2-D and 3-D Subsurface Liquefaction

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2-D and 3-D Subsurface Liquefaction Potential Profiling Using Tomography Surface Waves Method

Sri Atmaja P. Rosyidi

Abstract A 6.3 Mw earthquake struck Yogyakarta region in 2006 causing many geotechnical damages, e.g., ground cracks, surface displacement, landslides and local liquefactions and soil billings occurred in some regions. From field observations, it was shown that most minor to major structural damages in buildings and bridges were identified near to liquefaction locations. Consequently, a site investigation and advanced analysis for providing the subsurface liquefaction potential information plays important rule in infrastructure design related to structural damage analysis. The aim of this paper is to use of the tomography surface waves method in order to investigate the liquefaction potential in 2-D and 3-D subsurface profile. These seismic surveys were conducted on deep loose sand and sandy soil deposit located inside Universitas Muhammadiyah Yogyakarta (UMY)'s campus, Indonesia which consists of. The liquefaction potential profile was analyzed and generated from combination of the shear wave velocity and soil properties information. Two earthquake scenarios, 6.3 and 8 Mw, were used to simulate the sensitivity of 2-D profile for identifying the liquefaction potential in each soil layer. The results show that the liquefaction potential widely occurs in observed sandy soil and sand deposit layer for stronger earthquake. Finally, the tomography surface waves method is becoming an effective tool for observing liquefaction potential profile in the site investigation, particularly for the purpose of geohazards analysis in the concept of sustainable environmental development.

Keywords Surface waves method · Liquefaction potential · Earthquake · Tomography

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1 Introduction

Nowadays, a comprehensively system of soil dynamic analysis is becoming significant in order to provide suitable information for earthquake hazards. This analysis system can be used to evaluate the strong-ground motion parameters, microzonation map, liquefaction potential and ground settlements at observed site influenced by earthquakes. Moreover, the results from comprehensive soil dynamic analysis are employed in earthquake resistant design, seismic safety assessment and estimation of possible economical losses as well. Therefore, comprehensible surveys and site investigations relating to subsurface soil dynamic properties, i.e., shear wave velocity and soil modulus of sites play important rule in earthquake hazards analysis. Many studies conducted by Imai and Tonouchi [1] and Craig [2] which observed compressional (P)- and S-wave velocities in an embankment, and also in alluvial, diluvial, and tertiary layers, shows that shear (S)-wave velocity is one of the key parameters in seismic hazards analysis and S-wave velocities have a strong correlation to an index value of formation hardness used in soil mechanics and foundation engineering.

The aim of this study is to describe the use of surface wave technique for generating shear wave velocities profile and based on S-wave velocity, 2-D and 3-D mesh profile of soil liquefaction potential mapping can be developed. A case study was conducted at several observed locations in Universitas Muhammadiyah Yogyakarta (UMY) campus, Indonesia, where several buildings in study area suffered minor to moderate damage level caused by liquefaction. A 2-D shear wave velocity profile was produced based on the multichannel of surface wave survey. Thus, a liquefaction potential map was calculated by using cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) analysis based on the shear wave velocity profile.

2 Study Area

2.1 Geological of Yogyakarta

Yogyakarta region and the vicinity are located as part of the Mount Merapi area and Yogya-Bantul plain that extends toward the south coast [3]. The geologic formation in this region is dominated by recent deposits of Merapi Volcano namely young volcanic deposits of Merapi Volcano and sedimentary and inter-bedded volcanic rock deposit namely Sentolo Formation. The young volcanic deposit can be divided into two formations. The lower part of the young volcanic deposits is Sleman formation and consists of sand and gravel inter-bedded by andesite boulders. Whereas, the upper part of the volcanic deposits, i.e., Yogyakarta formation, consists of sand, gravel, silt and clay inter-bedded. The thickness of these formations is identified from several bore log data obtained at different location. The

