - D1 174 - 0.0267 - 1 174 - 0.008 - 1 5 DEPTH2 < 9:1 TRESS AW 0.65 - a - 072 - 1 TRESS IN AVE 0 0.65 - a - 072 - 1 TRESS IN 0.65 - a - 072 - 1 0.65 - a - 072 - 1 0.05 -	ABTHQUA DBCTION, IPTH2 DEPTH2 DEPTH2 IS.rd12.IF(D) EDAGE, rd2 TIO,	<mark>KE- INDUC</mark> EPTH ₂ < 23, r	ED STRES	3 5 4 ₂ < 30.rd3 ₂ .	rd42)))	R OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z}$, N	O LIQUEF?
26 27 28 29 30 31 32 33 34 35 36 36 36 37 38 39 40 41 42 43 44 45	- DEPTH, $MD_z = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (MD$ PORE VA $U1_Z = \frac{DS_1}{U}$ $U_z = IF(U)$ EFFECTIV $\sigma_{ZZ} = \sigma_{TZ}$	SOIL IN MD_z $EPTH_z - DEP 2 F5525. I_z - MD_{z-1}V_zTER PRESPTH_z - DEPT2I_z < 0.0.01_zE SVELSS- U_z $	$\frac{DEX PRO}{TH_{2-1}} + DEP$ south + σ_{72-1} SURE, $\frac{H_{2-1}}{DEPTH_{2}}$	TH ₂₋₁ $Y_W = (GWT \cdot Y_W)$	Sw)	SPT CORI Nconz Nconz ENERGY (CORRECT Ncz * FINES CO a1z = 0 a2z = a ²	RECTION (I $= \frac{9.78}{\sqrt{\pi}z_2}$ $= iF(\lambda_{conc} > connected)$ $= iF(DEPTH_2$ RED BLOV() $= N_{VALUE} + Nee$ NTENT CO	CORRE DA9821995) 2.2. Neorez DN. c 3. 0.75.1.0) DOUNT. RECTION FRECTION	CTIONS $\beta_{1_2} = 1.0$ $\beta_{2_2} = 0.99 + -$	<u>(FINES CON</u> 1000	EN7 <u>2)**</u>	DEFORM/ $rd1_{Z} = 1 \cdot$ $rd2_{Z} = 1.1$ $rd3_{Z} = 0.3$ $rd2_{Z} = 0.3$ $rd2_{Z} = 0.7$ $rd2_{Z} = 0.7$ SHEAR- S $rd2_{Z} = 0.7$ $rd2_{Z} = 0.7$ SHEAR- S $rd2_{Z} = 0.7$ $rd2_{Z} = 0.7$ $rd2_{Z}$	E ABILITY PE - 0.00765 - DJ 174 - 0.0267 - 1 174 - 0.008 - 1 5 DEPTH2 < 9:1 TRESS AM 165- a - dr2 - 1 TRESS INA AVE dr2 TRESS INA AVE DE SCALIN	ABTHQUA DUCTION, IPTH2 DEPTH2 DEPTH2 15.rd12.IF(D) FEDAGE, rd2 TIO,	KE- INDUC ₽₽TH₂ < 23,r ₽.	ED STRES	35 4 ₇ < 30,rd3 ₂ ,	rd+z)))	R OF SAF	ETY DUE T $\tilde{s}_z = \frac{CRR_z}{CSR_z}$, N	
23 26 27 28 30 31 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46	- DEPTH, $MD_z = \frac{D}{-}$ TOTAL ST $\sigma_{\tau z} = (MD$ PORE VA $U1_z = \frac{DE_1}{U}$ $U_z = IF(U$ EFFECTIV $\sigma_{zz} = \sigma_{\tau z}$	SCIL IN MDz MDz EPTHz - DEPT 2 F652S. 2 Iz - MDz-1)V; TER PR65 PTHz - DEPT 2 1z - 0.0.01z; 1z E STRESS - Uz	$\frac{DEX PRO}{TH_{z-1}} + DEP$ soll + σ_{Tz-1} soll + σ_{Tz-1} soll + σ_{Tz-1}	PERTIES TH_{2+1} $Y_W = (GWT \cdot Y_W)$	(₁₁)	SPT CORI N_{cosz} ENERGY ($C_{gxz} =$ CORRECT $N_{cz} :$ FINES CO $a1_z = 0$ $a2_z = a^2$ $a3_z = 5$	RECTION (I RECTION (I $= \frac{9.78}{\sqrt{\sigma_{E2}}}$ $= IF(N_{CORE} > I)$ CORRECTION $= IF(DEPTH_2 + N_{CO} + N_{CO})$ NTENT CO NTENT CO $= 10^{-10}$	CORRE DA9511995) 2.2. Neonz DN, c.3. 