JURNAL TEKNIK

Volume 23, No. 1, Juni 2025
P-ISSN: 1693-6191 E-ISSN: 2715-7660 DOI: https://doi.org/10.37031/jt.v23i1.621

Potential Soil Lateral Spreading and Settlement Induced Liquefaction in Indramayu Area

[1]Rifki Asrul Sani, [2]Eko Soebowo, [3]Imam A. Sadisun

[1] Mining Engineering Diploma Program, Polytechnic Islam Syekh Salman Al-Farisi Rantau
[2] Central Geotechnology, National Research and Innovation Agency (BRIN)
[3] Faculty of Technology and Earth Science, Institute Technology of Bandung
e-mail: kang.sani.geologi@gmail.com

Abstrak

Gempabumi yang pernah terjadi di kawasan Indramayu tahun 1847 menyebabkan bangunan dan fasilitas runtuh, nyawa hilang, celah selebar 1-2 kaki terbentuk di tanah, semua bangunan pada kawasan benteng mengalami rusak parah dan tidak dapat dihuni kembali. Berdasarkan simulasi dan evaluasi hasil penelitian sebelumnya pada daerah yang sama, sumber gempabumi yang merusak kemungkinan berasal dari sumber gempabumi dangkal yang saat ini disebut Segmen Sesar Baribis. Penelitian ini bertujuan memperoleh hubungan antara bencana gempabumi di masa lalu serta potensi kejadiannya di masa yang akan datang dengan sumber gempabumi yang sama. Pada penelitian ini, kami menggunakan data hasil pengujian di lapangan berupa nilai uji penetrasi standar (SPT) pada 4 titik pemboran teknik serta nilai hasil uji penetrasi konus pada 10 titik uji CPTu dan 13 titik uji CPT. Ketiga hasil pengujian lapangan digunakan dalam analisis fisik dan mekanik serta faktor keamanan terhadap likuefaksi dengan menggunakan pendekatan nilai PGA yang berbeda, dan nilai dari faktor keamanan tersebut menjadi pertimbangan dalam hal estimasi potensi penurunan dan perpindahan lateral tanah. Hasil analisis menunjukkan bahwa lapisan sedimen pasir (fluvial dan pematang pantai) dan sedimen pasiran (pasir lanauan muka delta) di area penelitian yang berpotensi likuefaksi memiliki nilai penurunan dan perpindahan lateral tanah yang spesifik, bergantung pada nilai PGA. Potensi perpindahan lateral tanah tertinggi sebesar 0,645 m, sementara itu nilai penurunan tanah tertinggi adalah 0,301 m.

Kata kunci: gempabumi, likuefaksi, perpindahan lateral, penurunan

Abstract

An earthquake that had occurred in the Indramayu area in 1847 caused buildings and facilities to collapse, lives were lost, gaps 1-2 feet wide formed in the ground, all buildings in the fort area were severely damaged and could not be rehabited. Based on simulations and evaluations of previous research results in the same area, the source of the damaging earthquake is likely to originate from a shallow earthquake source currently referred to as the Baribis Fault Segment. This study aims to establish a relationship between past earthquake disasters and the potential for their occurrence in the future with the same earthquake source. In this research, we used data from field tests in the form of standard penetration test (SPT) values at 4 technical drilling points, as well as cone penetration test (CPTu) results at 10 test points and CPT results at 13 test points. The three results from the field tests are used in physical and mechanical analysis, as well as safety factors against liquefaction using different PGA value approaches, and the values of these safety factors are considered in estimating potential soil lateral spreading and settlement. The results of the analysis showed that sand sediment layer (fluvial and beach ridges) and sandy sediment layer (delta front silty sand) in the study area had the potential against liquefaction with specific soil settlement and lateral spreading values, depending on PGA values. The highest potential value soil settlement against liquefaction is 0.301 m, while the highest lateral spreading potential of the soil is 0.645 m.

