

Liquefaction Hazard Mapping Based on Regional Geology, Local Geotechnical Data, and Cyclic Stress Ratio (CSR) Values: Dagupan City, Pangasinan, Philippines

C.J.D. Landingin¹, J.M. Dipatuan², M.C.B. Arpa³

^{1,2,3}School of Civil, Environmental, & Geological Engineering,
Mapúa University, Muralla St., Intramuros, Manila 1002, Philippines

Abstract

The presence of the Philippine Fault, Iba Fault, East Zambales Fault, and the Manila Trench makes the central Luzon plains one of the most seismically active areas in the Philippines. Given its geology, which consists primarily of quaternary alluvial deposits, it is known that the magnitude and intensity of the earthquakes induced by some of these faults may be accompanied by liquefaction. Dagupan City has been selected as a study area for this liquefaction hazard mapping since it is situated within the region and has historically experienced the effects of liquefaction, as proven by accounts from PHIVOLCS. In the study's methodology, a map will be produced utilizing the features provided in QGIS to determine degrees of susceptibility in liquefiable areas using regional and local geology and geotechnical data with cyclic stress ratio (CSR) values. The results show the entirety of Dagupan to be highly susceptible to liquefaction, with the CSR values ranging from +0.30 to +0.70 in contrast to existing hazard maps where liquefaction is generally susceptible in all areas. The study implies that even with the results, liquefaction is not guaranteed to occur in every seismic event. Peak ground acceleration (PGA), earthquake generators, and the recurrence interval of the earthquake magnitude must be kept in mind.

Keywords: alluvial deposits, cyclic stress ratio, Dagupan City, liquefaction, peak ground acceleration.

1. Introduction

On July 16, 1990, a 7.8 magnitude earthquake known as the 1990 Luzon Earthquake struck central Luzon, and notable effects along the liquefaction phenomenon were manifested throughout the vicinity, including Dagupan City, Pangasinan, where significant liquefaction-induced damages were recorded.

According to recent studies, the East Zambales Fault (EZF) is a locked fault that implies high earthquake potential and can rupture anytime [2]. This event may then cause liquefaction.

The seismic vulnerability of the city stems from its regional setting, which is bound to be struck by high-magnitude earthquakes. Dagupan City's topography is generally flat, with elevations less than five (5) meters above mean sea level (MSL). The other explanation is that shaking forces can be intensified in the surrounding environment. The 1990 Luzon earthquake, as aforementioned, and major

earthquakes over the years have lowered the city's elevation [4]. resulting in widespread floods.

Liquefaction is a phenomenon that occurs when the soil under a building loses its strength and stiffness due to violent ground shaking, such as earthquakes or construction blasts [14]. Certain soil types, groundwater levels, and a greater probability of earthquakes make certain areas more susceptible to liquefaction. Geomorphological characteristics such as rivers, lakes, ponds, and abandoned channels are often used to evaluate the area's susceptibility to liquefaction.

This hazard must be evaluated to provide public safety. To help assess the liquefaction hazard in an inexpensive yet effective approach, this study will create a Liquefaction hazard map of Dagupan City through simple methods. This is compared to the usual approach to liquefaction analysis which is specific-site-based using the factor of safety equation which is defined as the cyclic resistance ratio inversely proportional to the cyclic stress ratio.

Reference [28] was the method used in this study. In their methods, the delineation of the degrees of liquefaction susceptibility was determined from the cyclic stress ratio (CSR) derived if the total effective stress (σ_v), effective vertical stress (σ_v'), and nonlinear shear-mass participation factor (r_d) are constant near the ground surface and peak ground acceleration (A_{max}) varies depending on the geographical location.

A range of values will be based on the CSR value obtained, assigning a degree of susceptibility (low, moderate, or high). Regional and local data such as surface geology maps, soil maps, geomorphology, groundwater, and active fault data will also be considered in constructing the map to validate the study results. Besides the CSR results, regional and local data such as surface geology maps, geomorphology, groundwater, soil maps, and active fault data will also be considered in constructing the map to validate the study results.

In hopes of assisting local mitigation measures, a hazard map that delineates liquefaction-susceptible areas will be created. The study aims to (1) provide new information on surface and subsurface data such as boreholes, soil laboratory results, and other geotechnical investigations studies, geology, geomorphology, groundwater, soil, and fault proximity data, (2) delineate the degrees of liquefaction susceptibility through hazard mapping from existing and researched data, and (3) provide a liquefaction hazard map that can be used for city planning, building or structure designs, and emergency response by the local government units or private companies from projects in Dagupan City.

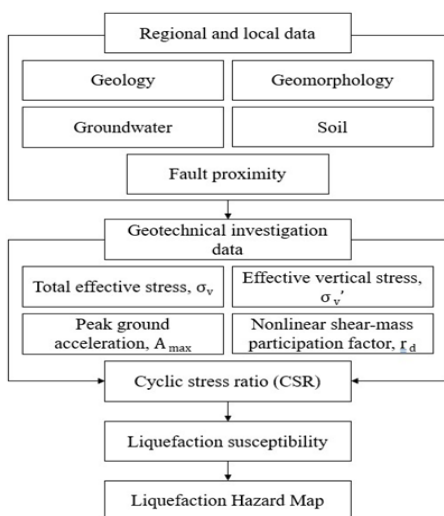


Fig.1. Conceptual Framework of the Liquefaction Hazard Mapping.