0.75,1.0) CQUNT, function Function	CTIONS 61 ₂ = 1.0 62 ₂ = 0.99 + . 93 ₂ = 1.2	<i>[FINES CONT</i> 1000	<u>ENT₂)¹⁴</u>	DEFORM/ $rd1_z = 1 \cdot rd2_z = 1.1$ $rd2_z = 2.1$ $rd2_z = 0.1$ $rd2_z = 0.2$ $rd2_z = 0.2$ $rd2_z = 0.2$ SHEAR- S $\tau_{avzz} = 0$ CYCLIC S' CSR _z = $\frac{1}{2}$ MAGNITU MSF = 1	E ABILITY RE - 0.00765 - D1 174 - 0.0267 - 144 - 0.008 - I DEPTH ₂ < 9.1 TRESS AM 0.65 - a - d ₇₂ - 1 TRESS INA - d ¹ E2 - d ² E2 - d	ARTHQUA DUCTION, IPTH: DEPTH: DEPTH: 15.rdl::IF(D: EDAGE, rd: TIO,	KE- INDUC 	AD STRES	55 	rd+z)))	R OF SAF	ETY DUE T	
26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 70	- DEPTH, $MD_z = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (MD)$ PORE VA $U1_Z = \frac{DE_1}{U_Z}$ $U_Z = IF(U)$ EFFECTIN $\sigma_{ZZ} = \sigma_{TZ}$	SCIL IN MD ₂ EPTH ₂ - DEP 2 FR55S. 1 ₂ - MD ₂ -1/Y, TER PRES 2 1 ₂ < 0.0.01 ₂ 1 ₂ < 0.0.01 ₂ 1 ₂ < 0.0.01 ₂ - IU ₂	DEX PRO $TH_{2-1} + DEP$ $sonz + \sigma_{72-1}$ (SURE, $H_{2-1} DEPTH_2$)	PERTIES <i>TH</i> ₂₊₁ <i>Y</i> _W = (<i>GWT</i> · <u>1</u>	(₁₀)	SPT CORI N_{cost} N_{cost} ENERGY ($C_{sst} =$ CORRECT $N_{cs} =$ FINES CO $a1_{s} = 0$ $a2_{s} = s^{2}$ $a_{s} = 5/2$	RECTION (I $=\frac{9.78}{\sqrt{7z_2}}$ $=IF(N_{CORE})$ CORRECTION $=IF(N_{CORE})$ $=IF(N_{CORE})$ $=IF(N_{CORE})$ $=N_{VALUE} \cdot N_{CO}$ NTENT CO	CORRE DA(98,21995) 2.2. Ncosz DN. c 3. 0.75,1.0) DQUNT. sc - C ss 2 FRECTION EST20 ⁴	CTIONS $S1_2 = 1.0$ $S2_2 = 0.99 +$ $S3_2 = 1.2$ EVENES CON	(FINES CONT 1000	<u>ENT2)**</u>	DEFORM/ $rd1_z = 1 \cdot rd2_z = 1.1$ $rd2_z = 1.3$ $rd3_z = 0.3$ $rd4_z = 0.2$ $rd4_z = 0.2$ $rd5_z = 0.2$ SHEAR- S twzz = 0 CYCLIC S $CSR_z = \frac{1}{2}$ MAGNITU $MSF = \frac{1}{2}$	E 40075 - D1 ABILITY RE - 0.00765 - D1 174 - 0.0267 - 1 5 DEPTH _Z < 9.: TRESS AV 0.65 - a - a _{TZ} - : TRESS INA 0.65 - a - d _{TZ} - : TRESS INA 0.65 - a - d _{TZ} - : TRESS INA 0.65 - a - d _{TZ} - : DE SCALIA 10 ²²⁴ m ²³⁶	ABTHQUA DUCTION, IPTH: DEPTH: DEPTH: IS.rdl:IF(D: EDAGE, rd: TIO,	<mark>KE− INDUC</mark> PTH ₂ < 23, r	42 ₂ 1F(DEPT)	35 I I ₂ < 30.rd3 ₂ .	rd42)))	R OF SAF	ETY DUE T $S_2 = \frac{CRR_2}{CSR_2} \cdot N$	O LIQUEFS ISF