***Keywords**: earthquakes, liquefaction, lateral spreading, settlement*

Diterima: April 2025
Disetujui: Mei 2025
Dipublikasi: Juni 2025

Introduction

The destructive earthquake in 1847 in the Indramayu and its surroundings area (Nguyen et al. 2015) became an important record in regional planning. The Indramayu area, which is mostly composed of quaternary loose sediment material and in an area of prone to earthquake shocks, makes this area vulnerable to liquefaction disasters (Buana et al. 2019; Sani, 2019; Sani et al. 2020 and 2022). Figure 1 shows earthquakes simulation which caused disaster in Indramayu and its surrounding area (Nguyen et al. 2015), with fault segment modelling close to Baribis Fault Segment with a potential magnitude of 6.5 Mw (Irsyam et al. 2017). Figure 2 shows the zone of the area with the potential for liquefaction in Indramayu with analysis referring to SNI 1726:2019 (Sani et al. 2022). Ground deformation like soil lateral spreading and settlement due to liquefaction may occured in loose sand material, these may affect deformation on building and foundation (Tokimatsu and Asaka, 1998; Bardet et al. 2002; Xu et al. 2021). This study evaluates the potential for soil lateral spreading and settlement against liquefaction with a different PGA value approach. It aims to get a more picture in the characterization of areas near to the earthquake source.

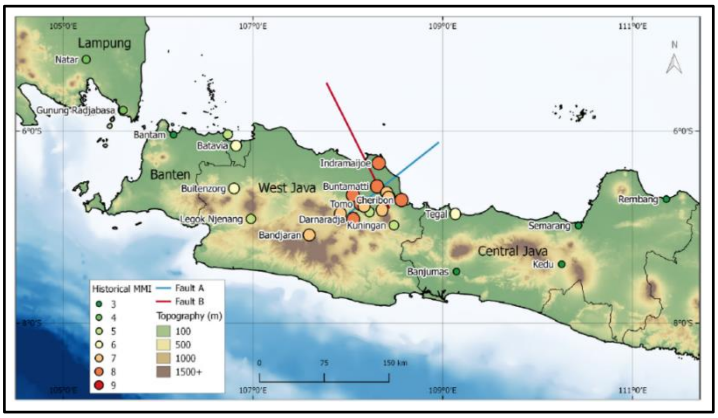

Figure 1. Model of observed earthquakes MMI based on historical evidence and fault traces used to model ground motion shaking in Indramayu area (Nguyen et al. 2015)

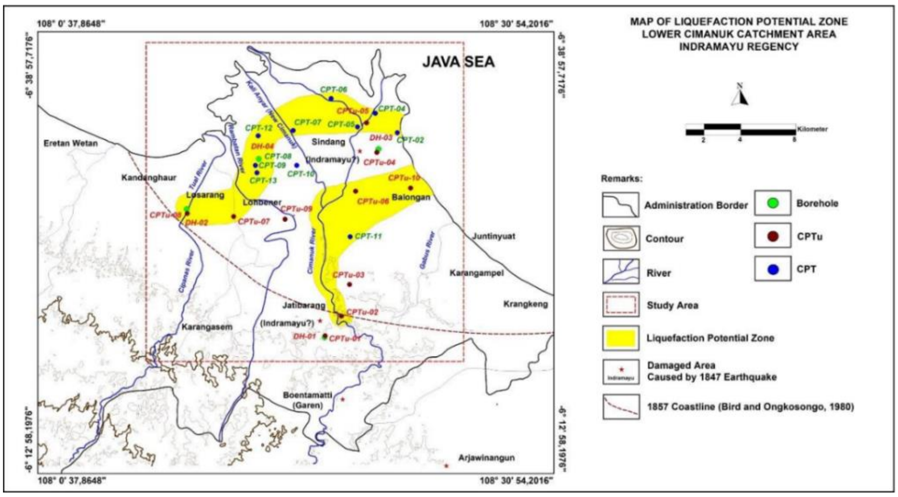

Figure 2. Map of potential liquefaction in Indramayu and its surrounding area (Sani et al. 2022).