2. Methodology

At the start of the thesis, two sets of data will be collected: (1) regional and local data and (2) geotechnical investigation data. The regional and local data will be independent variables which include geology and geomorphology studies, groundwater, soil data, and active fault maps. For the geotechnical investigation data, the values needed to obtain the cyclic stress ratio (CSR) are total effective stress (σ_v), effective vertical stress (σ_v'), nonlinear shear-mass participation factor (r_d), and peak ground acceleration (A_{max}). With all the mentioned data collected and calculated, the liquefaction susceptibility can now be assessed and generated through Liquefaction Hazard mapping.

Data Gathering

The Geologic map of Dagupan can be obtained from the Mines and Geosciences Bureau (MGB) and the Pangasinan Provincial Planning and Development website for regional and local data. Previous studies, such as those of Ishihara et al. (1993), will be used as a basis. Hydrogeology data such as river systems, water bodies, and groundwater depth will be obtained from Dagupan City LGU, PangPPDO, and google satellite imagery. Since Dagupan City has a flat terrain, geomorphology studies and satellite imagery will be used to show geomorphic units that must be considered for evaluating liquefaction.

Field boring logs and other geotechnical tests and investigations will be obtained from the Department of Public Works and Highways (DPWH) and private companies specializing in geotechnical services. This will be used in the values needed for the total effective stress (σ_v), effective vertical stress (σ_v'), and the Nonlinear shear-mass participation factor (r_d) in computing the cyclic stress ratio (CSR). Peak ground acceleration (A_{max}) will be obtained through computations using the attenuation formula [28]. Finally, the provincial, municipality, and barangay boundaries will be based on maps from the City Planning and Development Office of Dagupan City and existing hazard and topographic maps from PHIVOLCS and NAMRIA.

Data Processing

For the data from geotechnical investigations, the in-situ and laboratory tests will be used in computing the cyclic stress ratio (CSR) as shown in eq. 2.1 by obtaining the total effective stress (σ_v), effective

vertical stress (σ_v'), peak ground acceleration (A_{max}), and the Nonlinear shear-mass participation factor (r_d) from the formula of Seed and Idriss (1971). The peak ground acceleration is computed using the formula as shown in eq. 2.2 [28]. The r_d formula is expressed in eq. 2.3.

$$CSR = 0.65 \cdot \frac{\sigma_v'}{\sigma_v} \cdot A_{max} \cdot r_d \quad (\text{eq. 2.1})$$

$$\log_{10} A_{max} = 0.41M_s - \log_{10}(R + 0.032 \cdot 10^{0.41 \cdot M_s}) - 0.0034R + 1.30 \quad (\text{eq. 2.2})$$

Where:

A_{max} = Mean of peak ground acceleration

R = the closest distance to the fault

M_s = Surface-wave magnitude

$$r_d = \exp [\alpha(z) + \beta(z) * M] \quad (\text{eq. 2.3})$$

$$\alpha(z) = -1.012 - 1.126 \sin \left(\frac{z}{11.73} + 5.133 \right) \quad (\text{eq. 2.4})$$

$$\beta(z) = 0.106 + 0.118 \sin \left(\frac{z}{11.28} + 5.142 \right) \quad (\text{eq. 2.5})$$

Where: z = depth below the surface in meters.

The preparation of the Liquefaction hazard map using GIS is then conducted by overlaying GIS data types of the sets mentioned in the framework. Raster and Vector datasets such as provincial and municipal boundaries, roads, etc., will be used from the latest hazard and topographic maps online.

Evaluation of Results

After obtaining the different CSR values, the researchers will classify the areas as high if CSR is greater than 0.1 and moderate if it is greater than 0.05 but less than 0.1 [28]. This is based on the minimum CSR where liquefaction was observed is 0.05 for very loose to moderately loose sands and 0.1 for loose to medium dense sand [13].

Values will be distributed in Dagupan City, and together with regional and local data on geology, geomorphology, groundwater, soil, and fault proximity, the liquefaction degree of susceptibility in Dagupan City will be determined. It will be presented through a liquefaction hazard map of Dagupan City using the Quantum Geographic Information System (QGIS) program. The results will be validated based on the available data on liquefaction caused by the 1990 Luzon Earthquake as well as existing maps and studies on liquefaction in Dagupan City.

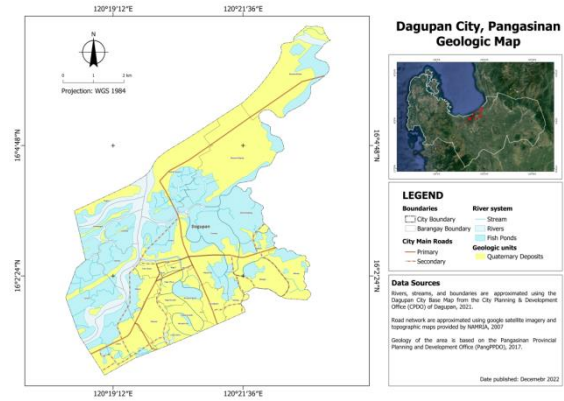


Fig.2. Geologic Map of Dagupan City.

3. Results and Discussion

1. Regional and Local Geologic Data

The generation of maps for the regional and local geologic data was prepared using the Quantum Geographic Information System (QGIS), a free software for creating geospatial information.