23 27 28 29 30 31 32 33 34 35 36 37 37 38 39 40 41 42 43 44 45 46 47 48 48	- DEPTH. $MD_z = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (ME)$ PORE VA $U1_T = \frac{DE_1}{2}$ $U_Z = IF(U)$ EFFECTIV $\sigma_{ZZ} = \sigma_{TZ}$	SCIL IN MD ₂ EPTH ₂ - DEP 2 F55S. ¹ ₂ - MD ₂₋₁)X, TER PRB2 PTH ₂ - DEPT 2 1 ₂ < 0.0.01 ₂) E STRESS - U ₂	$\frac{TH_{2-1}}{SOURE} + DEP$ $\frac{SOURE}{SOURE} + \frac{1}{2} DEPTH_2$)	PERTIES TH_{t-1} $Y_{W} = (GWT \cdot Y_{W})$	lir)	SPT CORI N_{cost} N_{cost} ENERGY ($C_{sst} =$ CORREC1 N_{ct} ; FINES CO $a1_{t} = 0$, $a2_{t} = e^{t}$ $a_{2} = IF(F)$ $a_{2} = IF(F)$ $a_{2} = IF(F)$	RECTION () = $\frac{9.78}{\sqrt{2}\pi_2}$ = IF(N _{CORE} > CORRECAL = IF(DEPTH ₂ = N _{PALUE} · Nec NTENT CO 1 ⁻¹ //////////////////////////////////	CORRE D299821995) 2.2. Ncosz DN. 4.3. 0.75.1.0) DQUNT. 827 Csts RAECTION E2723 ² TT ₂ < 5. 012.1 TT ₂ < 5. 012.1	CTIONS 612 = 1.0 622 = 0.99 + . 632 = 1.2 F(FINES CON F(FINES CON	(<i>FINES CON</i> 1 1000 TENT ₂ < 35, 1 FENT ₂ < 35, 1	$\frac{S_N(T_2)^{1.4}}{(2_2, \alpha_{3_2}))}$ (22, (3_2))	DEFORM/ $rd_2 = 1$ $rd_2 = 1.7$ $rd_2 = 0.7$ $rd_2 = $	EADILITY RE - 0.00765 - D1 - 0.00765 - D2 - 0.0267 - 174 - 0.0267 - 5 DEPTH ₂ < 9: TRESS AN 0.65 - a - σ ₁₂ - 1 TRESS FIA 	ABTHQUA DUCTION, IPTH2 DEPTH2 DEPTH2 IS.rd12 IF(D EDAGE, rd2 TIO, IQV25CTOI	KE- INDUC 1977H ₂ < 23.7	AD STRES	35 	rd+z)))	R OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z} \cdot h$	
26 27 28 29 30 31 32 33 34 35 36 37 37 37 38 38 39 40 41 42 43 44 45 46 45 48 49 50	- DEPTH. $MD_z = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (MD)$ PORE VA $U1_Z = \frac{DE}{2}$ $U_Z = 1F(U)$ EFFECTIV $\sigma_{ZZ} = \sigma_{TZ}$	SCIL IN MD_z $EPTH_z - DEP 2 ESTER z = MD_{z-1})Y_1TER PRESPTH_z - DEPT 2 1z < 0.0.01z_2E STRESS- U_z $	$\frac{DEX PRO}{TH_{2-1}} + DEP$ solt = σ_{72-1} SURE. $\frac{H_{2-1}}{DEPTH_2}$)	PERTIES <i>TH</i> ₂₊₁ <i>Y</i> ₃₀ - (<i>GWT</i> · Y	l'ar)	SPT CORI Nease Nease ENERGY ($C_{EE2} =$ CORREC1 N_{C2} (FINES CO $a1_E = 0$, $a2_E = e^2$ $a3_E = 5$, $a_E = IF(F)$	RECTION ($= \frac{9.78}{\sqrt{\pi}z}$ $= IF(N_{CORZ} > CORRECTION = IF(DEPTH_z = N_{CORT} + N_{CORT})= N_{VALUE} + N_{CORT}NTENT CO= N_{VALUE} + N_{CORT}= N_{VALUE} + N_{VA$	CORRE DA9821995) 2.2. Neosz DN. < 3. 0.75.1.0) COUNT. Az: Casz RECTION 22772) ² 727 < 5. 0.12.1 727 < 5. 