Methods

This research uses several primary data, with 4 engineering drilling, 10 CPTu and 13 CPT data test. According to the Indonesia Earthquake Source and Hazard Map Book 2017 (Irsyam et al., 2017), Indramayu Regency and its surroundings are located in areas with a peak acceleration on bedrock caused by active fault sources of 0.1 – 0.15 g and based on a 2500-year return period (2% in 50 years) of 0.25 – 0.3 g. The PGA value data will be used in the analysis of liquefaction potential due to earthquakes. Data on the depth of potential sand and sandy sediments and the distribution of potentially liquefaction sediment facies according to Sani et al. (2022). In terms of estimating the value of potential lateral spreading against liquefaction, it was carried out by the method of Zhang et al. (2004). The procedure in estimating the value of soil lateral spreading against liquefaction is as follows:

1. Relative density estimation (Dr) from Standard Penetration Test (SPT) or conus (qc) data with equation (1) and (2):

$$\boldsymbol{D_r = 16\ x\ ((N_1)_{78})^{0,5} = 14\ x\ ((N_1)_{60})^{0,5}} \qquad (1)$$

$$\boldsymbol{D_r = -85 + 76\log(q_{C1N})} \qquad (2)$$

2. Use Figure 3 as follow to gain value of *γ*γ_{max} (maximum cyclic shear strain) based on value of safety factor against liquefaction (FS_L) and estimated value of sediment relative density (Dr).
3. Value of LDI (Lateral Displacement Index) integrated with γ_{max} with equation (3):

$$\boldsymbol{LDI = \int_0^{z_{max}} \gamma_{max}} \qquad (3)$$

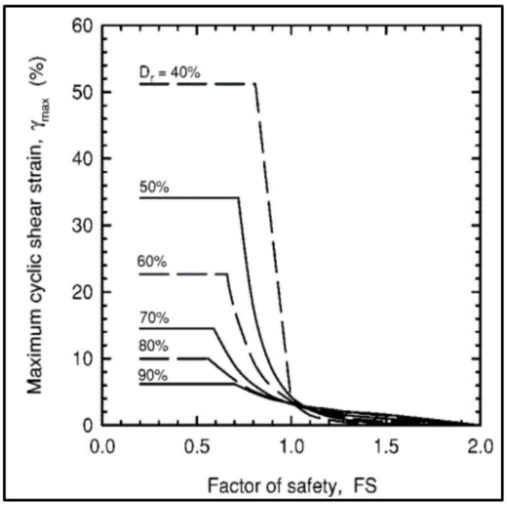

Figure 3. Graphic of γ_{max} (maximum cyclic shear strain) against safety factor of liquefaction for estimating soil lateral spreading value (Zhang et al. 2004).

Meanwhile, in terms of estimating the value of soil settlement against liquefaction based on SPT (Standard Penetration Test) carried out using the Ishihara and Yoshimine (1992) method. The procedure in estimating the value of soil settlement against liquefaction is as follows:

1. Estimation of the relative density value (Dr) of the SPT test from Equation (1).
2. Read the estimated settlement value based on Figure 4.a of the relative density result to obtain the volumetric strain (ε_v) value. Then calculate a whole through with equation (4):

$$S = \sum_{i=1}^{n} \varepsilon_{vi} \, \Delta z_i \qquad (4)$$

Procedure for estimating the value of soil settlement against liquefaction based on conus penetration data (CPT and CPTu) uses the method of Zhang et al. (2002). In terms of estimation to obtain volumetric strain (εv) values obtained through Figure 4.b based on safety factor data due to liquefaction (FS_L).