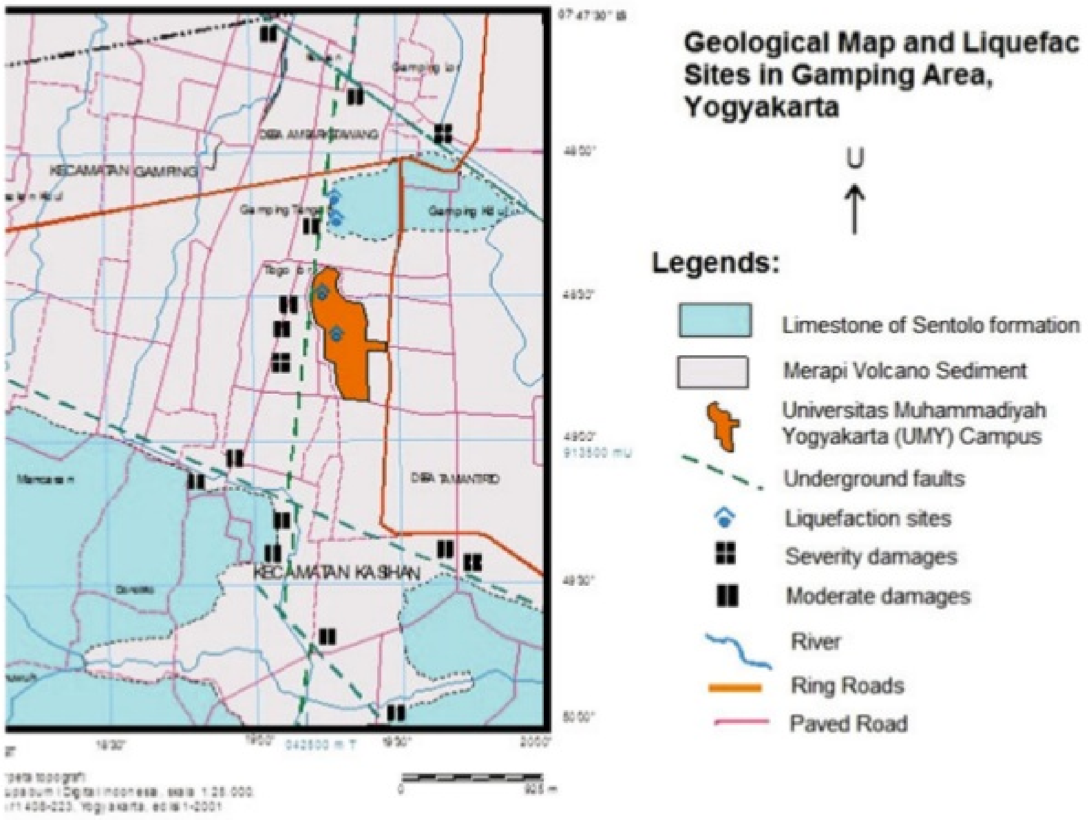

Fig. 1 Geology structure and fault lines locations close to study area Rosyidi et al. [4]

Sentolo Formation is found at depth of approximately 58 m. This formation consists of limestone and marly sandstone. The stratigraphy of Yogyakarta region can be seen in Fig. 1.

2.2 *Location of Study*

The location of study was chosen within the Universitas Muhammadiyah Yogyakarta (UMY) campus. Rosyidi et al. [4] conducted visual observations on structural and geotechnical damages in the UMY campus after the Yogyakarta earthquake, 27 May 2006. Based on the geological condition, i.e., rock formation (Fig. 1) and compilation of visual observation of the structural and geotechnical damages, a geological map and estimated underground faults for location of the study at UMY campus and surrounding area were reported by Rosyidi et al. [5]. From Rosyidi et al. [4], some predicted underground cracks and faults close to the damaged area were drawn with the direction of north to south (NS) located in the western part of the UMY campus. Consequently, a soil investigation by drilling test was carried out in this area by LKPT UMY [6], and underground faults analysis of selected site was conducted by Rosyidi et al. [5].

