*17th World Conference on Earthquake Engineering, 17WCEE*
*Sendai, Japan - September 13th to 18th 2020*

# MICROZONATION OF LONG-PERIOD SITE AMPLIFICATIONS BASED ON DEEP SEDIMENTARY LAYERS IN METRO DAVAO, PHILIPPINES

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## *Abstract*

Metro Davao is a fast-growing urban region on the southeastern coast of Mindanao Island. Residential, industrial and commercial structures are continuously and proportionally built to accommodate the demand of rapid urbanization and industrialization in this region. These infrastructures are highly concentrated, purposely built along the coastal bay areas of Metro Davao, making it the third most populous metropolitan area in the Philippines after Metro Manila and Metro Cebu. However, several earthquake generators surround this coastal region, and as a consequence, these infrastructures are vulnerable to ground-to-building period resonance or long-period site amplifications, which generally leads to structural failure and collapse. Hence, the need to resolve the long-period ground motion levels in Metro Davao is vital, which generally affects medium- to high-rise structures.

Estimation of long-period site amplification requires assessment of the shear-wave velocity (Vs) structure of the deep sedimentary layers within the area. Since conventional borehole drilling is limited to shallow sedimentary layers over engineering bedrock, an alternative geophysical method was conducted using a thirteen-station microtremor array survey. This technique allows deeper exploration and investigation of Vs profiles down to several kilometers reaching deeper, harder engineering bedrock or basement. For this study, microtremor array measurements were carried out at thirty-one (31) sites across the populated areas of Metro Davao. The study area covered only the eastern coastal lowlands of Metro Davao mainland dominated with coastal alluvial plains and minor rigid volcanic uplands, due to the method's limitations in applicability. Metro Davao's Island Garden City of Samal in the offshore was also covered in the survey. High-resolution frequency-wavenumber (f-k) spectral analysis was used in the processing of microtremor array data to determine the Vs profile for each site. These profiles were used to calculate the site amplification factors and identify the predominant long-period values of the surveyed sites. The output values were finally utilized to generate a long-period seismic microzonation map of Metro Davao.

Survey results showed that long-period ground motion values ranging from 1 to 2 seconds dominate the study area or the entire eastern coastal region of Metro Davao. This range also dominate the Island Garden City of Samal. The northern part of Metro Davao's lowlands exhibited long-period values ranging from 2 to 3 seconds. These relatively high range of long-period values are possibly associated with the Agusan-Davao sedimentary basin that roughly underlies Carmen and Tagum City. The highest long-period value of 2.86 seconds is found on this setting. Moreover, the dominant long-period values of 1s to 2s are mostly displayed on the central part and southern part of Metro Davao. The only portion on the central part of Metro Davao with 2 to 3 seconds ground period are delineated on areas with possibly extensive sedimentary deposits attributed from river floodplains and deltaic areas. Occasional higher values on the southern part of Metro Davao are found on the southeastern flank of Mt. Sibulan in Sta. Cruz.

The research results can be used as reference hazard map to verify areas or building designs susceptible or prone to potential building resonance or site amplification in Metro Davao. Furthermore, it can aid disaster risk management planning and urban engineering, to adjust existing or planned building and urban designs with the observed long-period values on site, therefore increasing the seismic resiliency of medium- to high-rise structures in Metro Davao.

*Keywords: building resonance; site amplification; long-period; shear-wave velocity*

## 1. Introduction

To popular knowledge, it is the large magnitude and duration of an earthquake, distance from the epicenter, and depth of the focus that contributes or dictates the destruction and fatality an earthquake could inflict. One overlooked factor is the local site effects or site amplifications. Even low-intensity or low-magnitude earthquakes can induce high level and prolonged ground shaking due to these site-specific amplifications anchored to the local surface-subsurface geology and geomorphological feature of an area. It is principally due to the transfer of seismic waves from deep, hard bedrock to the overlying shallow or superficial, soft sediments. Amplified and prolonged earthquake ground motion can also occur from surface waves generated in the basin-edge or valley-edge of a thick, deep-seated soft sediment deposits. These processes were demonstrated during the $M_S$ 8.1 1985 Mexico City Earthquake where ancient lake sediments with high water content underlie most of the city, resulting to amplified ground shaking and building resonance, damaging and collapsing substantial number of buildings within the city (Cassaro & Romero, 1986).

Metropolitan Davao (Metro Davao) is a coastal region, situated on the southeastern portion of the island of Mindanao, southern Philippines (Fig. 1a). It encompasses the 1st class highly urbanized city – Davao City, and portions of the Davao Del Norte (Tagum City, Panabo City, municipality of Carmen, and Island Garden City of Samal in the offshore) and Davao Del Sur (Digos City and municipality of Sta. Cruz). It is considered a seismically active region due to the occurrence of earthquake generators such as active faults and trenches (e.g. Central Davao Fault System & Philippine Fault Zone) inside and outside the region, leading Metro Davao in increasing vulnerability to earthquake disaster. Therefore, it is vital to explore and investigate the subsurface shear-wave velocity (Vs) structures of the deep rock layers within Metro Davao, in order to estimate and delineate the long-period site amplification within the metropolis. This long-period ground motion primarily affects medium- to high-rise buildings in the event of an earthquake, particularly if it matches the natural resonance of these buildings, which typically leads to structural damage and collapse.

To study the local site response or amplification of Metro Davao, Vs profiles must first be obtained. Conventional method of obtaining Vs profiles is relatively time-consuming, expensive and requires sufficient distribution of boreholes (site-specific) to infer the detailed Vs profile of an area. Alternative geophysical surveying technique is presented here that can estimate the subsurface physical properties in a fast and efficient way with respect to large study area (metropolitan-scale), cost-effective and non-intrusive approach that can cover wider range of surface area and depth of penetration down to several kilometers. It is without doubt, that the study and use of an array of microtremor observations has already gained popularity in the field of structural and earthquake engineering, and has already reached the realm of practical application. In fact, conducting Vs profiling requires only a simple circular array consisting of four seismometers (e.g. Okada et. al., 1987), and if the vertical component of microtremors are observed, it is inferred that the dispersive characteristic of Rayleigh wave can be extracted (e.g. Okada, 2003; Yamanaka et. al., 1994).