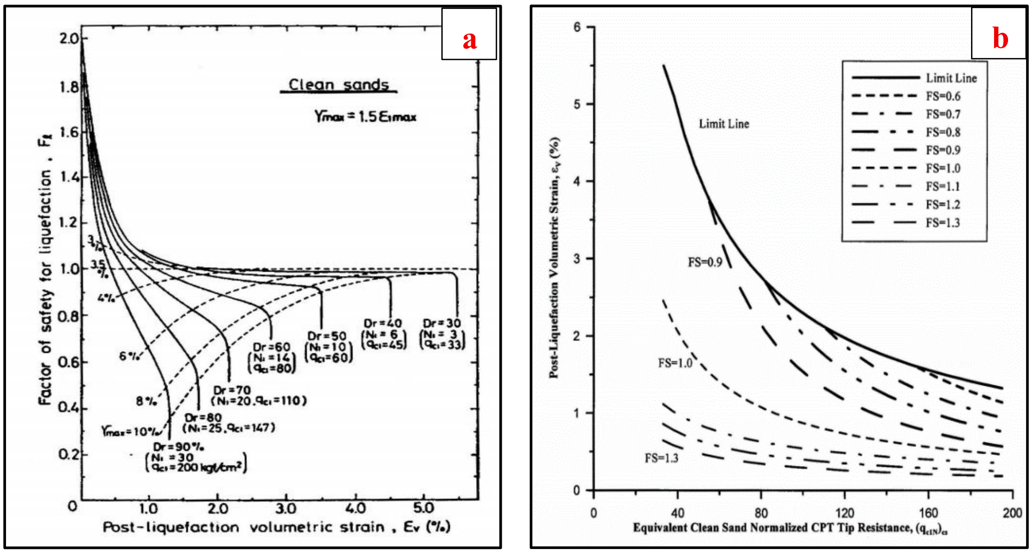

Figure 4.a) Graphic the relationship between volumetric strain (ε_v) value against liquefaction safety factor (FS_L) based on SPT data for estimation value of soil settlement (Ishihara and Yoshimine, 1992). b) Graphic the relationship between volumetric strain (ε_v) value against liquefaction safety factor (FS_L) based on CPT data for estimation value of soil settlement (Zhang et al. 2002).

Data on depth of sediment which potentially liquefied and safe ($FS_L > 1$), integrated into the estimation of soil lateral spreading and settlement values. The use of different maximum surface acceleration (PGA) values, in this case PGA 0.15 g and 0.3 g based on data from Sani et al. (2022) research. The selection of the two PGA values refers to SNI 1726:2019, as an initial description in estimating the liquefaction safety factor due to an earthquake and will reflect the condition of potential soil lateral spreading and settlement values against liquefaction.

Results

Evaluation of Liquefaction Potential and Deformation of Sand and Sandy Soils

Most of the sand and sandy sediments which potentially liquefied in this research are the north coast areas. This is related to the low N-SPT value (< 10) or the conus penetration value (q_c) less than 6,000 kPa (6 MPa). The thicker layers of sand and sandy sediments, coupled with the shallow groundwater table, will result in large estimates of soil lateral spreading and settlement. Referring to Boulanger and Idriss (2014), which is a method in estimating liquefaction potential, sediments with fine grain content (FC) ≥ 50% (sandy) also have the potential to liquefaction at depths of up to ± 9 m. Figures 6 and 7 show examples of analysis profiles at DH-02 and CPTu-10 test points on sand and sandy soil layers potentially against liquefaction.

Potential of Soil Lateral Displacement and Settlement Against Liquefaction

Almost all test points are potentially liquefied, with sediment types are sand sediments (fluvial sand and beach ridges sand facies) and sandy (sandy silt delta front facies). This has an impact on the potential distribution of sand and sandy soils that experience lateral displacement and settlement against liquefaction. The smaller the safety factor against liquefaction (FS_L) has an impact on the greater the value of cyclic shear strain (γ_{max}) and volumetric strain (ε_v) which affects the estimated value of lateral displacement and settlement (Tables 1 and 2).

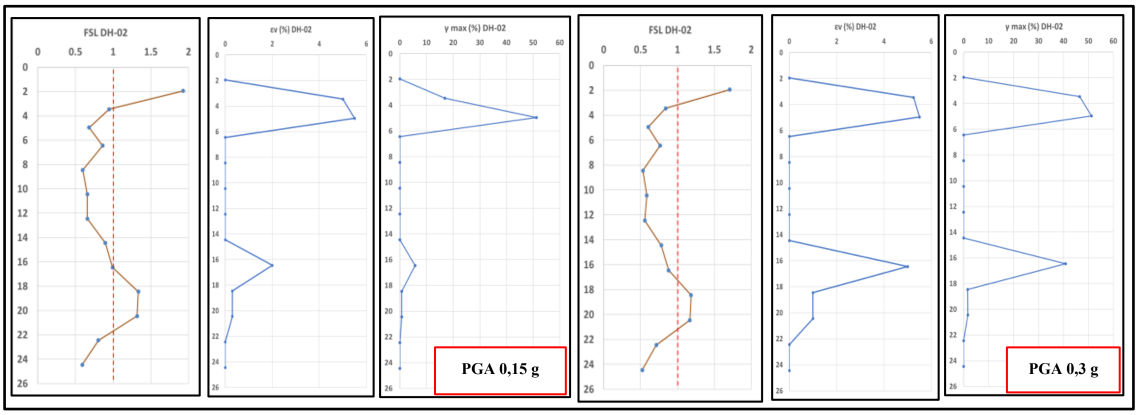

Figure 6. Evaluation of safety factor liquefaction (FS_L) in relation to soil deformation potential of sand and sandy at DH-02 test points with different PGA values.