0.12.1	CTIONS 51 ₂ = 10 52 ₂ = 0.99 + 53 ₂ = 1.2 F(FINES CON (FINES CON	(FINES CONT 1001 TENT ₂ < 35.6 TENT ₂ < 35.6	$\frac{E(NT_2)^{1,4}}{2_2, \alpha_{3_2}}$ $(2_2, \alpha_{3_2}))$	DEFORM/ $rd1_z = 1 \cdot r$ $rd2_z = 1.1$ $rd2_z = 0.1$ $rd2_z = 0.2$ $rd2_z = 0.2$ $rd2_z = 0.2$ $rd2_z = 0.2$ SHEAR- S carz = 0 CYCLIC S $cSR_z = \frac{1}{2}$ MAGNITU MSF = - CYCLIC R $CRR_z = 1$	E ABILITY PE = 0.00765 · DJ 174 - 0.0067 · J 5 DEPTH ₂ < 9. TRESS AM 1.65 · a · $\sigma_{\pi\pi}$ · 1 TRESS FIA $\sigma_{\pi\pi}$ DE SCALM 10 ²²⁴ ESISTANC 0.007 · (N _{erz})	ABTHQUA EDUCTION, IPTH: DEPTH: IS.rdl::/F(D: EDAGE, rd: TIO, IGN:SECTOI	KE− INDUC PTH ₂ < 23, r	ZED STRES	55 1 1 ₂ < 30, rd 3 ₂ ,	rd+z)))	R OF SAF	ETY DUE T	
26 27 27 28 30 31 32 33 34 35 36 37 38 39 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51	- DEPTH , $MD_z = \frac{D}{\tau}$ TOTAL ST $\sigma_{TZ} = (MD)$ PORE VA $U1_Z = DE$ $U_Z = IF(U)$ EFFECTIV $\sigma_{ZZ} = \sigma_{TZ}$	SCIL IN MD_z $EPTH_z - DEP 2PS_2S.z = MD_{z-1}N_zTER PRES PTH_z - DEPT21_z < 0.0.01_zI_z < 0.0.01_z$	DEX PRO TH ₂₋₁ + DEP sonz + 972-1 SURE. H ₂₋₁ DEPTH ₂)	PERTIES TH_{2-1} $Y_{W} = (GWT \cdot Y_{W})$	liv)	SPT CORI Near Near ENERGY (Carret CORRECT Ner ($a_{12} = 0$ $a_{12} = 0$ $a_{22} = c^2$ $a_{32} = 5$, $a_{32} = 1F(F)$, Ner (Ner ($a_{22} = a_{22})$	RECTION () $= \frac{9.78}{\sqrt{\pi_{g_2}}}$ $= IF(X_{CORP} > CORRECAL IF(DEPTH_2 + IF(DEPTH_2 + Neet))$ RECORRECAL IF(DEPTH_2 + Neet)) NTENT CO NTENT	CORRE OA(θa21995) 2.2. Neoaz DN. c 3. 0.75.1.0) COUNT. az· Casz FREECTION Taryof T ₂ < 5. 012.1 T ₂ < 5. 012.1	CTIONS 51z = 1.0 52z = 0.99 + - 52z = 1.2 F(FINES CON F(FINES CON	[FINES CONT 1000 TENT ₂ < 35. A FENT ₂ < 35. A	$\frac{g_{(N_{2}^{*})^{24}}}{(2_{2}, \alpha_{3_{2}}))}$ $(2_{2}, \beta_{3_{2}}))$	DEFORM/ rd1g = 1 rd2g = 1 rd3g = 0 rd3g	E ABILITY FE - 0.00765 - DJ - 1.74 - 0.0267 - 1.74 - 0.006 - I - 1.74 - 0.74 - 0.74 - 0.74 - 0.74 - 0.74 - 0.74 - 0.74 - 0.74 - 0.74 - 0.74 -	ARTHQUA EQUATION, IPTH_ DEPTH_ DEPTH_ DEPTH_ IS.rdl_IF(D. EDAGE, rd_ TIO, IGN/39CTOI	<mark>KE− INDUC</mark> 2 <i>PTH₂</i> < 23, r	20 STRES	5 5	rd42)))	R OF SAF	ETY DUE T $i_Z = \frac{CRR_Z}{CSR_Z}$, N	O LIQUEFS