3 Research Method

3.1 Field Measurement of Surface Wave Technique

The multichannel analysis of surface wave (MASW) method as surface wave technique developed by Park [7] for generating the shear wave velocity data was used in this study. All the procedures in the data collection and data processing of MASW method are adopted from [8]. In this study, MASW surveys were conducted at three different locations representing as three different parts of UMY campus, i.e., northern, middle and southern part of campus area. At each location, three different measurement points of the survey were carried out. Twenty four receivers of 4.5 Hz vertical geophone were employed along a linear survey line with receivers connected to a multichannel seismograph. Seismograph used in this measurement was OYO Mac Seis 24ch. One multichannel record consists of a multiple number of time series or seismic traces from all the receivers in an ordered manner. A heavy sledgehammer weighing 16 lb (7.3 kg) was selected as a mechanical source.

3.2 Data Processing of MASW

Data processing consists of three steps, i.e., (1) preliminary detection of surface waves, (2) constructing the dispersion image panel and extracting the signal dispersion curve, and (3) back-calculating shear wave velocity (Vs) variation with depth. The preliminary detection of surface waves examines recorded seismic waves in the most probable range of frequencies and phase velocities. Consequently, construction of the image panel is accomplished through a 2-D (time and space) wavefield transformation method.

The experimental dispersion curve is then associated with surface wave energy in the frequency–wavenumber (f–k) domain from a 2-D Fourier transform. This curve shows the relationship between phase velocity and frequency for seismic waves including fundamental and higher modes propagated horizontally and directly from the impact point to the receiver line Park and Miller [9]. Consequently, the extracted fundamental-mode Rayleigh waves from an experimental dispersion curve is used as a reference to produce the 1-D Vs with depth in the inversion process. In the inversion process, a profile of a homogeneous layer extending to infinity in the horizontal direction is assumed. Based on the initial profile, a theoretical dispersion curve is then calculated using Knopoff method [10]. The theoretical dispersion curve is ultimately matched to the experimental dispersion curve of the lowest RMS error based on an optimization technique.

3.3 2-D Shear Wave Velocity (V_s) Mapping

A 2-D Vs map is constructed from the acquisition of multiple records of 1-D Vs profile with a fixed source–receiver configuration and a fixed increment of the configuration. A small increment is required when horizontal variation plot is expected. In most soil-site applications, total receiver spread length is set up in the range 10–30 m that will give an optimal fixed increment in the range of 5–15 m. A 2-D Vs map is then obtained from multiple 1-D Vs profiles with a particular fixed increment of the configuration by using tomography interpolation. In this study, all the seismic records are processed using SurfSeis version 2.01 that was developed by Kansas Geology Survey (KGS), USA.

3.4 2-D and 3-D Liquefaction Potential Analysis Based on V_S

Evaluation of liquefaction resistance involves two important calculation, i.e., cyclic stress ratio (CSR) and cyclic resistance ratio (CRR). A simplified CSR calculation was proposed by Seed and Idriss [11] based on the peak ground acceleration. CRR value can be calculated from the shear wave velocity using the method developed by Andrus and Stokoe [12]. Gridding algorithms, such as kriging, minimum curvature, etc., may be used to generate a 2-D liquefaction potential of a vertical section. With density information, a stiffness section can be generated simultaneously. 2-D data processing techniques, such as regression analysis, could be easily applied to a vertical section of liquefaction potential to enhance local anomalies of liquefaction. The calculation procedure is shown in Fig. 2. The summarized equations are described as follows.

1. *Cyclic Stress Ratio*

$$CSR = \frac{\tau_{av}}{\sigma'_v} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma'_v}{\sigma_v}\right)r_d \qquad (1)$$

where τ_{av} is the average cyclic shear stress, a_{max} is peak ground acceleration, σ_v and σ'_v are the total and effective vertical overburden stresses, respectively, g (9.81 m/s^2) is the gravity acceleration and r_d is a stress-reduction factor.