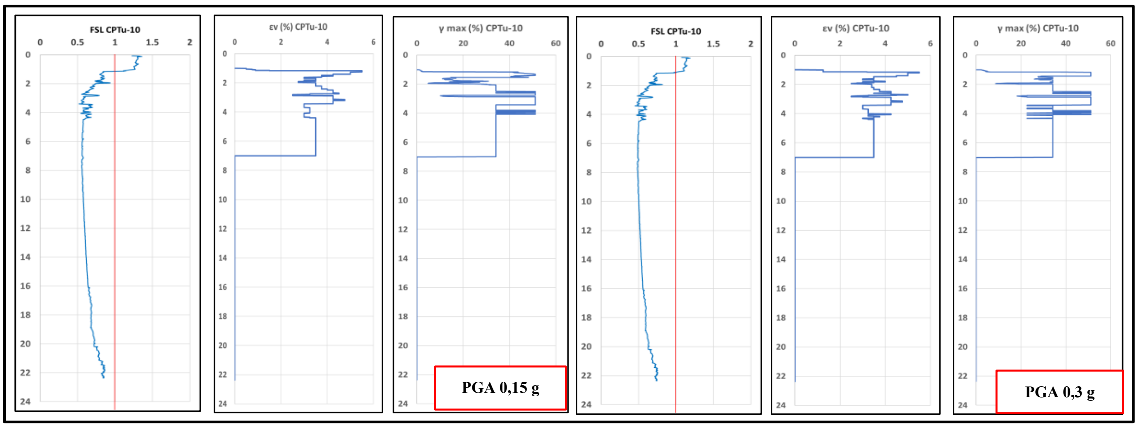

Figure 7. Evaluation of safety factor liquefaction (*FS$_L$*) in relation to soil deformation potential of sand and sandy at CPTu-10 test points with different PGA values.

Table 1. Recapitulation of the estimated soil lateral spreading (LD, in meters) against liquefaction from all test points in research area with different PGA.

Test Points	**0,15 g**	**0,3 g**
DH-01	-	-
DH-02	0,244	0,493
DH-03	-	-
DH-04	0,616	0,645
CPTu-01	-	-
CPTu-02	-	0,106
CPTu-03	-	0,044
CPTu-04	-	-
CPTu-05	0,297	0,325
CPTu-06	0,395	0,425
CPTu-07	0,13	0,174
CPTu-08	0,244	0,493
CPTu-09	0,035	0,042
CPTu-10	0,441	0,451
CPT-01	0,155	0,163
CPT-02	0,339	0,35
CPT-03	0,108	0,132
CPT-04	0,24	0,277
CPT-05	0,024	0,057
CPT-06	0,224	0,274
CPT-07	0,21	0,291
CPT-08	0,616	0,645
CPT-09	0,156	0,197
CPT-10	-	-
CPT-11	0,176	0,288
CPT-12	0,219	0,263
CPT-13	0,239	0,341

Table 2. Recapitulation of the estimated soil settlement (S, in meters) against liquefaction from all test points in research area with different PGA.

Test Points	0,15 g	0,3 g
DH-01	-	-
DH-02	0,21	0,301
DH-03	-	-
DH-04	0,285	0,293
CPTu-01	-	-
CPTu-02	-	0,08
CPTu-03	-	0,056
CPTu-04	-	-
CPTu-05	0,162	0,178
CPTu-06	0,211	0,232
CPTu-07	0,094	0,099
CPTu-08	0,21	0,301
CPTu-09	0,022	0,025
CPTu-10	0,213	0,214
CPT-01	0,078	0,091
CPT-02	0,172	0,176
CPT-03	0,067	0,072
CPT-04	0,136	0,155
CPT-05	0,034	0,051
CPT-06	0,14	0,161
CPT-07	0,163	0,175
CPT-08	0,285	0,293
CPT-09	0,097	0,11
CPT-10	-	-
CPT-11	0,166	0,196
CPT-12	0,137	0,144
CPT-13	0,196	0,212