26 27 27 28 30 31 32 33 34 35 36 37 38 39 34 35 36 37 38 39 44 41 42 43 44 45 46 47 48 49 50 51 52	- DEPTH. $MD_z = \frac{D}{\tau_z}$ TOTAL ST $\sigma_{\tau z} = (MD)$ PORE VA $U1_z = \frac{DE_1}{U_z}$ $U_z = IF(U)$ EFFECTIV $\sigma_{zz} = \sigma_{\tau z}$	SCIL IN MD_z $EPTH_z - DEP 2 FIS28. I_z - MD_{z-1}N_yTER PREPTH_z - DEPT 2 I_z < 0.0.01z_1I_z < 0.0.01z_1I_z < 0.0.01z_1I_z < 0.0.01z_1$	DEX PRO	PERTIES TH ₂₋₁ Y _W = (GWT · 1 COR. 1970	(₁₁)	SPT CORI Nease Nease ENERGY (Case = CORRECT Nex : FINES CO $a1_2 = 0$ $a2_2 = e^2$ $a3_2 = 5$; $a_2 = IF(F)$ $\beta_2 = IF(F)$	RECTION () $= \frac{9.78}{\sqrt{\sigma_{22}}}$ $= IF(N_{CORP} > CORRECTION)$ () () () () () () () () () ()	CORRE DA98,21995) 2.2. N _{coaz} DN. < 3.0.75.1.0) CQUINT. nz· C _{ERZ} FIRECTION T _Z < 5. σ1 ₂ .1 T _Z < 5. σ1 ₂ .1	CTIONS 51z = 1.0 52z = 0.99 + 53z = 1.2 F(FINES CON F(FINES CON CUDCLIST	(FINES CONT 1000 TENT ₂ < 35, p	$\frac{g(\sqrt{r_2})^{1/2}}{(2_2, \alpha_{3_2}))}$ $(2_2, \beta_{3_2}))$	DEFORMA $rd1_2 = 1$ $rd2_2 = 1.3$ $rd2_2 = 0.3$ $rd2_2 = 0.2$ $rd2_2 = 0.2$ $rd2_2 = 0.2$ CYCLIC S CSR ₂ = $\frac{1}{2}$ CYCLIC S CSR ₂ = $\frac{1}{2}$ CYCLIC R CRR ₂ = 1	E ABILITY RE 0.00765 · DJ 174 - 0.026 · D DEPTHz < 9.1 TRESS AN 0.65 · a · drz · · · TRESS FIA 0.65 · a · drz · · TRESS FIA 0.65 · a · drz · · DE SCALIN 10 ²²⁴ m ²³⁴ ESISTANC 0.007 · (N _{crz})	ABTHQUA EQUATION, IPTH; DEPTH; DEPTH; EEPAGE, rd; TIO, IGN:SOCTOI	KE - INDUC PTH ₂ < 23. r	ED STRES	35 d _z < 30,rd3 ₂ .	rd42)))	R OF SAF	ETY DUE T $s_z = \frac{CRR_z}{CSR_z}$, N	O LIQUEFS
26 27 28 29 30 31 32 33 34 35 36 37 37 38 39 40 41 41 42 43 44 44 45 46 47 44 50 51 52 14	- DEPTH. $MD_z = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (MD)$ PORE VA $U1_Z = \frac{DZ}{U}$ $U_Z = IF(U)$ EFFECTIV $\sigma_{ZZ} = \sigma_{TZ}$ ())	SOIL IN MDz EPTHz - DEP ESSES (z - MDz-z)/Y, TER PRESE PTHz - DEPT 2 1z < 0.0.01z) E STRESS - Uz SOMPUTA	DEX PRO TH ₂₋₁ + DEP 20112 + σ ₇₂₋₁ SURE. H ₂₋₁ DEPTH ₂	PERTIES TH ₂₋₁ Y _W - (6WT - Y SOIL IND	ژیر) EX GRAPH	SPT CORI Nease Nease CORRECT Next FINES CO $a_{1g} = 0$ $a_{2g} = e^2$ $a_{3g} = 5$; $a_{2g} = F(F)$ Next = a_{2g} S _ FACC	RECTION () RECTION () $= \frac{9.78}{\sqrt{\sigma_{g_2}}}$ $= IF(N_{cosx} > CORRECTION = IF(DEPTH_z = N_{cosx} - N_{c$	CORRE DA(\$4,1995) 2.2. Noosz ON, 3.3.75,10) DOUNT. 