The history of the practice of microtremor studies in the Philippines is short, and can only be drawn from limited studies and case histories. Some examples were from the work of Ohmachi and Nakamura (1992) after the devastation of the $M_S$ 7.8 1990 Luzon Earthquake. They conducted three-component microtremor measurements utilizing short-period microtremors, and applied the concept of horizontal-to-vertical (H/V) spectral ratio. They estimated the predominant ground period of Manila City (capital city of the Philippines) to be approximately 1 second, explaining why certain structures were damaged even with substantial distance (~120 km) from the epicenter. It was not until Yamanaka et. al. (2000) that array measurements of long-period microtremors was first applied in the country, for the exploration of the deep sedimentary layers within Metro Manila. Using frequency-wavenumber (f-k) spectral analysis, they inferred deeper sedimentary rocks, and an inferred basement at a depth of 2km with Vs of ~3km/s. Another research using microtremor array measurements was from Grutas and Yamanaka (2012), they mapped the shallow-shear-wave velocity structures of Metro Manila using spatial autocorrelation (SPAC) method, calculated the site amplifications and grouped it based on NEHRP site classes which can be used in the assessment of local site effects in the area. They also found out that the inferred Vs profiles are in good agreement or correlation with the mapped surface geology and inferred subsurface stratigraphy of the metropolis. From the above studies, we now see the imperative need of a detailed assessment of the Vs structures and site amplifications particularly on metropolitan-scale areas like Metro Davao, were rapidly-growing population, sprawling urbanization and industrialization are paving the way for the exponential rise in the development and construction of medium- to high-rise buildings. This study will present a reconnaissance exploration and investigation of the deep Vs profiles and long-period site amplifications of the deep sedimentary layers within Metro Davao by conducting long-period microtremor array measurements along the eastern coastal plains of the metropolis and the Island Garden City of Samal. Processing procedures involved extraction of the Rayleigh wave information from the microtremor measurements in the form of phase velocity dispersion curves, using high-resolution frequency-wavenumber (f-k) spectral analysis. A heuristic approach called hybrid genetic simulated annealing algorithm (HGSAA) inversion method was employed to these dispersion curves to infer the deep Vs profiles of the surveyed areas. These imaged Vs profiles were then utilized to assess the local site amplifications and estimate the predominant long-period ground motion values of the surveyed areas. Lastly, in order to further delineate identified areas susceptible to large amplification, microzonation of the estimated long-period values were done to display a more detailed spatial distribution and variation of the long-period ground response levels in Metro Davao.

## 2. Geological Setting

Metro Davao according to MGB (2010), is stratigraphically divided into two different grouping, namely the Central Mindanao Arc (SG-22) and Agusan-Davao Basin (SG-23). The rugged mountainous portions and rigid volcanic uplands dominating the central and southern Metro Davao forms part of the Central Mindanao Volcanic Arc. Generally, the core of this cordillera is comprise of north-trending uplifted complex of basement rocks and Tertiary sedimentary rocks buried by Quaternary volcanic deposits (Ranneft et. al, 1960). According to Sajona et. al. (1993), it is considered to be the most extensive field of active volcanoes in the Philippines, wherein it is subdivided into three arc segments namely the Misamis Arc, Bukidnon Arc, and the Davao Arc that includes Mt. Apo, Mt. Talomo and Mt. Sibulan. The edifices or slopes of these volcanoes are mostly underlain by tuffs, and agglomerates that have basaltic andesite and pyroxene andesite composition cemented by tuffaceous matrix (MGB, 2010). The near-surface geology of the southern and southwestern part of Metro Davao is predominantly composed of volcanic flows and pyroclastic rocks.

Northern Metro Davao and the Island Garden City of Samal generally forms part of the sedimentary stratigraphic character of Agusan-Davao Basin. This sedimentary basin is an elongated trough, trending N-S passing from Butuan City in the north, down to the northern coastal lowlands of Davao City. At the eastern flank of this basin, lies the Mindanao Pacific Cordillera (SG-24) which bounds the basin to the east, and at the western flank is the Central Mindanao Volcanic Arc that bounds it to the west. It is considered to be the basin with the thickest sedimentary fill, sometimes with thickness reaching more than 12,000 m (Ranneft et. al., 1960). Based on the accounts of MGB (2010), the sedimentary fill is composed of Upper Oligocene – Lower Miocene limestones, followed by alternating layers of conglomerates, sandstones, shales and sometimes thin Middle Miocene carbonaceous layers. The Pliocene-Quaternary cover is dominated by shallow marine deposits upgrading into fluviatile facies. Furthermore, the N-S orientation of the basin is traversed longitudinally by the Philippine Fault Zone (PFZ). Aside from relatively distant PFZ, Central Davao Fault System (CDFS) traverses mainly the Davao City proper, suggesting the metropolis' proclivity to seismic activity. Some active faults proximal to the metropolis are the Tangbulan Fault south of Digos City, Colosas Fault near Panabo City and Carmen, and an unnamed fault southwest of Digos City.

## 3. Significance and Objectives

Metro Davao is a coastal metropolitan area consisting of densely populated urban core cities surrounded by less populated territories sharing industry, infrastructure and housing. It is experiencing incremental increase in population densities over fixed land areas, and continuous development of housing projects, buildings, industrial plants and other infrastructures on already built environments. Inevitable coexistence of earthquake generators such as active faults, trenches and volcanoes make these lands highly vulnerable to potential earthquake disasters. The resonance effects of buildings to an earthquake associated with an underlying deep sedimentary fills or layers have already been observed and studied to primarily affect high-rise structures. Present level of understanding is that distant, shallow and large magnitude earthquakes have the potential to generate slow and long-period ground motion, similarly affecting medium-to-high rise buildings. Also, thick, deep-seated soft sediments found in valleys, river delta and floodplains tend to amplify long-period seismic waves. In addition, both type of surface waves, the Rayleigh and Love waves can be generated in the basin-edge of a thick deep-seated soft sediment deposits that would prolong the earthquake ground motion.

