Assessment of liquefaction hazard along shoreline areas of Peninsular Malaysia

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ABSTRACT

Using a collection of 2074 boreholes extracted from soil investigation reports utilized by standard penetration test, this study examines the susceptibility of soil liquefaction hazard along the shoreline of Peninsular Malaysia. Data collection and site visit were conducted to gather all the basic information related to soil liquefaction hazard. Three types of results are presented in the form of photos (recent shoreline condition), graphical illustrations (soil composition, SPT-N distribution and zone of saturation) and liquefaction susceptibility plots. The findings indicate there is obviously a critical need to adapt further liquefaction analysis in the shoreline region of Peninsular Malaysia to better understand liquefaction hazard and produced beneficial information on the matter. A risk assessment matrix is also introduced in classifying the severity and recommended mitigation measures of the studied areas.

KEYWORDS

Soil liquefaction; shoreline; Peninsular Malaysia; illustrations

Introduction

The shoreline areas of Peninsular Malaysia which stretches approximately 1972 km are found to be concentrated with alluvium, marine and continental deposits (clay, sand and peat with minor gravel) (Hawkes et al. 2007). It is further categorized into muddy and sandy beaches. Sandy beaches are found mostly in the east coast areas running north along Kelantan state shoreline and all the way south to eastern Johor state while the muddy beaches are found concentrated in the west coast areas. The existing development along these areas includes oil and gas sector, tourism, residential township, coastal roads, power plants and port industry (Lee 2010; Marzuki 2010; Pourebrahim et al. 2011). These man-made surroundings are vulnerable to strong earthquake hazard due to seismogenic zones (Adnan et al. 2005). The two main sources of ground motion are from the Sumatra subduction fault and Sumatran fault in which cover a total distance range of 300–600 km from the epicentre. Local faults are also reported to have contributed to tremors in Peninsular Malaysia. A few major faults were found in Peninsular Malaysia such as Bukit Tinggi Fault, Kuala Lumpur Fault, Lebir Fault, Baubak Fault and Mersing Fault. There are about 70 tremors of Mw > 7.0 occurring from 1977 to 2007 in the South Asian region, those of which being felt in the Peninsular Malaysia region. The local settings are bordered to the west and to the south by seismically active Sunda–Banda Volcanic Arc which moves at 6–8 cm/year and to the east by the Philippines-Pacific Plate which moves at 11 cm year.

The recent Sabah earthquake in 2015 in east Malaysia region which was the strongest to affect Malaysia since 1976 has introduced us with new perspective and views on regional natural disaster. Study and investigation into the topic has becoming more important as tremors are being felt in...
nearby locations. Missing information on regional setting is likely to be a major disadvantage in the sense towards promoting safe and quality built environment. The damage effect from such event in neighbouring countries has presented increased resources in handling maintenance and repair on assets and facilities after the shock event. Many parties may lose trust which could result in decreasing revenues and profits. Moreover, it further affects the construction quality reputation besides risking public safety.

Alluvial soils are known to increase earthquake intensity and can further contribute to soil liquefaction hazard if vulnerable condition is present. We believe that the soil stiffness and thickness control the amplification and duration of ground shaking, which are the most significant factors controlling liquefaction occurrences (Beroya et al. 2009; Singh et al. 2017). In Malaysia, the knowledge on soil liquefaction has not been extensively attained and widely investigated. There are very few in the literature and limited study conducted to recognize the liquefaction potential areas, especially on the shoreline area which is highly concentrated with saturated cohesionless soil and is located near the Sumatra fault and Sunda trench (Sun and Pan 1995; Koh et al. 2009; Teh et al. 2009; Zahari et al. 2013). Therefore, the shoreline areas require further information on the hazard (Li et al. 1998). Boreholes may provide useful information for soil liquefaction hazard assessment. The objective of this study is to apply boreholes data for details of liquefaction hazard assessment along the shoreline areas to find the soil particle size information and other related parameters of liquefaction-governing factors for initial screening of the studied site.