The maps prepared by the Pangasinan Provincial Planning and Development Office to display the geophysical environment of Pangasinan were mainly used [22]. Maps derived from the developmental office are of the geology, groundwater, soil, and fault proximity within the boundaries of Dagupan City. The geomorphology map was based on LiDAR-derived maps from the vulnerability assessments on the Dagupan River Basin and existing geomorphology studies with verifications of its said units in up-to-date Google satellite imagery [1].

The provincial boundary is approximated using geophysical maps from PangPPDO, while city and barangay boundaries, and river systems, are approximated on the Dagupan City Base Map prepared by the City Planning and Development Office (CPDO) of Dagupan City. Road networks and the delineation of fishponds are based on topographic maps from NAMRIA and Google satellite imageries.

A city-scale base map for the study area was created to serve as a visual reference in overlaying geospatial data acquired from resources that help prepare the data maps and the final output of the study – the liquefaction hazard map. The representation of the surface provides unchanging geographic and geologic features such as administrative boundaries, road networks, and river systems. These make up the framework where raster and vectors are efficiently incorporated.

Geology

The geology of the study area is underlain with quaternary alluvium, which consists of gravel, sand, silt, and clay, which is most likely deposited by the river channels and flood plains surrounding Dagupan. The lithology of the Luzon central plains where Dagupan is situated mostly originated from the Agno River. These deposits are of Late formation, Quaternary deposits- characterize the Dagupan River Basin which verifies the said ages of the deposits [9].

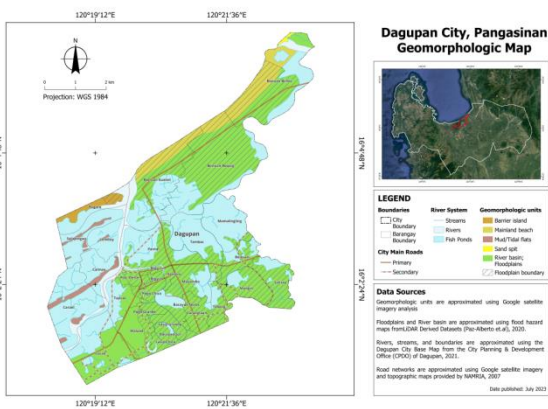


Fig.3. Geomorphologic Map of Dagupan City.

Geomorphology

The Dagupan River basin, which is a deltaic (fluvial) environment, mainly covers the city's geomorphology. A river system that stems from the tributaries of the Sinocalan, Bued-Cayanga, and Agno rivers, which headwaters originate in the Cordillera mountains, flows across the floodplains of

the basin. The east margin of the Agno River, which is a part of the Dagupan River system, forms a confluence with the Sinocalan River, forming the Calmay River, which exhibits the largest width among rivers. Besides river systems, there are also vast ponds for aquaculture along river channels,

making it suitable for the cause. These deposits are composed of granular soils – gravel, sand, silt, and some clay.

Some of the remaining geomorphic units can be identified using simple satellite imagery analysis on recent images available on Google Earth. As seen in the map, we can see marine depositional environments that extend up to the western margin of the Agno River mouth. On the western side, up to the coast of the city, are the beach ridge succession that forms barangay Calmay, Carael, Lomboy, Pugaro, and

Salapingao. In these ridges, specific units are the barrier island (Barangay Pugaro) and the mud and/or tidal flats (Barangays Calmay, Carael, Lomboy, and Salapingao). The barrier island is mostly sand with silt beds, while mud and/or tidal flats are muddy sediments of silt-clay particles (JICA, nd). Lastly are the beach sand deposits on the coasts east of the Calmay River mouth. Geomorphologic units are the mainland beach of the Bonuan barangays and the sand spit on the east of the Bued-Cayanga river mouth.

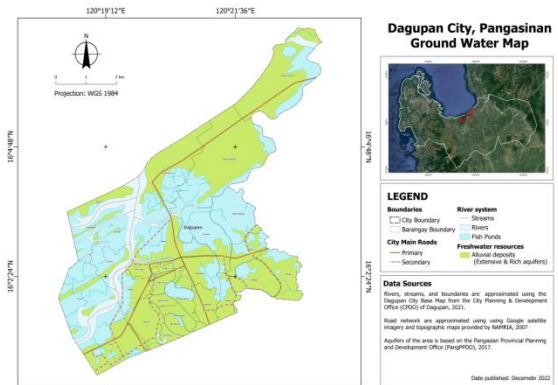


Fig.4. Groundwater Map of Dagupan City.

Groundwater

Given the geology of Dagupan City of alluvial deposits, mostly sand, gravel, and silt, aquifers in the area are extensive and rich. Since these are in porous formation, making them water-logged and loose, they are subjected to possible. Liquefaction. Liquefaction may be influenced by aquifer pressure and groundwater movement and thus must be considered in determining liquefiable areas [26].

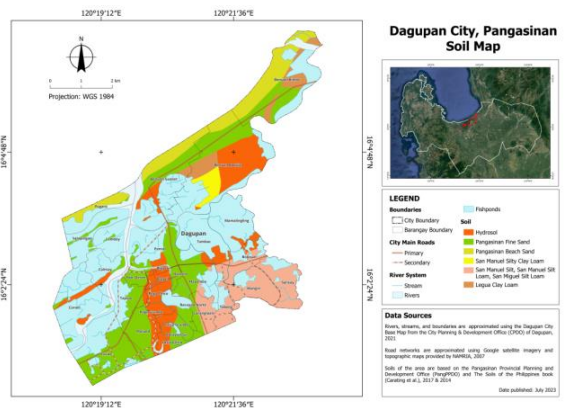


Fig.5. Soil Map of Dagupan City.