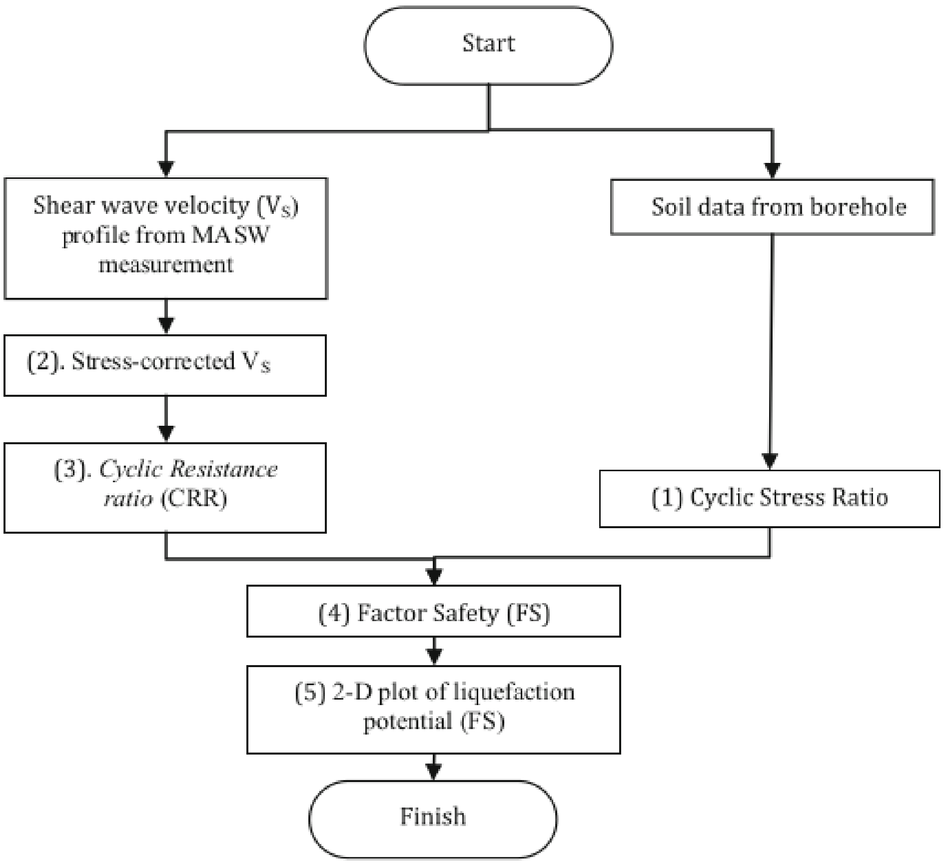

Fig. 2 Flowchart of liquefaction potential analysis

2. *Stress-Corrected Shear Wave Velocity*

$$V_{s_k} = Vs\left(\frac{P_a}{\sigma'_v}\right)^{0.25} \tag{2}$$

where Vs_k is corrected shear wave velocity, and P_a is referenced stress (100 kPa).

3. *Cyclic Resistance Ratio, CRR*

$$CRR = \left\{a\left(\frac{V_S}{100}\right)^2 + b\left(\frac{1}{V^*_{S_k} - V_{S_k}} - \frac{1}{V^*_{S_k}}\right)\right\}MSF, \tag{3}$$

where V^*_{Sk} is upper limit of corrected shear wave velocity for liquefaction events, *a*, *b* are curve fitting parameters and $MSF = \left(\frac{M_w}{7.5}\right)^n$ is the magnitude scaling factor, with $n = -2.56$ and M_w = earthquake magnitude.

4. *Factor of safety, FS*

$$FS = \frac{CRR}{CSR}. \tag{4}$$

4 Results and Discussion

4.1 Shear Wave Velocity Profile

For shear wave velocity analysis, series of seismic data for nine measurement locations of MASW survey were transformed from time to frequency domain. By f–k analysis, the phase velocities of surface waves for each frequency and their amplitudes were calculated and then were plotted in the experimental dispersion curve. In Fig. 3 an example of dispersion curve results from MASW surveys at observed location is shown. From these curves, the seismic wave events, i.e., fundamental mode, higher modes and interferenced body wave are clearly visualized. However, construction of shear wave velocity profile from these dispersion curves only considers the fundamental mode of surface wave.