3.2. Cssz FRECTION Tr < 5.012,1 Tr < 5.012,1 Tr < 5.012,1	CTIONS 61z = 1.0 92z = 0.99 + 93z = 1.2 F(FINES CON CEINES CON SUBSURF/	IPINES CONT 1000 TENT ₂ < 35. EENT ₂ < 35. KCE DIAGE	<u>εχτερνα</u> (2 ₂ , α3 ₂)) (2 ₂ , β3 ₂))	DEFORMA rd 1 ₂ = 1 · rd 2 ₂ = 1.1 rd 2 ₃ = 0.0 rd 2 ₄ = 0.0 rd 2 ₄ = 0.0 SHEAR-S T _{avez} = 0 CYCLIC S CYCLIC S CSR ₂ = 1 CYCLIC S CSR ₂ = 1 CYCLIC R CRR ₂ = 1	E ABILITY FE - 0.00765 - Di //4 - 0.008 - Z DEPTH _Z < 9.1 TRESS AX DEFTH _Z < 9.1 TRESS FA 	ABTHQUA BUCTION, IFFH; DEPTH; DEPTH; SEPTH; SEPAGE, rd; TIO, IGN:SCTOI	KE- INDUC PTH ₂ < 23, r	42 ₂ IF(DEPT)	55 4 ₂ < 30.rd3 ₂ .	rd42)))	R OF SAF	ETY DUE T $S_Z = \frac{CRR_Z}{CSR_Z}$, N	O LIQUEFE
26 27 28 29 30 31 32 33 34 35 36 37 37 37 38 39 40 41 42 43 44 45 46 47 8 49 50 51 52 14	- DEPTH., $MD_2 = \frac{D}{2}$ TOTAL ST $\sigma_{TZ} = (MD)$ PORE VA $U1_2 = \frac{DE}{2}$ $U_2 = 1F(U)$ EFFECTIV $\sigma_{ZZ} = \sigma_{TZ}$	SOIL IN MD_2 $EFTH_2 - DEP$ $EFTH_2 - DEPT$ TER PRESPECTION (12) (12) (12) (12) (12) (12) (12) (12)	DEX PROI	PERTIES TH2-1 Yw - (GWT - 1) SOIL IND	Ser)	SPT CORI Neonz Neonz ENERGY (Casz = CORRECT Nez + FINES CO alg = 0 alg = 0 alg = s alg = 1F(F) $B_{2} = 1F(F)$ Nez = ag IF(Nez = ag IF(Nez = ag) S (FACT)	RECTION () $= \frac{9.76}{\sqrt{\pi_{22}}}$ $= IF(x_{cons} > $ CORRECTION IF(DEPTH ₂) IFED BLOV: IFED BLOV: IFED BLOV: IFED BLOV: IFED BLOV: IFED BLOV: IFED BLOV: IFEC BLOV	CORRE CARRENDA 2.2. Neonz DN. < 3. 0.75.1.0) CQUNT. nz: Canz RECTION Tz < 5. n1z.1 FETY FETY	CTIONS 51z = 1.0 52z = 0.99 + 53z = 1.2 F(FINES CON F(FINES CON SUBSURF/	IFINES CONT 1000 TENT ₂ < 35, J TENT ₂ < 35, J	<u>ε.ντ₂).</u> (2 ₂ , α3 ₂)) (2 ₂ , β3 ₂))	DEFORM/ rd1g = 1 · rd2g = 1.1 rd2g = 0.0 rd2g = 0.0 rd2g = 0.0 rd2g = 0.0 rd2g = 0.0 CYCLIC S' CSRg = 1 CYCLIC S' CSRg = 1 MAGNITU MSF = CYCLIC R CRRg = 1	E4 2017 17 4 2017 17	ARTHQUA EDUCTION, IFTH: DEPTH: DEPTH: SEPTH: SEPAGE, rd: TIO, IGN:SECTOI	KE - INDUC IPTH ₂ < 23.r	al _z if(depti	SS	rd+z)))	IR OF SAF	$\overline{z}_{z} = \frac{CRR_{z}}{CSR_{z}}$, λ	O LIQUEFE (SF

Figure 5.2 Sample User Interface of the Potential Liquefaction Program

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З			U	SCS			0	м					Coaurse and Fine Grained Soils						
				INDRGANIC SILTS	Martin States	children al	//							Inorgani	c Silts &	Very Fine			
4				1101101110 01210			0.45	м					ML	Sanas, S	layey Silt	gyey Fine			
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5							1.5	M					CL	Med	um Plastic	aity,			