Soil Data

In evaluating liquefaction, identifying the soil types in a study area can qualitatively assess liquefaction susceptibility,

as some of these can amplify its effects. In saturated, sandy soils, liquefaction is most likely to take place. Large granular sediments, like sands, do not fit together well and have a lot of space – high porosity. This is described as a loose soil structure, meaning the soil will also permeate more water. Gravel and silts are also known to liquefy depending on the soil structure [13].

There are two (2) notable soil series – the Pangasinan and San Manuel series – in the study area where the different soil types are a part. Not a part of this series is the Legua Clay Loam which is said to be from hard igneous bedrock materials in the upland areas. Due to its organic materials and fine sediments, its deposition can be associated with waters that flow from a fluvial environment.

The Pangasinan series is situated in the coastal areas of the central Luzon Plain, where the mouth and beds of the Agno, Sinocalan, and Bued Rivers are located. Like most soil in the area, it is transported through streams [23]. The soil types, which are hydrosols and fine sand, are placed in this series because of their similar origin. The hydrosols are saturated soils for most of the year and are found in swamps, nipa, mangrove areas, and fishponds. Silt, sand, and clay make up the hydrosols in fishponds. In nipa and mangrove areas, it is made up of organic matter, silt, sand, and small quantities of clay. The elevated regions of the hydrosol areas are covered in reddish-brown fine sand, which is another soil type in the series called the Pangasinan fine sand. Lastly, along the coasts of Dagupan are the Pangasinan beach sand which has a greenish-gray color, and silt beds.

The San Manuel series found in the study area are of the loamy alluvial plains of central Luzon [23]. Fine sediments such as sand, silt, and clay can be found in its profile. Characteristically, the soil horizons are slightly compact and have no bands of stones or gravel. Under this loam soil are sandy sediments extending to greater depths.

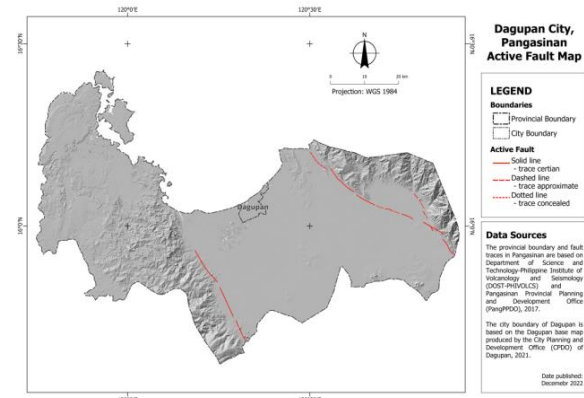


Fig.6 Active Fault Map of Dagupan City.

Fault

No faults cross along Dagupan City, but it has proximity to two active faults – the East Zambales Fault (EZF) at the east,

and the Philippine Fault Zone (PFZ): San Manuel fault segment at the west. These faults divide the central valley of Pangasinan from the northern flanks of the Zambales mountain range and the Cordillera central mountains of Luzon. The distance of EZF from the site ranges from 15 to 22 km, while the distance from PFZ ranges from 23 to 30 km. Thus, for the attenuation formula to be used in calculating the

peak ground acceleration (PGA), a composite of PGA obtained from EZF and PFZ: San Manuel segment is used.

2. Geotechnical Data

The borehole logs were acquired from the Department of Public Works and Highways (DPWH). Boreholes 7 to 31 were used because they were within the boundary of Dagupan City. The depth of the boreholes is 15 meters. Soils in boreholes 7 to 11, 17 to 19, and 21 to 31 are characterized by poorly graded sand with silt and silty sand. Borehole 12 to 14 mostly has silty sand with a few layers of poorly graded sand with silt. Borehole 15 mostly has poorly graded sand with silt with a few layers of silty sand. Borehole 16 contains fat clay and silty sand. Borehole 20 is purely characterized by silty sand. All the computed CSR values are greater than 0.1, indicating that the selected points are highly susceptible.

3. Liquefaction Susceptibility

CSR Value Computations

The given data from DPWH already provided the depth, soil type, and unit weight. The r_d values were

computed based on the given depth in the first column of the table below. σ_v was calculated by multiplying the unit weight of the soil by its given depth, while σ_v' was computed by subtracting pore water pressure from the vertical stress. α values range from -1.15639 to 0.02702 while β values from 0.0035 to 0.12812 using the max depth of 15 m. This results in the r_a values ranging between 0.991033 to 0.822452 in almost every borehole and inferred site. PGA values from boreholes 7 to 31 have a range from 0.355 to 0.401. It was computed using the attenuation formula where the distance of each site from the East Zambales Fault was acquired using HazardHunterPH by inputting the coordinates of each site.

CSR values were determined for the remaining soil types. It has assigned sites on the map with field types of Inferred Points (IP) to organize the attribute table of boreholes and other soil types in QGIS. Inferred and established values are used for the computation of CSR values in ISPs from the soil map – San Manuel soils, Legua Clay Loam, and Pangasinan Fine Sand. The unit weight for the inferred points, such as sand and clay, was based on the average unit weight from the boreholes, while loam soils are based on well-established resources from StructX (2022).

Table I. A summary of PGA and CSR values from the borehole and inferred sites.