1-D shear wave velocities (Vs) profile is then obtained by the inversion process. Therefore, the inversion of the dispersion of subsequent movement of the source to

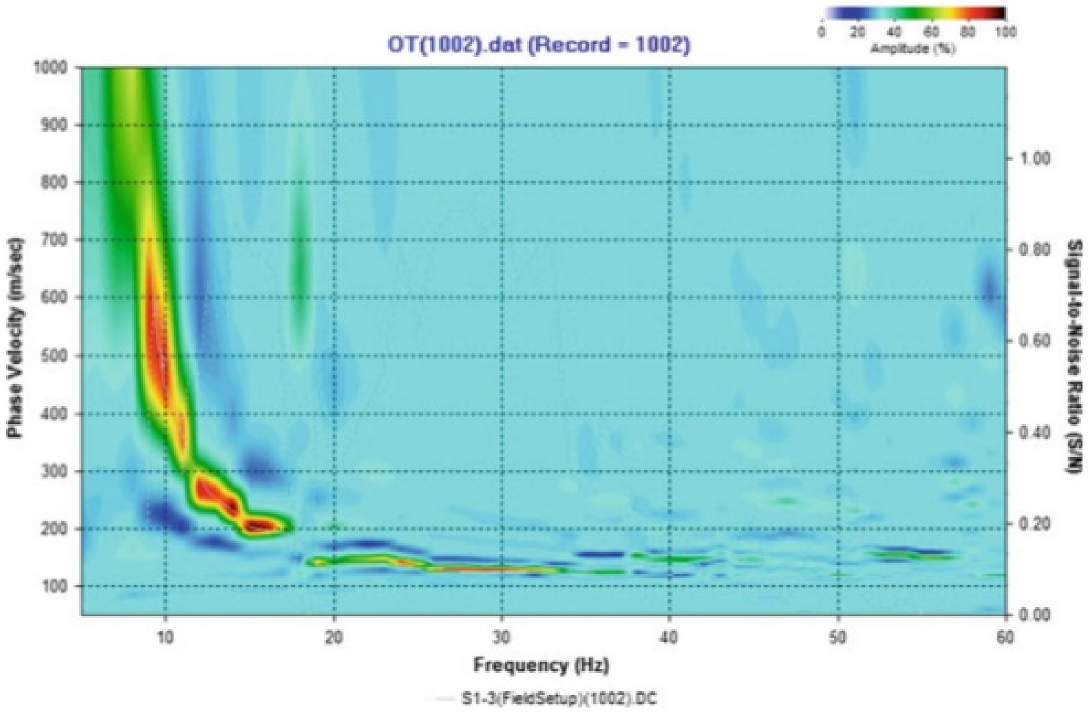

Fig. 3 Example of dispersion curve generated for the southern part of UMY campus

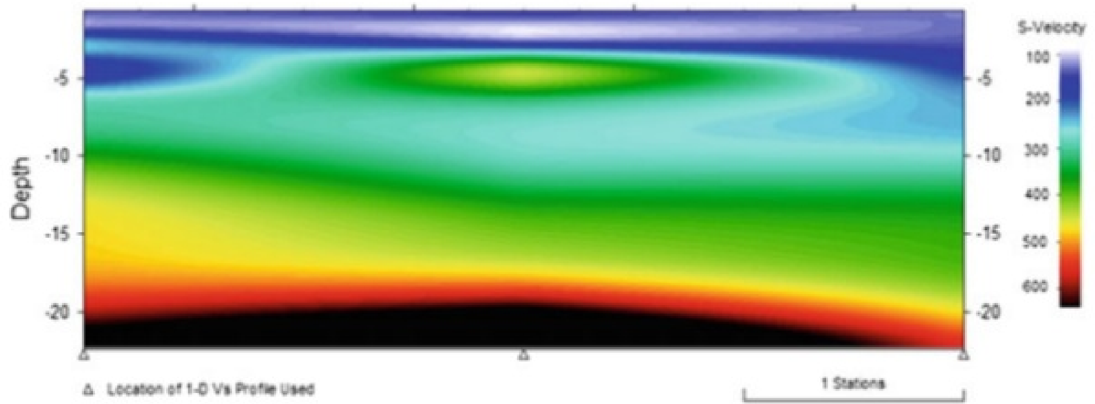

Fig. 4 A plot of 2-D shear wave velocity profile for southern part of UMY campus

geophone array then produces the final 2-D shear wave velocity profile of Fig. 4. The 2-D Vs profile was calculated by tomography correlation on minimum three different V_S profiles with the fixed increment of 5 m.