Like any other major cities around the world, Metro Davao is also hosting high-rise buildings to accommodate the consequences of urbanization and economic growth. However, surface geology corresponding to soft Quaternary alluvium (Qal) mapped along: the coastal alluvial plains and lowlands of Metro Davao surrounding Davao Gulf; localized along river floodplains and deltas within the metropolis, and possible thick, deep-seated basin fill sediments of the Agusan-Davao sedimentary basin, are possible culprits that can amplify and prolong the ground shaking effects of seismic waves during an earthquake. The influence of these long-period seismic waves on Metro Davao has not been studied, in which this research aims to estimate and delineate. The implication of this study is crucial and vital to the increasing number of medium-to high-rise buildings in Metro Davao. Due to evidences of possible future destructive earthquakes that could hit Metro Davao, vulnerability of already built structures, growing population, and the presence of thick, deep-seated soft sediments in Metro Davao: this study aims to identify the Vs profiles of the deep sedimentary layers, determine and map the corresponding long-period amplification values of Metro Davao.

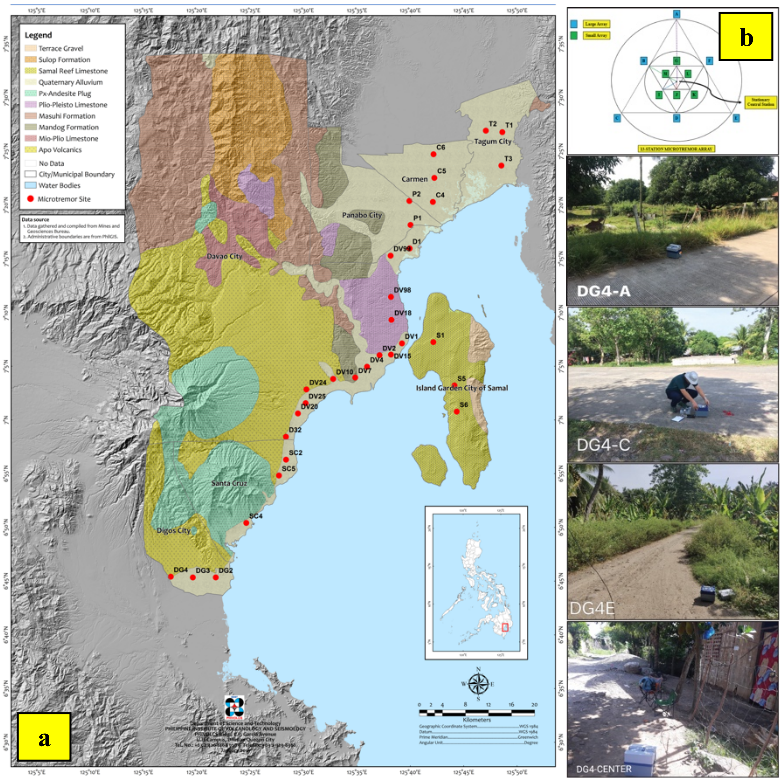

Fig. 1 – a) The geologic map of Metro Davao (compiled maps from Mines and Geosciences Bureau) plotted with the locations of the 31 microtremor array central stations. b) Geometry or configuration of a 13-station microtremor array employed in the surveys. Displayed also are the sample actual field survey procedures in microtremor array sensor stations: A, C, E and Center of DG4 large array in Digos City.

## 4. Methodology

To fulfill the objectives of the study, a conceptual framework or flowchart was created in Fig. 2. The upper part (green diagrams) represent the methods or processes used in the study, while the lower part (orange diagrams) represent the corresponding outputs of these processes. The paramount output of this study is the Long-Period Microzonation Map of Metro Davao, which delineates the spatial distribution and variation of long-period ground motion levels within the region, an important parameter in the seismic hazard assessment for medium- to high-rise buildings situated within the metropolis.

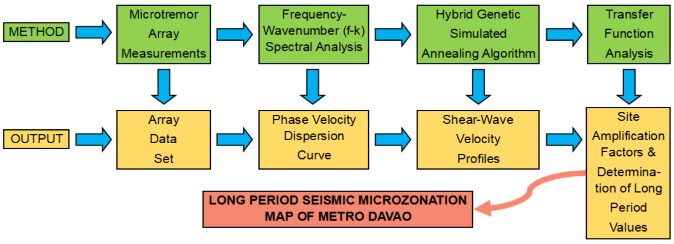

Fig. 2 – Flowchart of the study employed in the microtremor array surveys to identify the Vs profiles of the deep sedimentary layers and long-period site amplification values in Metro Davao.

### 4.1 Microtremor Array Measurements

Microtremor array measurements is a passive seismic method that positively harnesses or utilizes one of the natural fields of the Earth called ‘microtremors’, which are ubiquitous, weak, low-amplitude background vibrations or ambient noises generated from combined natural phenomena and anthropogenic sources recorded on the surface of the Earth (e.g. Okada, 2003). It is characterized from other seismic surveys by the used of an array of microtremor sensors that records ambient surface waves. In fact, a simple circular array with only four sensors are all needed to conduct Vs profile estimation (e.g. Okada et. al., 1987; Okada, 2003). This method determines the dispersive characteristics of seismic waves, and aims to estimate the shear-wave velocities of the corresponding media it passes through. As an alternative to conventional borehole drilling, this approach allows investigation in a fast, cheaper, non-invasive approach with a wider area of coverage and depth of exploration down to several kilometers. In addition, there is no alternative to microtremor surveys in areas where conventional seismic methods are prohibitively difficult or impossible to access and implement, such as environmentally-sensitive areas and built-up, densely-populated urban areas, where microtremor as a seismic noise militates or dominates, inducing low signal-to-noise ratio. Also, microtremor surveying and operation is relatively simple and safe, it does not require intensive safety precautions compared to sophisticated equipment and procedures done in conventional drilling techniques.