Sites		Fukushima and Tanaka, 1990 (PGA)		Seed and Idriss, 1971 (CSR)	
		EZF	PFZ: SMS	EZF	PFZ: SMS
Boreholes	BH-7	0.355	0.310	0.460	0.402
	BH-8	0.356	0.309	0.458	0.397
	BH-9	0.358	0.307	0.486	0.417
	BH-10	0.360	0.306	0.478	0.406
	BH-11	0.362	0.305	0.466	0.393
	BH-12	0.364	0.304	0.510	0.427
	BH-13	0.364	0.303	0.505	0.420
	BH-14	0.366	0.302	0.490	0.403
	BH-15	0.368	0.300	0.475	0.387
	BH-16	0.372	0.298	0.691	0.554
	BH-17	0.374	0.297	0.479	0.380
	BH-18	0.375	0.303	0.550	0.445
	BH-19	0.376	0.295	0.499	0.392
	BH-20	0.378	0.294	0.507	0.395
	BH-21	0.380	0.293	0.491	0.379
	BH-22	0.382	0.291	0.493	0.376
	BH-23	0.382	0.290	0.534	0.405
	BH-24	0.385	0.288	0.526	0.394
	BH-25	0.388	0.287	0.515	0.381
	BH-26	0.390	0.286	0.458	0.336
BH-27	0.392	0.285	0.460	0.335	
BH-28	0.394	0.284	0.463	0.333	
BH-29	0.396	0.282	0.489	0.348	
BH-30	0.398	0.281	0.564	0.398	

Sites		Fukushima and Tanaka, 1990 (PGA)		Seed and Idriss, 1971 (CSR)		
		EZF	PFZ: SMS	EZF	PFZ: SMS	
		<i>BH-31</i>	<i>0.401</i>	<i>0.279</i>	<i>0.559</i>	<i>0.390</i>
<i>Inferred</i>	<i>Hyd</i>	<i>ISP-1</i>	<i>0.371</i>	<i>0.308</i>	<i>0.692</i>	<i>0.574</i>
		<i>ISP-2</i>	<i>0.381</i>	<i>0.292</i>	<i>0.709</i>	<i>0.544</i>
		<i>ISP-3</i>	<i>0.312</i>	<i>0.353</i>	<i>0.582</i>	<i>0.657</i>
		<i>ISP-4</i>	<i>0.372</i>	<i>0.298</i>	<i>0.693</i>	<i>0.555</i>
		<i>ISP-5</i>	<i>0.342</i>	<i>0.322</i>	<i>0.638</i>	<i>0.599</i>
		<i>ISP-6</i>	<i>0.345</i>	<i>0.319</i>	<i>0.642</i>	<i>0.594</i>
		<i>ISP-7</i>	<i>0.383</i>	<i>0.290</i>	<i>0.712</i>	<i>0.540</i>
		<i>ISP-8</i>	<i>0.325</i>	<i>0.340</i>	<i>0.604</i>	<i>0.633</i>
		<i>ISP-9</i>	<i>0.322</i>	<i>0.341</i>	<i>0.600</i>	<i>0.634</i>
		<i>ISP-10</i>	<i>0.357</i>	<i>0.308</i>	<i>0.665</i>	<i>0.574</i>
		<i>ISP-11</i>	<i>0.359</i>	<i>0.308</i>	<i>0.668</i>	<i>0.574</i>
	<i>LCL</i>	<i>ISP-12</i>	<i>0.322</i>	<i>0.342</i>	<i>0.694</i>	<i>0.735</i>
		<i>ISP-13</i>	<i>0.301</i>	<i>0.367</i>	<i>0.648</i>	<i>0.790</i>
		<i>ISP-14</i>	<i>0.289</i>	<i>0.383</i>	<i>0.623</i>	<i>0.824</i>
	<i>SM</i>	<i>ISP-15</i>	<i>0.325</i>	<i>0.340</i>	<i>0.399</i>	<i>0.633</i>
		<i>ISP-16</i>	<i>0.349</i>	<i>0.315</i>	<i>0.430</i>	<i>0.388</i>
		<i>ISP-17</i>	<i>0.325</i>	<i>0.339</i>	<i>0.399</i>	<i>0.417</i>
	<i>PFS</i>	<i>ISP-18</i>	<i>0.323</i>	<i>0.340</i>	<i>0.457</i>	<i>0.481</i>
		<i>ISP-19</i>	<i>0.362</i>	<i>0.304</i>	<i>0.512</i>	<i>0.430</i>
		<i>ISP-20</i>	<i>0.351</i>	<i>0.315</i>	<i>0.497</i>	<i>0.446</i>
		<i>ISP-21</i>	<i>0.322</i>	<i>0.342</i>	<i>0.455</i>	<i>0.485</i>
		<i>ISP-22</i>	<i>0.384</i>	<i>0.290</i>	<i>0.543</i>	<i>0.411</i>
		<i>ISP-23</i>	<i>0.297</i>	<i>0.373</i>	<i>0.420</i>	<i>0.528</i>
		<i>ISP-24</i>	<i>0.354</i>	<i>0.312</i>	<i>0.501</i>	<i>0.442</i>
		<i>ISP-25</i>	<i>0.301</i>	<i>0.367</i>	<i>0.426</i>	<i>0.520</i>
		<i>ISP-26</i>	<i>0.365</i>	<i>0.302</i>	<i>0.517</i>	<i>0.428</i>
		<i>ISP-27</i>	<i>0.366</i>	<i>0.301</i>	<i>0.519</i>	<i>0.426</i>
		<i>ISP-28</i>	<i>0.380</i>	<i>0.290</i>	<i>0.538</i>	<i>0.411</i>