4.2 Liquefaction Potential Analysis Based on Shear Wave Velocity Values

Based on the shear wave velocity data, evaluation of liquefaction potential was carried out using the procedure mentioned in Eq. 1–4. Soil data of sites, i.e., density, particle distribution, water table and fines content were collected from laboratory tests on the borehole samples. In addition, the ground water level was observed at depth of 1.0–1.5 m from the borehole data. Based on the previous investigation carried out by Muntohar [13], the critical accelerations ranging from 0.34 to 0.69 g will generate liquefactions at all depths of loose sand layers in hazard areas. Consequently, the value of 0.47 g was obtained as peak ground acceleration in this study. An earthquake magnitude of 6.3 and 8 M_W was also selected as scenarios of past (26 May 2006) and future earthquakes for assessing the liquefactions at observed sites, respectively.

The results of liquefaction potential analysis are presented in Fig. 5. The shear wave velocity data was corrected by the stress-based liquefaction assessment procedure from Andrus and Stokoe [12] as mentioned in Eq. 2.2. Therefore, values of CRR at each observed depth were calculated by corrected shear wave velocity and magnitude scaling factor as described in Eq. 2.3.

Finally, the factor of safety (FS) can be obtained by ratio of CRR and CSR as shown in Fig. 5d. Liquefaction may occur when FS value is less than 1. By using 2-D shear wave velocity data, the 2-D and 3-D mesh plot of FS can be generated as presented in Figs. 6, 7 and 8, respectively. This figure can provide understandable information of critical parts in 2-D and 3-D subsurface profile that may have liquefaction potential during 6.3 and 8 Mw earthquakes at observed locations.

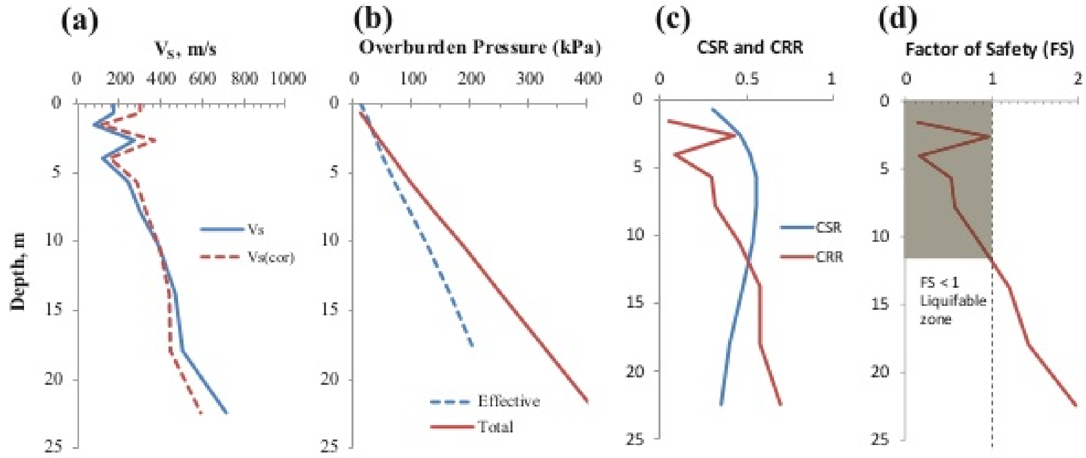

Fig. 5 Liquefaction potential analysis based on the shear wave velocity profile for first scenario of 7.5 M_W Yogyakarta's earthquake at southern part of UMY campus: **a** overburden stress-corrected shear wave velocity **b** total and effective overburden stresses **c** cyclic stress ratio (CSR) and cycle resistance ratio (CRR) and **d** factor of safety for predicted liquefaction