For this study, a thirteen-station microtremor array (Fig. 1b) was deployed on thirty-one (31) sites across the constituent cities and municipalities of Metro Davao, which are all located fringing the coastal bay areas of Davao Gulf. These land areas are generally characterized as coastal lowlands and alluvial plains with minor rugged mountainous areas and rigid volcanic uplands particularly on the southern portion of the metropolis. Located on this bay, the isolated Island Garden City of Samal offshore of the mainland was also covered in the survey. During the pre-fieldwork planning and discussions, microtremor array measurement sites were strategically plotted on densely populated and built-up urban areas, especially in Davao City, which is the largest city in the metropolis and in the country in terms of land area, and the most populous city outside Metro Manila where medium- to high-rise buildings are also in great number. The distribution of microtremor array measurement sites within Metro Davao is shown in Fig. 1a. In the field surveys, each array site has a configuration of 13 microtremor sensor stations: 1 stationary sensor at the center of the spread (central station), with other sensors arranged to form 2 equilateral triangles of different size concentric with the central station (Fig. 1b). The larger equilateral triangle (large array) has a radius range of 2500 to 1200 meters, while the smaller equilateral triangle (small array) has radius range of 600 to 300 meters. Two recording set ups were deployed at each array site, one for the large array and one for the small array. A GPS clock in each sensor station allows time synchronization of all recordings during simultaneous measurements in both large and small array. Recording period for a large array is 45 to 50 minutes, and 30 to 40 minutes for the small array. The sensors were oriented vertically to respond to Rayleigh wave propagation. Sampling interval used in the survey was 10 milliseconds with a frequency response of 0.1 to 200 Hz. Also, prior to fieldwork, each of the 13 microtremor sensor stations are plotted using Google Earth for terrain consideration. It must be accessible by land vehicles, and there must be access to available roads (paved or unpaved) for safe, easy and fast-efficient logistics and survey operations since recording is simultaneous. Weather disturbances could also affect the survey and integrity of the data gathered. Microtremor array survey is not suggested to be conducted during extreme windy and rainy conditions, not only due to wet environments that can damage the instruments, but also due to the false data gathered from the signals induced from rainfalls and not of the natural frequency of the ground.

### 4.2 High-Resolution Frequency-Wavenumber (f-k) Spectral Analysis & Phase Velocity Dispersion Curves

High-resolution F-K spectral analysis was executed through Geopsy (Wathelet, 2005), an open-source graphical user interface and core library that can handle seismic signals especially the long ones, such as in this study. Phase velocity dispersion curves from microtremor observations can be generated and modeled using this program, and be inverted to yield a layered-earth model of the subsurface. This method was conceptualized by Capon (1969), which observes the vertical component of surface wave microtremors, and calculates the frequency-wavenumber power spectral density function (f-k spectra) from an array of multiple observation stations. It assembles the data and estimates the phase velocity and direction of the most dominant surface wave in the f-k spectrum with the highest power (e.g. Okada, 2003). Using the principles of Capon (1969), which Wathelet (2005) followed to create high-resolution F-K algorithm, four parameters laid out in different parts of the high-resolution F-K toolbox of the Geopsy software were utilized for this study, which needs to be set up first before proceeding to F-K processing. The first parameter is the pre-processing phase, which involves excluding energetic, bursting high-amplitude transient signals from the continuous ambient vibration recordings, selecting and keeping only the windows with the most quasi-stationary signal amplitudes for processing. Removing these unwanted transient signals requires application of anti-triggering algorithm in the F-K toolbox. The second parameter is selecting time windows on the remaining data, and specifying the window length for each single analysis window to be processed, in terms of number of cycles for each frequency band. ‘Frequency-dependent’ was the window length parameter used in the processing, because it is the most reasonable and only implemented setting in the context of narrowband dispersion curve processing. The third parameter is the selection of narrow frequency bands for processing, specifying the minimum and maximum central frequencies to be sampled. The frequency axis or limits used for long-period processing was 0.20 to 1.00 Hz. Step parameter used on the frequency axis was set logarithmically so that the frequency axis is sampled logarithmically and frequency bands are closed spaced at lower frequencies. The fourth parameter is related to the output of results from F-K processing. Given that F-K toolbox relies on an iterative refined sampling strategy, this parameter is about optimizing the grid search approach in the wavenumber plane. The grid step needs to be as small enough as to sample the peaky structure of the array response. Also, the minimum velocity (v min) to be modified in this parameter need to be site-dependent. In this study, the typical v min values used was 500 m/s, however, knowledge about the site conditions will provide the researchers some scientific judgement as to what might be the minimum physical propagation velocity on site, based on local surface geology, subsurface stratigraphy and geomorphological feature of the surveyed area. Lastly, the power spectrum maxima in this parameter was set to ‘1’ to obtain dispersion curves at lower frequencies for long-period processing.

After testing the parameter settings employed using the frequency-wavenumber window browser, and checked the impacts of the settings implemented, array data set can now be progressed to high-resolution F-K processing to produce FK max files of each array data set. For graphical display and interpretation of the results of high-resolution F-K processing, generated files and multi-column files are loaded into the Max2curve tool of Geopsy. It is in this software where manual definition and picking of phase velocity dispersion pattern is performed. The generated dispersion curves will later undergo hybrid genetic simulated annealing algorithm (HGSAA) inversion process (Yamanaka, 2007; Takekoshi & Yamanaka, 2009) to deduce their velocity profiles. Highlighted in the figures below are the phase velocity dispersion curves of the array sites from DV99-C4-T2 section line across Panabo City, Carmen and Tagum City in Metro Davao (refer to Fig. 4a). This dispersion curves have maximum allowable deviation or misfit value of 1.00 (Fig. 3).