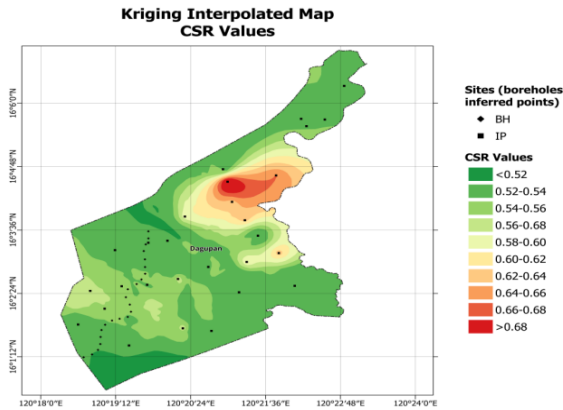


Fig.7. Composite of Kriging Interpolation Maps.

In Table I, two (2) PGA values are obtained separately for the two (faults) in proximity, the EZF and the PFZ. Thus,

separate values from each fault are also calculated for CSR. The range of values for peak ground acceleration PGA is 0.28 to 0.40, while the range of values for CSR is 0.33 to 0.82.

Kriging Interpolation of CSR Values

Since all CSR values computed from the borehole logs and inferred soil points fall under high liquefaction susceptibility where CSR values greater than 0.1, a kriging method of

mapping will be used to display the variations of the CSR values. The kriging interpolation maps are generated using a plugin – Smart-Map – which allows data to be imported from a QGIS layer and create the interpolation using ordinary kriging.

With two (2) kriging interpolated maps, the CSR values are delineated into 0.02 intervals from values less than 0.52 to values greater than 0.68. The results of the ordinary kriging are dependent on the available geotechnical data and inferred values from CSR variation are based on. One (1) map was generated using the PGA values obtained from the magnitude and distance of EZF, while the other is from the values from PFZ: San Manuel Fault segment.

A composite map of the two (2) generated Kriging interpolation maps from Smart-Map will be produced. This composite map shows a maximum-value raster in QGIS where the highest CSR value obtained in a single pixel from the two (2) maps will be displayed on the final liquefaction hazard map.

Liquefaction Susceptible Map

With the parameters – Geology, Geomorphology, Groundwater, Soil, Fault – where data maps are produced from the regional and local data, combined with CSR values derived from geotechnical soil parameters – soil layer depth, soil type, unit weight, total effective stress (σ_v), effective vertical stress (σ'_v), peak ground acceleration (A_{max}), and nonlinear shear-mass participation factor (r_d) – the liquefaction susceptibility map was generated (Fig.8).

The CSR values gathered within Dagupan fell within the range of high susceptibility. This indicates that the entire city of Dagupan is vulnerable to the effects of liquefaction generated by strong shaking from earthquakes. To better illustrate the varying CSR values across the study area, the

Dagupan City base map is underlaid with the composite map of the kriging interpolated maps derived from the CSR values of the two faults in proximity – EZF and PFZ: San Manuel fault segment.

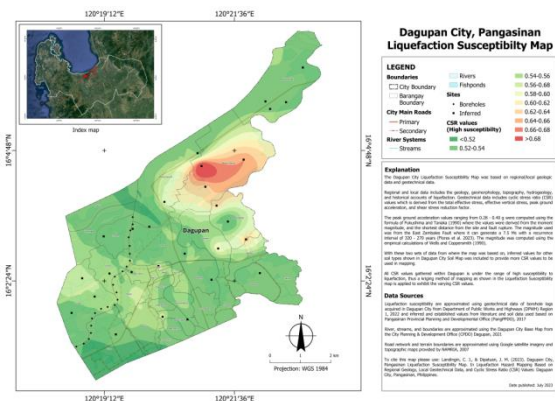


Fig.8 Liquefaction Susceptibility of Dagupan City Using CSR Values.

In the liquefaction susceptibility map, the illustration of the CSR values that are derived from boreholes and Inferred soil points are indicated along with the 0.02 intervals of the categorized CSR vector polygons representing ten (10) ranges.

4. Conclusions and Recommendations

The final output of the study showing the liquefaction susceptibility in Dagupan City is delineated and shows that the entire study area is highly susceptible to liquefaction compared to existing liquefaction hazard maps which only show general susceptibility in the alluvial and the coastal regions of Pangasinan where Dagupan is located.

Although other degrees of liquefaction – low, moderate, and high – were not indicated, the CSR

values where the degrees are based varied from +0.30 to +0.70, which is illustrated on the final map generated. In terms of the map's accuracy, it can be said that the values, especially those inferred and established, are not fairly accurate in contrast to computations done from the data collected from the geotechnical investigation report from DPWH. Additionally, due to the inconsistent spacing of the sites – boreholes and inferred points – the CSR contours are rough compared to typical interpolated maps.

Since the liquefaction susceptibility map shows high susceptibility throughout the entire study area, it implies that there must be a significant concern for the safety of structures in the area, as liquefaction can lead to severe ground deformation, settlement, lateral spreading, and potential damage to buildings, roads, bridges, and other critical infrastructures. Considering Dagupan is a center for commercial, educational, and health establishments in the province of Pangasinan, infrastructure planning, enforcement of building codes, land-use, and development restrictions, and retrofitting structure designs will make use of these hazard maps to mitigate the effects of liquefaction. A quantitative assessment of liquefaction susceptibility, such as the method done in this study, can significantly aid city planning.