The approach commonly introduced after a deadly event resulted in various findings and governing factors on soil liquefaction. During the Padang earthquake in 2009, numerous sand boils were observed at various affected locations after the earthquake (Hakam and Suhelmidawati 2013). It was found that most of the soil satisfies the criteria of liquefaction susceptibility when plotted in the limit curve. A hazard map introduced shows that the affected areas are likely to be concentrated along riverbeds and beaches in which there is a high possibility of saturated deposits existing in the areas. The Tohoku 2011 earthquake presents a wide soil liquefaction affected areas covering farm land, river dikes, flood channels, reclamation sites, fill areas and sites having young alluvium (Tsukamoto et al. 2012; Yamaguchi et al. 2012). An investigation carried out in the Christchurch earthquake in 2011 highlighted loose deposits of silts and sands in many of the affected liquefaction sites which are a reclaimed site or old river channels which have been diverted away (Reyners 2011; Wotherspoon et al. 2015).

The aim of this study is to identify potential liquefaction areas along shoreline of Peninsular Malaysia based on governing factors found in literatures. The scope of the present study is as follows:

1. Eleven major states which consist of Kelantan, Terengganu, Pahang, Johor, Melaka, Negeri Sembilan, Selangor, Perak, Penang, Kedah and Perlis are included in study. The shoreline district in each state is selected as to present a continuous line surrounding the Peninsular Malaysia region.
2. The liquefaction analysis is conducted using standard penetration test (SPT) data.

The main idea of the paper is to conduct a screening which is essential as a guideline for government bodies, local authorities, land developers and construction industries in understanding more on the regional settings towards liquefaction hazard. The study investigation is a step in providing awareness and safety to the public as well as protecting the assets and facilities in Peninsular Malaysia (Olaniyi et al. 2012).

Methodology

Site visit on the studied areas has been conducted to document general information of the shoreline areas. Prior to site visit, SPT report is collected from various governing bodies. Later, related
geotechnical information from SPT report is extracted and by using the linear stratigraphy correlation method, the illustration of soil profile, corrected SPT-N distribution and zone of saturation is produced. Most developed areas have been covered significantly for this study as to reflect the potential of soil towards soil liquefaction hazard on built environment. The natural environments along shoreline which are inaccessible are emerged with developed location using spatial analysis based on inverse distance weighting (IDW). IDW assigns more weight to features closest to the starting point than to point farther away. In other words, the weight of a given point is in inverse proportion to its distance from the interpolated points.

Grain size distribution plot developed using sieve analysis from laboratory reports is extracted to further examine soil in gradation curves of liquefiable soils. The finer and discrete particles such as clay and silt are determined through particle size analysis (hydrometer method) from the laboratory report (Beverwijk 1967). A risk assessment matrix is introduced in classifying the severity and recommended mitigation measures of studied location based on the findings. Figure 1 presents the flowchart of study development. Geographic Information System (GIS) (QGIS), Microsoft Excel and soil profile visualization software (RockWorks17) are applied in aiding the process of study.

**Site visit**

The site includes 11 states consisting of 40 shoreline districts which cover a total distance of 1972 km. In summarizing the database, abbreviation for each studied location is introduced and information of data collections is presented in Table 1.

Figure 2 presents the Peninsular Malaysia map with studied location and Figure 3 presents the state maps with studied locations. Both figures are plotted using the abbreviations provided in Table 1. SI report based on SPT is the main source of input in producing the graphical illustrations of study. Hence, extensive data collection was carried out in gathering 2074 boreholes data along the shoreline stretch as presented in Table 1.

**SPT and soil sampling**

The SPT was carried out in accordance with clause 3.3 B.S 1377: Part 9: 1990, “Determination of the penetration resistance using split-barrel sampler”, using a self-tripping hammer of 63.5 + 0.5 kg weight of an approved design (British Standard Institution 1990). Soil samples from all sites were collected in the form of undisturbed or disturbed but representative when drilling. The disturbed samples are used for identification and laboratory classification tests. The disturbed samples were sealed in polythene bags and labelled with detailed information before sending to laboratory,
whereas the undisturbed samples were collected by employing hydraulic thrust on thin wall sampling tubes of 60 mm diameter for very soft cohesive soils. The sampling tubes are later sealed with paraffin wax to prevent dryness. All the samples were placed in cushioned boxes and transported to laboratory to ensure minimum disturbance to the soil samples.