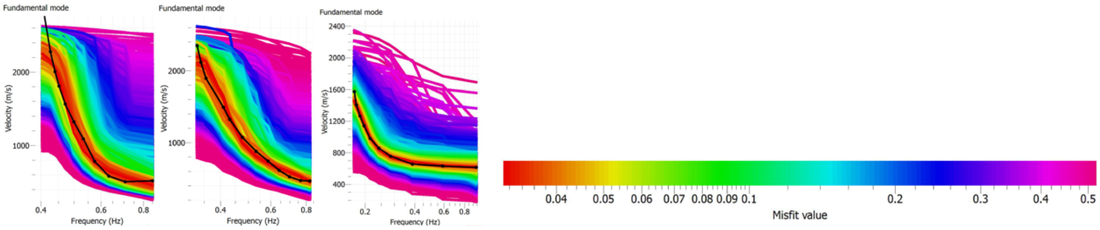

Fig. 3 – Phase velocity dispersion curves of the array sites from DV99-C4-T2 section line across Panabo City, Carmen and Tagum in Metro Davao.

### 4.3 Inversion of Phase Velocity Dispersion Curves & Deep Shear-Wave (Vs) Profiles

In order to extract the Vs profiles from the phase velocity dispersion curves, hybrid genetic simulated annealing algorithm (HGSAA) inversion method was applied. It is an integrated heuristic procedure that observes a selective number coding and provides the best selection and dynamic mutation that minimizes the misfit throughout the inversion. This technique evolved from the genetic algorithm (GA) endeavors of Yamanaka and Isihida (1996), integrated with the simulated annealing (SA), therefore called a ‘hybrid heuristics method’, due to the fact that it can search and generate velocity models with the smallest misfit function. This method extract models near the best fitting or global minimum solution at a reasonable computational cost (Grutas & Yamanaka, 2012), wherein one advantage is that they do not require derivatives of the misfit functions or specific initial models compared to the linearized least-squares method.

Inversion processes of the all the dispersion curves were run using the HGSAA inversion to produce the velocity structure of the deep sedimentary layers within the study area. Parameterization in the processing of Vs profile utilized models up to 4 layers and 3000 meter depth limit. Minimum misfit values were applied to the dispersion curves, and as result, 3- to 4-layered model of Vs profiles were generated depending on geological interpretation per survey area. Several assumptions were applied to output models such as isotropic, homogenous, horizontal layers, and density-Vs increasing with depth. Surface geology, subsurface stratigraphy, and geomorphology of the surveyed areas are also put into consideration. Geological thinking is of importance to normalize misfits and ambiguity, and ultimately infer the deduced Vs profile generated from the inversion process. If softer sediments like Quaternary alluvium were mapped on the surface and at the same time located on the interior of a valley, it is geologically presumed that inversion will produce Vs profile with upper layers exhibiting lower phase velocity (softer) that progress to deeper parts (considerably thick upper layer). Succeeding lower, deeper layers will have higher velocity.

Section line drawn from DV99, C4 and T2 located in Panabo City, Carmen and Tagum City respectively (Fig. 4a), were used to construct a cross section across the Agusan-Davao sedimentary basin in northern Metro Davao (Fig. 4c). This reconnaissance cross section model with 3x vertical exaggeration, were derived from the corresponding Vs profiles of each site (Fig. 4b). Three distinct layers of varying velocities have been identified and modelled from the surveyed sites. A relatively thin topmost layer with an averaged velocity ($V_1$) of ~400 m/s is observed to thicken from the basin-edge at DV99 towards the interior of the basin at T2. This trend of velocity structure is followed by the other underlying, lower thicker sedimentary layers (e.g. $V_2$ = ~1300 m/s), including the inferred deep, hard engineering bedrock ($V_3$ = ~2600 m/s). This gradual increase in depth is possibly attributed to the intercepted Agusan-Davao sedimentary basin.

### 4.4 Transfer Function Analysis, Site Amplification Factors and Predominant Long-Period Values

The shear-wave velocity (Vs) profiles generated from the inversion process were applied with transfer function analysis (Haskell, 1953) to calculate the site amplification factors, and ultimately determine the predominant long-period motion of the ground for each surveyed site (Table 1). Generally, transfer function analysis calculates the ratio of the amplitude of harmonic motion between two media being observed, given that these two layers varies directly with frequency. It is related to impedance contrast experienced by waves incident to the interface between two layers of differing velocity and density. The ratio is related to the large velocity contrast between sedimentary layers and hard bedrock or basement rock. The highest peaks represent the fundamental or first mode of vibration reflecting the largest site amplification possible. The other higher peaks represent other higher modes of vibration of the surveyed sites.