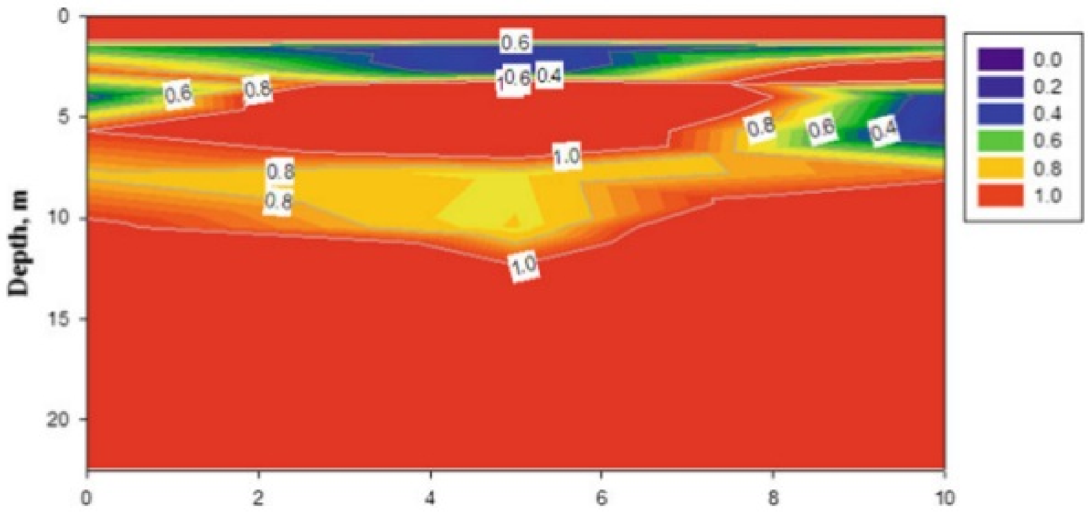

Fig. 6 A plot of 2-D liquefaction potential for first scenario of 6.3 Mw Yogyakarta's earthquake at southern part of UMY campus

A 2-D display of liquefaction potential can easily and quickly be done by contouring the FS data. It provides an efficient way to map FS liquefaction in a vertical section. The 2-D display reduces non-uniqueness of liquefaction potential and the potential for misinterpretation based on 1-D liquefaction potential versus depth plot. 2-D and 3-D data processing techniques, such as regression analysis, could be easily applied to a vertical section of FS to enhance local anomalies of subsurface profile.

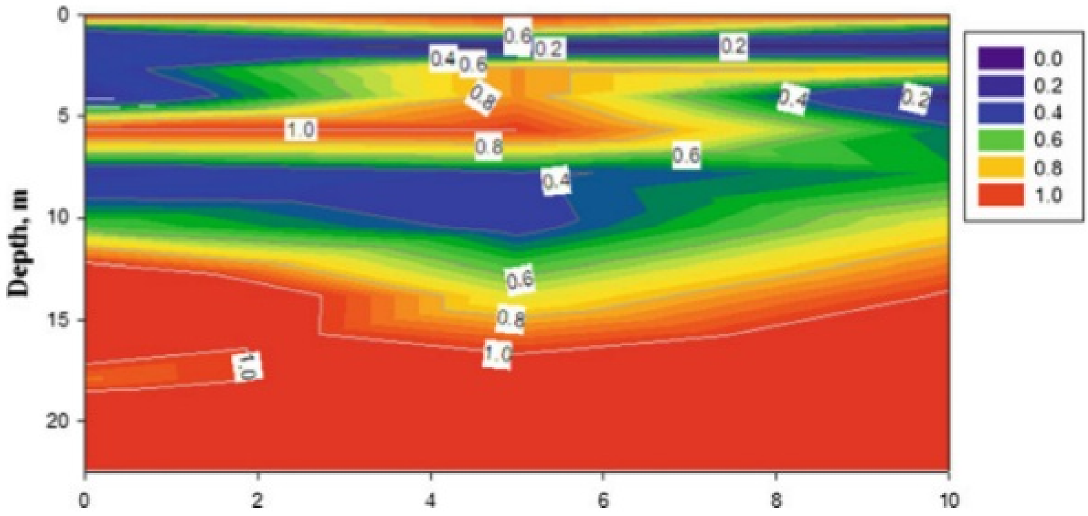

Fig. 7 A plot of 2-D liquefaction potential for first scenario of 8 M_W Yogyakarta's earthquake at southern part of UMY campus