### SPT-N correction

The value of SPT-N is subjected to a large number of variables that affect the results. The SPT-N values are standardized to $N_{(1)60}$ values in reducing the significant variability. Hence, appropriate correction factors for the SPT-N values are introduced in the collection of database, regardless of the equipment used in site exploration (Chang et al. 2011). This approach is to ensure that the SPT-N data used is representative of the actual subsurface conditions. The equation for $N_{(1)60}$ is as follows (Bolton Seed et al. 1985; Ibrahim 2014):

$$N_{(1)60} = N_{SPT} \times C_n \times C_e \times C_b \times C_r \times C_s$$  \hspace{1cm} (1)

### Table 1. Abbreviation and information of studied location.

| State   | State label | Shoreline district | Shoreline district label | Shoreline distance (km) | Number of borehole |
|---------|-------------|--------------------|--------------------------|-------------------------|--------------------|
| Perlis  | R           | Perlis             | R1                       | 20                      | 86                 |
| Kedah   | K           | Langkawi           | K1                       | 148                     | 104                |
|         |             | Kubang Pasu        | K2                       |                         |                    |
|         |             | Kota Setar         | K3                       |                         |                    |
|         |             | Yan                | K4                       |                         |                    |
|         |             | Kuala Muda         | K5                       |                         |                    |
| Penang  | P           | Penang Island      | P1                       | 152                     | 178                |
| Perak   | A           | Kerian             | A1                       | 230                     | 210                |
|         |             | Larut, Matang & Selama | A2                      |                         |                    |
|         |             | Manjung            | A3                       |                         |                    |
|         |             | Hillir Perak       | A4                       |                         |                    |
| Selangor| B           | Sabak Bernam       | B1                       | 213                     | 79                 |
|         |             | Kuala Selangor     | B2                       |                         |                    |
|         |             | Klang              | B3                       |                         |                    |
|         |             | Kuala Langat       | B4                       |                         |                    |
|         |             | Sepang             | B5                       |                         |                    |
| Negeri Sembilan | N   | Port Dickson     | N1                       | 58                      | 20                 |
| Melaka  | M           | Alor Gajah         | M1                       | 73                      | 27                 |
|         |             | Melaka Tengah      | M2                       |                         |                    |
|         |             | Jasin              | M3                       |                         |                    |
| Johor   | J           | Muar               | J1                       | 492                     | 384                |
|         |             | Batu Pahat         | J2                       |                         |                    |
|         |             | Pontian            | J3                       |                         |                    |
|         |             | Johor Bahru        | J4                       |                         |                    |
|         |             | Kota Tinggi        | J5                       |                         |                    |
|         |             | Mersing            | J6                       |                         |                    |
| Pahang  | C           | Kuantan            | C1                       | 271                     | 103                |
|         |             | Pekan              | C2                       |                         |                    |
|         |             | Rompin             | C3                       |                         |                    |
| Terengganu | T       | Besut              | T1                       | 244                     | 546                |
|         |             | Setiu              | T2                       |                         |                    |
|         |             | Kuala Terengganu   | T3                       |                         |                    |
|         |             | Marang             | T4                       |                         |                    |
|         |             | Dungun             | T5                       |                         |                    |
|         |             | Kemaman            | T6                       |                         |                    |
| Kelantan| D           | Tumpat             | D1                       | 71                      | 341                |
|         |             | Kota Bharu         | D2                       |                         |                    |
|         |             | Bachok             | D3                       |                         |                    |
|         |             | Pasir Puteh        | D4                       |                         |                    |
| Total   | 11          | 40                 | 1972                     | 2074                    |                    |
where \( N_{(1)60} \) is the final corrected SPT value; \( N_{SPT} \) is the raw SPT data measured at field; \( C_o \) is the overburden correction factor, \( C_e \) is the energy correction factor; \( C_b \) is the borehole diameter correction factor; \( C_r \) is the rod length correction factor; \( C_s \) is the sampler correction factor; and \( C_b \) is the borehole diameter correction factor.

**Results and discussions**

The liquefaction hazard screening presents a compilation of photos along with three graphical illustrations and two liquefaction susceptibility plots that are translated from the collection of SI reports and site visit.