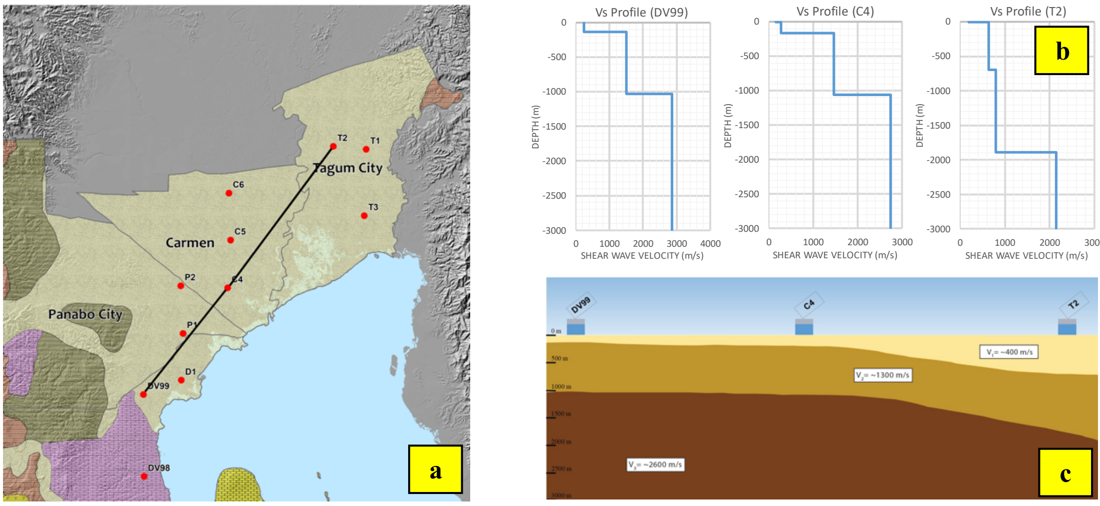

Fig. 4 – a) Geologic map zoomed in to Panabo City, Carmen and Tagum City, Metro Davao, showing DV99-C4-T2 section line. b) Shear-wave velocity (Vs) profiles of DV99, C4 and T2. c) Reconnaissance cross section model derived from Vs profiles in b, 3x vertical exaggeration.

Table 1 – List of microtremor array measurement sites in Metro Davao, with the coordinates of the central station, estimated array radius, and predominant long-period values estimated.

| Array Site | Location | Latitude (N) | Longitude (E) | Maximum Array Radius (km) | Minimum Array Radius (km) | Period (s) |
|---|---|---|---|---|---|---|
| T1 | Apokon Rd., Brgy. Magugpo, Tagum City | 7.446951 | 125.810329 | 2.00 | 0.50 | 2.86 |
| T2 | Purok 3, Brgy. San Miguel, Tagum City | 7.448605 | 125.78456 | 2.00 | 0.50 | 2.00 |
| T3 | Brgy. Madaum, Tagum City | 7.374472 | 125.808795 | 1.70 | 0.34 | 2.22 |
| C4 | Kabangkalan, Carmen | 7.33809 | 125.701868 | 2.00 | 0.50 | 0.76 |
| C5 | Purok 4, Brgy. Ising, Carmen | 7.375421 | 125.704126 | 2.00 | 0.50 | 2.86 |
| C6 | Brgy. Tuganay, Carmen | 7.412089 | 125.702859 | 2.00 | 0.43 | 1.18 |
| P1 | Calubian, New Visayas, Panabo City | 7.302416 | 125.666936 | 2.00 | 0.36 | 1.82 |
| P2 | Purok 6, Southern Davao, Panabo City | 7.339683 | 125.665166 | 2.20 | 0.25 | 2 |
| D1 | A.L. Navarro Nat’l H. School, Davao City | 7.265932 | 125.665538 | 1.10 | 0.30 | 2.22 |
| DV99 | Brgy. San Isidro, Bunawan, Davao City | 7.254724 | 125.635914 | 2.20 | 0.44 | 2.22 |
| DV98 | Purok 5, Brgy. Tibungco, Davao City | 7.190741 | 125.63645 | 2.10 | 0.51 | 1.82 |
| DV18 | Malagamot, Panacan, Davao City | 7.15517 | 125.637162 | 1.90 | 0.50 | 2.5 |
| DV1 | Brgy. Sasa, Donya Pass, Davao City | 7.118742 | 125.653548 | 1.00 | 0.18 | 1.43 |
| DV2 | Dumanlas Rd., Bajada, Davao City | 7.100377 | 125.618544 | 2.00 | 0.43 | 1.05 |
| DV15 | Duplex, Lanang, Davao City | 7.10134 | 125.636433 | 1.50 | 0.32 | 2.50 |
| DV4 | San Rafael, Davao City | 7.082413 | 125.599054 | 2.00 | 0.43 | 1.43 |
| DV7 | Shrine Hills, Davao City | 7.065735 | 125.580654 | 2.00 | 0.50 | 2.50 |
| DV10 | Bangkal Shortcut Road, Davao City | 7.063663 | 125.546254 | 2.00 | 0.40 | 2.50 |
| DV24 | Brgy Baliok, Davao City | 7.047278 | 125.504398 | 2.10 | 0.48 | 1.67 |
| DV25 | Brgy. Lubogan, Toril, Davao City | 7.025917 | 125.503283 | 1.50 | 0.36 | 1.67 |
| DV20 | Babisa Lizada, Toril, Davao City | 7.009993 | 125.491202 | 1.50 | 0.38 | 2.5 |
| D32 | Brgy. Binugaw, Sta. Marina, Davao City | 6.973803 | 125.472477 | 1.30 | 0.18 | 1.54 |
| SC2 | Franklin Baker Area, Sta. Cruz | 6.938349 | 125.472647 | 2.00 | 0.30 | 1.43 |

| | | | | | | |
|---|---|---|---|---|---|---|
| SC4 | Amlo Village, Zone 3, Sta. Cruz | 6.840199 | 125.410527 | 1.00 | 0.27 | 2.22 |
| SC5 | Brgy. Astorga, Sta. Cruz | 6.913733 | 125.461563 | 1.00 | 0.20 | 1.82 |
| DG2 | Brgy. Zone 1, Digos City | 6.755753 | 125.362901 | 2.00 | 0.53 | 1.18 |
| DG3 | Brgy. Tres de Mayo, Digos City | 6.755681 | 125.327123 | 2.20 | 0.36 | 2.5 |
| DG4 | Latasa-Daugdug Village, Digos City | 6.756825 | 125.2927 | 2.00 | 0.14 | 1.33 |
| S1 | Brgy. San Agustin, Purok 7, Samal City | 7.120609 | 125.702609 | 2.20 | 0.42 | 2.00 |
| S5 | Brgy. San Agustin, Del Monte, Samal City | 7.053411 | 125.735562 | 1.70 | 0.17 | 1.82 |
| S6 | Brgy. Anonang, Purok 4, Samal City | 7.01284 | 125.739057 | 2.10 | 0.33 | 1.67 |

### 4.5 Generation of Long-Period Seismic Microzonation Map

The calculated long-period site amplification values, as point values on the map of Metro Davao, were interpolated using inverse distance weighting (IDW) function of the geostatistical analyst tool of ArcMap software. This method uses the measured values surrounding the prediction location to predict a value for any unsampled location, based on the assumption that things that are close to one another are more alike than those that are farther apart. The interpolation process was guided by the scientific inputs and discretions from the geologists and engineers of the team to produce a more accurate and best fitting output. Ultimately, a color-shaded long-period seismic microzonation map of Metro Davao were generated in Fig. 5.