Discussion

This research area according to Tjia et al. (1968) and Rimbaman (1992) is a region with a fairly active sedimentation process, primarily sourced from the Cimanuk River, with sediment ages of < 500 years. The layers of sand and sandy soils that have liquefaction potential ($FS_L < 1$) in the research area have N-SPT values < 10 ($(N_1)_{60}) < 15$) or $q_c < 6$ MPa (6,000 kPa), occurring in both river sediment sand facies (fluvial sands) and beach ridges sand facies as well as delta front sandy silt facies. The large factor of estimated lateral soil spreading and settlement value against liquefaction is influenced by the main factor in the form of PGA value, which affects the thickness of sand and sandy sediments which potentially liquefied in the research area. In this research, the PGA value of 0.3 g based on a 2,500-years re-period according to SNI 1726:2019 requirements resulted in deformation of the soil due to greater liquefaction, with the main distribution being in the northern coastal of the research area.

Ground settlement induced liquefaction < 10 cm indicates that the testing area has not experienced damage or has light damage, areas with ground settlement values of 10 – 20 cm fall into the moderate damage category, and ground settlement values > 30 cm indicate that the area falls into the heavy damage category. In the heavy damage category, there will usually be sand boils, cracks, and significant displacement of soil material (Ishihara and Yoshimine, 1992). Thus, the research area generally falls into the moderate damage category based on the analysis using different PGA values, and the potential damage caused by earthquakes is likely to align with the findings of previous research (Nguyen et al. 2015). Further research can be related to the use of different methods in analyzing liquefaction potential, especially in using tests to obtain shear wave velocity values and amplification that will enrich the vulnerability level of the Indramayu region to liquefaction potential due to earthquakes originating from the Baribis Fault Segment. Also, further study like using end-bearing piles to resist the earthquake induced ground deformation of buildings is needed in order to reduce casualties and disaster risk (Cubrinovski and Ishihara, 2004; Elgamal et al. 2005; Xu et al. 2017; Xu et al. 2021).

Conclusion

From this study, several conclusions can be drawn including:

1. The use of different PGA values in the analysis of areas near earthquake sources, in addition to affecting the depth of liquefaction potential will help engineering design according to the needs and designation of the area.
2. The potential for soil lateral displacement and settlement is influenced by the thickness of the sand and sandy layer which has the potential for liquefaction (FS_L < 1), which affected large value of cyclic shear strain (γ_{max}) and volumetric strain (ε_v).
3. The highest soil lateral spreading potential of 0.645 m at the DH-04 test point with a PGA scenario of 0.3 g. Meanwhile, the highest land subsidence value was 0.301 m at the DH-02 and CPTu-08 test points with a PGA scenario of 0.3 g. The test points are located in the northern coastal of the research area.

From this study we can conduct similar effect based on earthquakes phenomena, such as potential ground movement which may causing soil movements and damage on buildings. PGA value as the main factor may influence different effect on potential ground movement induced liquefaction in sandy and sand soil, especially on coastal sediment.

References

Bardet, J. P., Tobita, T., Mace, N. & Hua, J. (2002). Regional modeling of liquefaction-induced ground deformation. *Earthquake Spectra*, 18, 19-46. doi: 10.1193/1.1463409

Bray, J. D. & Dashti, S. (2014). Liquefaction-induced building movements. *Bulletin of Earthquake Engineering*, 12, 1129-1156. doi: 10.1007/s10518-014-9619-8

Boulanger, R. W. & Idriss, I. M. (2014). *CPT and SPT Based Liquefaction Triggering Procedures*. Department of Civil and Environmental Engineering. University of California.

Buana, T. W., Hermawan, W., Rahdiana, R. N., Widyaningrum, R., Wahyudin, Hasibuan, G., Wiyono, & Sollu, W. P. (2019). *Atlas of The Indonesia Liquefaction Susceptible Zone*. Geological Agency, Bandung.