6			DRGANIC CLAY OF L	OW-MED PLASTICITY	LIQUEFIA	BLEZONE	3	м					———		Loan anay	č.			
					LIDITIES IN	THE POINT							MH	Fine S	and or Sil	ty Soils,			
7				INURGANIC SILTS	DQUEFIA	BLE ZUNE	4.5	м							Elastia Si	11ts			
				INORGANIC SILTS	LICIUEFIA	BLEZONE							CH	Inor		5 of			
8							6	м					ĢН	High Pi	osticity, 1	Fat Clays			
			ORGANIC CLAY OF L	OW-MED PLASTICITY	LIQUEFIA	BLEZONE	7 5	14					C W	Wel	I Groded S	Sonds,			
-							. 7.3	IVI					24	LÎ	ttle or no	Fines			
10			DRGANIC CLAY OF L	OW-MED PLASTICITY	LIQUEFIA	BLEZDNE	9	м					SP	Poor	ly Graded	Sands,			
				INDRGANIC SILTS	HOUSEIA	RIEZONE							01	LĨt	tle or no	Fines			
11				INDITIONING OLD TO			10.5	м					SM		Silty Sand	s,			
			DRGANIC CLAY OF L	OW-MED PLASTICITY	LIQUEFIA	BLEZONE								Sana	1 - 511T MI	XTUP 05			
12							12	м					SC	Sono	layey Song	15,			
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14				INURGANIC SILTS	LIQUEFIA	BLEZONE	15	м											
				INDRGANIC SILTS	HOUFFIA	BLEZONE													
15				INDITION INDIVIDUAL IN			16.5	м											
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16							18	M											
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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.

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 Summary of Liquefaction Susceptibility of the Selected Locations

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.

Soil	Soil Profile	Average Soil Properties for Top 30m of Soil Profile						
Profile	Name/ Generic	Shear Wave	SPT, N	Undrained Shear	Factor of Safety Due to			
Туре	Description	Velocity, V _s	(blows/300	Strength, S _U	Liquefaction, FS			
		(m /s)	mm)	(kPa)	(at Magnitude 7.5)			
S _A	Hard Rock	>1500			-			
S _B	Rock	760 to 1500			-			
S _C	Very Dense Soil	360 to 760	>50	>100	>2			
	and Soft Rock							
S _D	Stiff Soil Profile	180 to 360	15 to 50	50 to 100	>1 but <u><</u> 2			
$\mathbf{S}_{\mathrm{E}}^{-1}$	Soft Soil Profile	<180	<15	<50	<u>≤</u> 1			
S _F	Soil Requiring Sit	e-specific Evaluation	n					

Table 7.1 Augmented Table of Soil Profile Types

(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

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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.

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