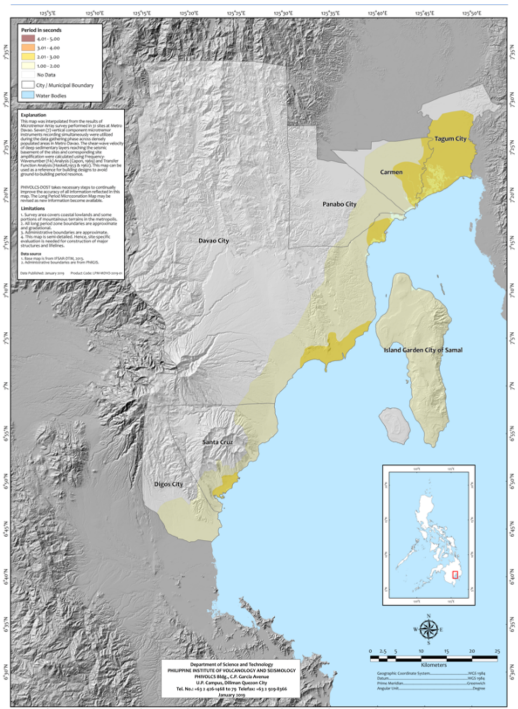

Fig. 5 – The Long-Period Seismic Microzonation Map of Metro Davao.

## 5. Discussion of Results

### 5.1 Deep Sedimentary Layers in Metro Davao

All of the 31 microtremor array measurement sites displayed graphs with shear-wave velocity (Vs) proportional with depth. Most of the velocity structures are interpreted based on local surface and shallow subsurface geology and geomorphological feature of the surveyed site, which significantly affects local seismic motion called local site effects or site amplifications. The differing layers deduced from the microtremor exploration and investigation of the deep Vs profiles in Metro Davao are discussed below.

The softer, upper first layers of the Vs profiles in Metro Davao are mostly inferred as the Quaternary alluvium (Qal) deposits, with phase velocities ranging from 151 to 430 m/s. Exceptions are the first layers in Island Garden City of Samal with phase velocities ranging from 163 to 267 m/s, inferred as the residual or in-situ, weathered and loose, less consolidated upper portions of the Samal Reef Limestone forming shallow, superficial soft sediment cover on the island. The underlying second layer in this island with phase velocity of around 740 m/s is inferred as the unweathered or unaltered consolidated lower Samal Reef Limestone. This limestone formational unit is geologically mapped to mostly underlie the whole island. It is interpreted that this shallow, soft first layer varies in thickness throughout Metro Davao. The thickest of this soft Qal deposits were found in Tagum City, where also the estimated largest long-period site amplification values ranging from 2 to 2.86 seconds dominate the area. This is possibly due to the large impedance contrasts between the subsurface sedimentary layers, owing to its sedimentary basinal setting. Subsurface sedimentary layers including the hard engineering bedrock in Tagum City are observed to increase in thickness or depth from basin-edge (T1 and T3) towards inner basin (T2).

The second layers of Metro Davao exhibit wide range of phase velocities depending on the local surface geology and shallow subsurface stratigraphy. In general, these second layers with phase velocities ranging from 601 to 2313 m/s, are inferred as the moderately hard, consolidated sedimentary rocks and volcanic rocks, underlying the softer, upper Qal overburden. Some second layers are inferred as mapped formational units based on the locations of microtremor array measurement sites on the geologic map. D1, DV99, DV98, DV18, DV1, DV15 and DV2, located from northern coast to central coast of Davao City respectively, have second layers inferred as the Pliocene-Pleistocene Limestone, due to their locations on the geologic map, either on top of this identified limestone unit or proximal to an inferred lithologic contact with this limestone. This limestone is relatively hard with inferred phase velocities ranging from 910 to 1703 m/s. DV7 and DV10, even though plotted and deployed on identified Qal deposits, are proximal or located close to an inferred lithologic contact with Mandog Formation, thus having second layers equivalent to this lithology. Mandog Formation is identified to consist of poorly consolidated sedimentary rocks, having relatively lower phase velocity range of 742 to 907 m/s. DV24, DV25, DV20 and D32 located on southern Davao City, have inferred second layer equivalent to Apo Volcanics, due to their locations on the geologic map, either on top of this identified volcanic rocks or near the inferred lithologic contact of this rock unit. The slightly hard Apo volcanics have phase velocities ranging from 734 to 915 m/s, and are mapped on volcanic upland setting resulting to survey sites located on it exhibiting a relatively thin topmost Qal layer.

Phase velocities ranging from 1957 to 3029 m/s, generally corresponds as the third layer equivalent to the inferred deep-seated, hard engineering bedrock or basement rock, intercepted in all of the array sites in Metro Davao. Most of this hard bedrock are intercepted and estimated to be deeper than 1000m from survey elevation, wherein the deepest is inferred at around 2200m depth at array site DV24.