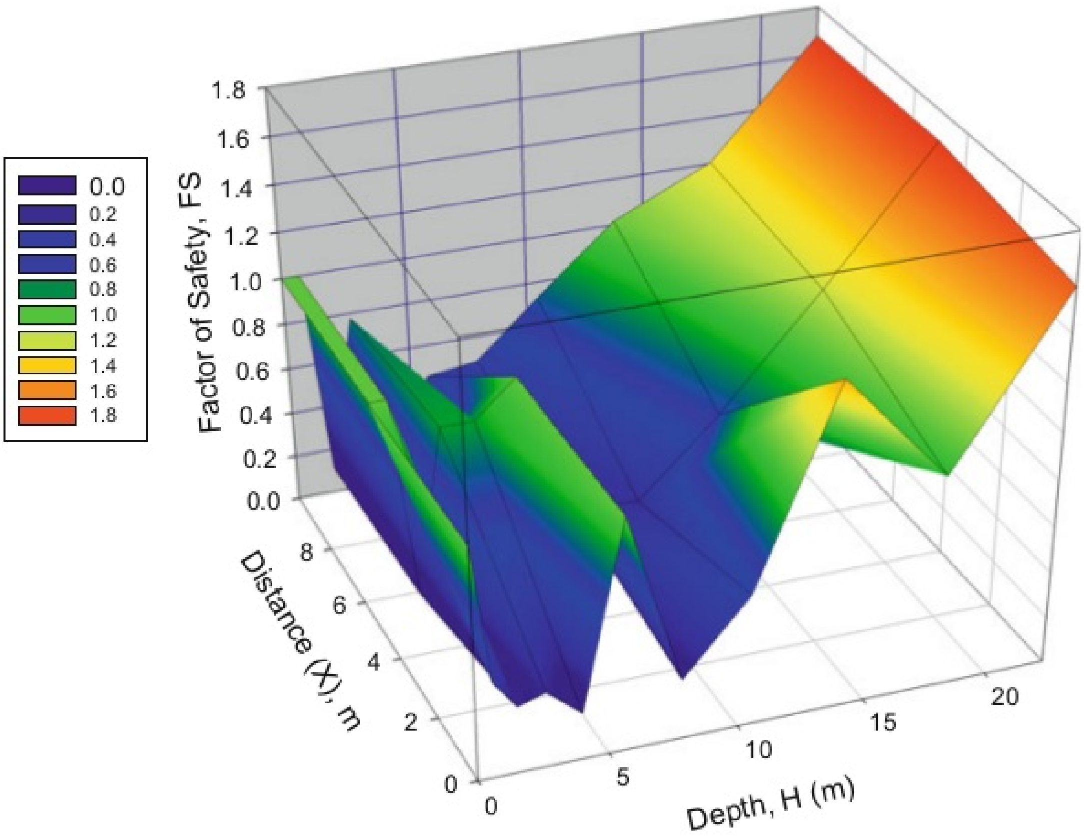

Fig. 8 A plot of 3-D liquefaction potential for first scenario of 8 M_W Yogyakarta's earthquake at southern part of UMY campus

5 Conclusions

The compilation and analysis between seismic (MASW) method and geotechnical site investigation successfully generates the 2-D shear wave velocity of study area. 1-D and 2-D shear wave velocities profiles can be efficiently estimated by MASW method. Based on the 2-D shear wave velocity profile, lateral variation in dynamic properties of soil layer can be clearly obtained. The use of MASW method as an alternative non-destructive method is found to be one of the foremost cost-effective options to estimate in situ shear wave velocities. By using the shear wave velocity, physical soil characteristics and seismicity data, the liquefaction potential of sand layers deposit at observed sites can be analyzed using procedure described in [12]. 2-D and 3-D liquefaction maps are also generated in order to provide understandable information of subsurface liquefiable sections during the earthquake. This analysis is useful and effective in presenting the main data for seismic hazards analysis for the sustainable development.

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