In any case, safeguarding the security and resilience of communities located in high-susceptibility areas requires implementing precautionary measures and being aware of the possible risk of liquefaction. A high liquefaction susceptibility map does not guarantee that liquefaction will happen in every earthquake event. It is crucial to bear in mind the PGA, earthquake generator, and the recurrence interval of the earthquake magnitude used as parameters in this model. The likelihood and severity of liquefaction-induced effects will depend on the magnitude of an earthquake's ground shaking as well as the depth and area of liquefiable soil layers.

The data received from DPWH was along Agno River; therefore, the given borehole data is limited; the researchers recommend gathering more borehole data for the San Manuel Silt, Hydrosol, San Manuel Silty Clay Loam, and Legua Clay Loam in Dagupan City to get more accurate CSR values for a better liquefaction map. The map assumes that the groundwater is at ground level. Therefore, another recommendation is to acquire a groundwater depth

map to properly identify the level of groundwater and accurately determine which depth of the soil is saturated for effective vertical stress.

Additional studies should be done for the cohesive soils – fine-grained soil or clays – since they experience the same strain-softening phenomenon but do not liquefy the same as sand. This is particular to sensitive clays, which are defined as the ratio of undisturbed and remolded strengths.

Given the high susceptibility to liquefaction of Dagupan City, it is vital to apply the Design Guidelines, Criteria, and Standards (DGCS) by the Department of Public Works and Highways (DPWH) on liquefaction potential analysis. This involves the factor of safety formula involving the cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) values. This is highly recommended for conducting borehole logs in specific sites for geohazard assessments on preliminary building designs.

To generate an exposure map, the researchers recommend including the density of built-up areas in the map. This is done to identify the communities in Dagupan City that are at risk.

To precisely identify which regions are liquefiable, the researchers also recommend that the approach used in this study be used in other study areas or neighboring areas that may enter the criteria of potential liquefaction accompanied by an abundance of borehole data.

5. Acknowledgement

We thank Dr. Maria Carmencita B. Arpa for contributing and supporting us throughout the progress and development of our study. We thank Dr. Arturo S. Daag, Mr. Federico B. dela Peña, Mr. Winston Philip C. Pioquinto, and Engr. Joel D. Nuñez, for also contributing and reviewing for the betterment of our paper. We are grateful for the sources made available to accomplish this work by the Pangasinan Provincial Planning and Development Office (PangPPDO), Dagupan City Planning and Development Office (CPDO), and Department of Public Works and Highways (DPWH). We are also grateful to Mapúa University for providing us with an academic shelter together with anonymous affiliated friends and reviewers to improve our manuscript.

References

- [1] A. M. Paz-Alberto, J. A. A. Espiritu, & K. Mapanao, (2020). Dagupan River Basin Exposure and Vulnerability Assessment of Buildings Extracted from LiDAR Derived Datasets. *American Journal of Climate Change*, 09(04), pp. 454–479. <https://doi.org/10.4236/ajcc.2020.94029>
- [2] C. M. Flores, et al., “Shallow structures, interactions, and recurrent vertical motions of active faults in Lingayen Gulf, Philippines”, *Journal of Asian Earth Sciences: X*, volume 9, 100152, pp. 15-16; June 2023
- [3] CPDO Dagupan. (2017). Geophysical Profile. Retrieved from The Official Website of the City Government of Dagupan website: <https://www.dagupan.gov.ph/the-city/physical-profile/>.
- [4] Dagupan - Philippines - City Profile - Beta Version: Campaign. (n.d.). [Www.unisdr.org](http://www.unisdr.org). <https://www.unisdr.org/campaign/resilientcities/cities/philippines/dagupan.html>
- [5] Department of Science and Technology - Philippine Institute of Volcanology and Seismology. (2020). 1990 July 16 Ms7.8 Luzon Earthquake. Retrieved from <https://www.phivolcs.dost.gov.ph/index.php/earthquake/destructive-earthquake-of-the-philippines/2-uncategorised/212-1990-july-16-ms7-9-luzon-earthquake>
- [6] Department of Science and Technology - Philippine Institute of Volcanology and Seismology. (2021). Ground Shaking Hazard Map of the Province of Pangasinan. Retrieved from <https://gisweb.phivolcs.dost.gov.ph/gisweb/earthquake-volcano-related-hazard-gis-information>.
- [7] Department of Science and Technology - Philippine Institute of Volcanology and Seismology. (2021). Liquefaction Hazard Map of Dagupan City, Pangasinan Province. Retrieved from <https://gisweb.phivolcs.dost.gov.ph/gisweb/earthquake-volcano-related-hazard-gis-information>.
- [8] Department of Science and Technology - Philippine Institute of Volcanology and Seismology. (2019, April 19). PRIMER ON THE 22 APRIL 2019 MAGNITUDE 6.1 CENTRAL LUZON EARTHQUAKE. Retrieved January 5, 2022, from www.phivolcs.dost.gov.ph website: <https://www.phivolcs.dost.gov.ph/index.php/news/8233-primer-on-the-22-april-2019-magnitude-6-1-central-luzon-earthquake-23-april-2019>
- [9] E. C. Paringit, & A. M. Paz-Alberto, (2017). Hazard Mapping of the Philippines Using LIDAR (Phil-LIDAR 1) 2. Retrieved from <https://dream.upd.edu.ph/assets/Publications/LiDAR-Technical-Reports/CLSU/LiDAR-Surveys-and-Flood-Mapping-of-Dagupan-River.pdf>.
- [10] G. F. Wieczorek, C. G. Newhall, & L. G. Wennerberg, (1992). Faulting, structural damage, liquefaction, and landslides from the Luzon, Philippines earthquake of July 16, 1990. Retrieved from <https://pubs.usgs.gov/of/1992/0367a/report.pdf>
- [11] GeoRiskPH. (n.d.). HazardHunterPH - Hazard assessment at your fingertips. Retrieved from hazardhunter.georisk.gov.ph website: <https://hazardhunter.georisk.gov.ph/>.
- [12] I. Idris, & R. Boulanger, (2010). SPT-BASED LIQUEFACTION TRIGGERING PROCEDURES. University of California. Retrieved from https://faculty.engineering.ucdavis.edu/boulanger/wp-content/uploads/sites/71/2014/09/Idriss_Boulanger_SPT_Liquefaction_CGM-10-02.pdf.
- [13] Inter-Agency Committee for Documenting and Establishing Database on the July 1990 Earthquake.
- [14] J. Johansson, (2000, January 27). What is soil liquefaction. Retrieved January 8, 2022, from depts.washington.edu website: <https://depts.washington.edu/liquefy/html/what/what1.html#:~:text=Liquefaction%20is%20a%20phenomenon%20in>.
- [15] K. Ishihara, A. Acacio, & I. Towhata, (1993). NII-Electronic Library Service. https://www.jstage.jst.go.jp/article/sandf1972/33/1/33_1_133/_pdf/-char/en
- [16] K. Tokimatsu, H. Kojima, & A. Abe, (1992). Liquefaction - Induced Damage, and Geological and Geophysical Conditions During the 1990 Luzon Earthquake. Volume I. https://www.iitk.ac.in/nicee/wcee/article/10_vol1_135