Cubrinovski, M & Ishihara, K. (2004). Simplified method for analysis of piles undergoing lateral spreading in liquefied soils. *Soils and Foundations*, 44, 119-133. https://doi.org/10.3208/sandf.44.5_119

Elgamal, A., Lu, J., & Yang, Z. (2005). Liquefaction-induced settlement of shallow foundations and remediation: 3D numerical simulation. *Journal of Earthquake Engineering*, 9, 17–45. https://doi.org/10.1142/S136324690500216X

Irsyam, M., Widiyantoro, S., Natawidjaja, D. H., Meilano, I., Rudiyanto, A., Hidayati, S., Triyoso, W., Hanifa, N. R., Djarwadi, D., Faisal, L., & Sunarjito. (2017). *Map of Indonesia's Earthquake Sources and Hazards in 2017*. Center for Research and Development of Housing. Research and Development Agency. Ministry of Public Housing and Works Republic Indonesia.

Ishihara, K. & Yoshimine, M. (1992). Evaluation of settlement in sand deposits following liquefaction during earthquakes. *Soil and Foundations*, 32, 173-188. https://doi.org/10.3208/sandf1972.32.173

Knappett, J. A. and Madabhushi, S. P. G. (2008): Liquefaction induced settlement of pile groups in liquefied and laterally spreading soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 134, 1609-1618. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:11(1609)

Nguyen, N., Griffin, J., Cipta, A., & Cummins, P. R. (2015). *Indonesia’s Historical Earthquakes: Modelled Examples for Improving the National Hazard Map. Record 2015/23*. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2015.023

Rimbaman, I. (1992). The Role of Sea-level Changes on The Coastal Environment of Northern West Java (Case Study of Eretan, Losarang and Indramayu). *Journal of*

Southeast Asian Earth Sciences, 7, 71-77. https://doi.org/10.1016/0743-9547(92)90017-6

Sani, R. A. (2019). *Study of Liquefaction Potential Induced Ground Settlement and Lateral Spreading in Lower Cimanuk Catchment Area, Indramayu Regency, West Java Province*. Master's Program Thesis, Bandung Technological Institute.

Sani, R. A., Soebowo, E., Fikri, A. M. & Sadisun, I. A. (2020). Engineering characteristics of quaternary sediment related to potential geological hazards in the lower Cimanuk catchment area. *Journal of Environment and Geological Hazards*, 11, 161-173. http://dx.doi.org/10.34126/jlbg.v11i3.294

Sani, R. A., Soebowo, E., & Sadisun, I. A. (2022). Quarternary sediment facies induced liquefaction potential in Cimanuk catchment area, indramayu, west java. *Journal of Technology*, 15, 110-117. https://doi.org/10.34151/jurtek.v15i2.3158

Shahien, M. M. (1998). *Settlement of Structures on Granular Soils Subjected to Static and Earthquake Loads*. Ph.D. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL.

SNI 1726:2019 about *Earthquake Resistance Planning Procedures for Building and Non-Building Structures*.

Tjia, H. D., Asikin, S., & Atmadja, R. S. (1968). Coastal accretion in western Indonesia, *Bulletin of National Institute of Geology and Mining*, 1, 15-45.

Tokimatsu, K. & Asaka, Y. (1998). Effects of liquefaction-induced ground displacements on pile performance in the 1995 Hyogoken-Nambu earthquake. *Soils and Foundations*, 38, 163-177. https://doi.org/10.3208/sandf.38.Special_163

Xu, L. Y., Cai, F., Wang, G. X., Chen, G.X., & Li Y. Y. (2017). Nonlinear analysis of single reinforced concrete piles subjected to lateral loading. *KSCE Journal of Civil Engineering*, 21, 2622-2633. https://doi.org/10.1007/s12205-017-1010-2

Xu, L. Y., Song, C. X., Chen, W. Y., Cai, F., Li, Y. Y., & Chen, G. X. (2021). Liquefaction-induced settlement of the pile group under vertical and horizontal ground motions. *Soil Dynamics and Earthquake Engineering*, 144, 1-13. https://doi.org/10.1016/j.soildyn.2021.106709

Zhang, G., Robertson, P. K., & Brachman R. W. I. (2002). Estimating liquefaction-induced ground settlement from cpt for level ground. *Canadian Geotechnical Journal*, 39, 1168-1180. DOI: 10.1139/t02-047

Zhang, G., Robertson, P. K., & Brachman R. W. I. (2004). Estimating liquefaction-induced lateral displacement using the standard penetration test or cone penetration test. *Journal of Geotechnical and Geoenvironmental Engineering*, 130, 861-871. doi:10.1061/(ASCE)1090-0241(2004)130:8(861)