Davao City is characterized with varied predominant long-period ground motion of 1.05 to 2.5 seconds. The largest site amplification estimated with more than 2 seconds are localized or delineated on areas with possible extensive Qal and other soft sediment depositions, such as in DV15 located near a coastal setting or beach environment, and in D1 & DV99 and DV7 & DV10 that are localized near river floodplains and deltaic systems of Lasang River and Davao River respectively, where thick accumulation of sediments is typical. The coastal sediments southeast of Mt. Sibulan in Sta. Cruz (SC4) exhibit a thin topmost layer probably corresponds to a residual or in-situ, weathered and loose upper portions of the Mt. Sibulan volcanic flows (indicated as px-andesite plug lithology on the geologic map). The underlying second layer is the thick unweathered or unaltered variety of the said volcanic flows with an estimated phase velocity of 601 m/s and reaching depths more than 500m. The occurrence of this thick low-velocity volcanic flows overlying a deep, hard bedrock results to a large long-period amplification of 2.22 seconds estimated in this area.

### 5.2 Long-Period Seismic Microzonation Map of Metro Davao

The map of Metro Davao shown in Fig. 5 illustrates the interpolated predominant long-period site amplification values generated from the deep Vs profiles of each surveyed sites. On the map, color intensity or warmth increases with respect to an increase in the long-period ground motion value. The warmest color or highest intensity indicated by those areas shaded in yellow, display ground period values of 2.0 to 3.0 seconds, which is the highest range of long-period values estimated in Metro Davao. Pale yellow areas signify the lowest long-period ground motion values of 1.0 to 2.0 seconds, which is the dominant range throughout Metro Davao. Zones that are shaded in white indicate currently unexplored areas by the method. Most of these areas were not surveyed because of the method's limitation not suggested for mountainous, rugged terrain where underlying geology and elevation greatly vary per array sensor station.

This emerging seismic innovation can be used as a reference hazard map to verify areas or buildings designs susceptible to ground-to-building period resonance, which generally leads to structural failure and collapse. This process occurs when the natural period or resonance of the structure matches the predominant period of the ground, causing amplified and prolonged ground shaking. This study roughly demonstrate the effects of surface geology, subsurface stratigraphy and geomorphology on seismic motion. Moreover, this study can help disaster risk management planning and urban engineering, to suggest structures that would need further retrofitting, or adjust existing or planned building and urban designs with the observed long-period ground motion values on site, which is timely for a galloping economic metropolitan area in Mindanao where development of real estate projects, construction of industrial plants and other multistorey structures are imminent in the near future. This viable tool, if left overlooked, unresolved or unregulated by the local government in the least, may perhaps risk cities to resonance disasters, unknown to many. This map aims to identify areas suitable and fit for development of medium- to high-rise structures in Metro Davao based on local ground conditions. Furthermore, this research can be a supplementary data to comprehensive land use programs (CLUPs) of local government, and NSCP for nationwide city planning on controlling building height for a specified area based on the generated municipal- or city-scale microzonation maps.

## 6. Summary and Conclusions

In this study, we have estimated the deep Vs profiles at 31 microtremor array measurement sites to assess local site responses, along the eastern coastal alluvial plains and rigid uplands of Metro Davao mainland, including the offshore Island Garden City of Samal. The inferred Vs profiles and long-period site amplification factors are in good correlation with the surface geology, shallow subsurface stratigraphy and geomorphology of Metro Davao, as the thick, deep-seated, soft Quaternary alluvium deposits are identified in: the southern termination of Agusan-Davao sedimentary basin in Carmen and Tagum City; coastal alluvial plains of Davao City and Sta. Cruz, and those localized along the river floodplains and deltaic areas in northern and central coast of Davao City. Rugged, mountainous areas and volcanic rigid uplands in southern Davao City, Digos City and Sta. Cruz exhibit relatively higher phase velocities at low periods.

Long-period ground motion values ranging from 1s to 2s dominate the study area or the eastern coastal region Metro Davao. It is mostly displayed on the central and southern part of Metro Davao. This long-period values also dominate the Island Garden City of Samal. The northern part of the Metro Davao's lowlands exhibited long-period values ranging from 2 to 3 seconds. These relatively high range of long-period values are possibly attributed with the Agusan-Davao sedimentary basin that roughly underlies Carmen and Tagum City. The highest long-period value of 2.86 seconds is found on this setting. Localized high long-period values of 2 to 3 seconds were also delineated on areas with possible extensive Quaternary alluvium depositions from coastal setting and river processes such as along river floodplains and deltaic systems of Lasang River and Davao River on the northern coast and central coast of Davao City, respectively. Occasional higher values on the southern part of Metro Davao were observed on probably scree deposits on the southeastern foot of Mt. Sibulan in Sta. Cruz.

## 7. Acknowledgement

This research project is supported and funded by the Department of Science and Technology (DOST), through the leadership of Engr. Fortunato Dela Peña, and the Philippine Council for Industry, Energy and Emerging Technology Research and Development (PCIEERD). We thank Dr. Renato U. Solidum, Jr. (Undersecretary -

DOST, and OIC - PHIVOLCS), Dr. Bartolome Bautista (Deputy Director - PHIVOLCS), Mr. Ishmael C. Narag (OIC - SOEPD), Mr. Robinson Jorgio (Lapu-Lapu Seismic station), Mr. Carluz Bautista (PCIEERD) and CA Camanaga (PCIEERD) for their guidance, professional inputs, and leadership towards the accomplishment of this study. We extend our appreciation to the local government units of Metro Davao for giving us the opportunity to conduct the surveys in their area. The authors would like to give special thanks to Davao City – LGU for their significant contribution to Metro Davao Specific Earthquake Project Workshop. Lastly, we also want to thank and acknowledge the research team composed of Hans Jake F. Felosopo, Mary Wenzel A. Andaya, Maeben Mariah V. Angay, Angelica G. Olaes, Andre Dastine A. Gomez, Jenth P. Dales, Miguel Antonio T. Magandi, Abellardo C. Pabayo, Jr., and Paul Albert Frederick P. Castillo (including former members: Ivan Jay D. Jumahali, Omar B. Soberano, Clement Christian A. Fajardo, Socrates M. Simbe II, and Aufelyn T. Reolalas).

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