- [17] K. Tokimatsu, H. Kojima, S. Kuwayama, A. Abe, & S. Midorikawa, (1994). Liquefaction-Induced Damage to Buildings in 1990 Luzon Earthquake. *Journal of Geotechnical Engineering*, 120(2), 290–307. [https://doi.org/10.1061/\(asce\)0733-9410\(1994\)120:2\(290\)](https://doi.org/10.1061/(asce)0733-9410(1994)120:2(290))
- [18] K. Tokimatsu, S. Kuwayama, A. Abe, S. Tamura, S. Midorikawa, Tamura, Shuji, & Preliminary. (1990). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics* (p. 11). https://core.ac.uk/download/pdf/229082796.pdf?fbclid=IwAR13XLf8fRXH_gZxZ-6_zPLCLmImUUukJOA72husJONemjNCegG8k_Xzg
- [19] K. Wakamatsu, N. Yoshida, N. Suzuki, & T. Tazoh, (1992). Liquefaction-Induced Large Ground Deformations and Their Effects on Lifelines During the 1990 Luzon, Philippines Earthquake. <https://nehprsearch.nist.gov/static/files/NSF/PB92197243.pdf>
- [20] M. Naghizadehrokni, A. J. Choobbasti, & M. Naghizadehrokni, (2018). Liquefaction maps in Babol City, Iran through probabilistic and deterministic approaches. *Geoenvironmental Disasters*, 5(1). <https://doi.org/10.1186/s40677-017-0094-9>
- [21] M. S. Power, & T. L. Holzer, (1996). Liquefaction Maps. ATC TechBrief. Retrieved from <https://www.atcouncil.org/pdfs/atc-35.pdf>.
- [22] PangPPDO. (2017). Pangasinan History and Geophysical. Retrieved from Pangasinan Provincial Planning and Development Office (PPDO) website: <https://ppdo.pangasinan.gov.ph/planners-and-researchers-kiosk/pep-2019/history-and-geophysical/>.
- [23] R. B. Carating, R. G. Galanta, & C. D. Bacatio, (2014). *The Soils of the Philippines*. Dordrecht Springer Netherlands.
- [24] R. P. Orense, (2011). Soil liquefaction during the 2010 Darfield and 1990 Luzon Earthquakes: A comparative study. www.semanticscholar.org/paper/Soil-liquefaction-during-the-2010-Darfield-and-1990-Orense/2eb9184ca96c9722db8323b252e30c6f6134b944
- [25] R. Saikia,(2013). Critical Review on the Parameters influencing Liquefaction of Soils. www.academia.edu, 3(4). https://www.academia.edu/6117521/Critical_Review_on_the_Parameters_influencing_Liquefaction_of_Soils
- [26] S. Cox, (2021, June). Earthquake Hydrology and Liquefaction. Retrieved July 19, 2023, from New Zealand Geotechnical Society website: <https://www.nzgs.org/libraries/earthquake-hydrology-and-liquefaction/>.
- [27] StructX. (2022). Densities of Different Soil Types. Retrieved July 20, 2023, from structx.com website: <https://structx.com/>.
- [28] T. I. Mote, & J. N. Dismuke, (2012). Liquefaction Hazard Maps for Australia. Retrieved from https://www.iitk.ac.in/nicee/wcee/article/WCEE2012_3982.pdf.
- [29] Y. Fukushima, & T. Tanaka, (1990). A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan. *Bulletin of the Seismological Society of America*, 80(4), pp. 757–783. <https://doi.org/10.1785/BSSA0800040757>