**Photos of shoreline areas**

Figure 4 presents the photographs of studied shoreline states along the Peninsular Malaysia region. In this study, Peninsular Malaysia is divided into two parts namely the west coast and the east coast.
The west coast consists of Perlis state, Kedah state, Penang state, Perak state, Selangor state, Negeri Sembilan state, Melaka state and Johor state. The east coast, on the other hand, consists of Kelantan state, Terengganu state, Pahang state and another portion of Johor state overlooking the South China Sea. In general, the west coast is densely populated compared to the east coast. States such as Penang, Perak, Melaka and Johor have undergone land reclamation projects in catering future demands of economic growth and increasing population, whereas the east coast offers a more laid back environment which is suitable for tourism industry.

Most of the developed shoreline areas contribute to the commercial and recreational sectors whereas the natural environment is generated by fishery-related activities and agricultural sectors.

Figure 3. State maps and studied locations.
The highest population is found to be near the river mouth where port city is located. The port city is undergoing massive expansion in catering the demand from oil and gas industries and international trade. Hence, existing structures along shoreline areas need to be maintained and managed by observing the performance of soil towards soil liquefaction hazard.

**Soil composition, SPT-N distribution and zone of saturation**

Four types of soil (clay, silt, sand, and gravel) are highlighted in Figure 5 in presenting fundamental soil layer composition of shoreline areas in 11 states of Peninsular Malaysia. It is found from the soil
illustrations that the coastal zone which stretches approximately 1972 km are found to be concentrated with marine and continental deposits: clay, sand, and peat with minor gravel. Basalt of early Pleistocene age is observed in Kuantan, Pahang area. Also, the beaches can be categorized into two types which are muddy and sandy beaches. The borehole data reveal the entire study area comprising the alluvial soil with alternate layers of the clays of different plasticity, silty, sand, gravel and with the various penetration resistance. In the absence of logs deeper than 30 m, thicknesses of the weathered rocks are not available (Figure 5). Sandy beaches are found mostly in the east coast of Peninsular Malaysia running north along Kelantan shoreline and all the way south to eastern Johor while the muddy beaches are found concentrated in the western part of Peninsular Malaysia (Ngah et al. 1996).

The corrected SPT-N values provide soil stiffness which is significant in the foundation design of structures and soil improvement techniques. Soft and loose soil tends to experience settlement when load is applied compared to stiffer and uniform soil. The loose sand is found to be abundant in the first layer of the soil strata, and this is presented with lower corrected SPT-N value. For $N_{(1)60} > 30$, granular soils are unlikely to liquefy (Youd et al. 2001).
Figure 6 presents the distribution of corrected SPT-N values in shoreline areas of Peninsular Malaysia. In the context of earthquake, soft soil tends to amplify the seismic tremors resulting in increased ground acceleration in the soil strata. If three main factors exist alongside (ground tremor with high ground acceleration, loose sands with low corrected SPT-N values, and shallow ground-water table), soil liquefaction during an earthquake is likely to occur at site. Hence, by observing Figure 6, a decision in the soil liquefaction context can be highlighted by the low corrected SPT-N values together with the main factors mentioned.

Figure 7 presents the zone saturation of studied shoreline areas. The yellow colour indicates the unsaturated zone whereas the blue colour indicates the saturated zone. More than 80% of water table is located near the surface. In addition, the condition of soil below the water table is saturated and consists of loose deposits as indicated by the low SPT-N values from Figure 6. Liquefaction phenomenon is most likely to occur at condition where the water table is very close to the surface as reported from earlier studies (Bhattacharya et al. 2011; Ibrahim 2014; Papathanassiou et al. 2015). This indicator can also be a useful tool in assessing the saturated and unsaturated zones along the shoreline.

Figure 6. SPT-N distribution of Peninsular Malaysia.
areas. Extensive distribution of aquifers along the shoreline areas is very important for the ground water level monitoring and residential development (Suratman 2004).

**Liquefaction susceptibility plots**

The grain size distribution plot in liquefaction margin is produced from the collection of SI report. Selected borehole which best fits the liquefy plot is presented in Figure 8. Another plot adapted for this study is the liquefaction susceptibility margins (Figure 9). According to researchers (Bray and Sancio 2006), by using simple terms relating moisture content (wc), liquid limit (LL) and plasticity index (PI), the margins define whether or not finer particles are prone to liquefy. Soils with (i) \( \frac{wc}{LL} > 0.85 \) and \( PI < 12 \) are vulnerable to liquefaction, and soils having (i) \( \frac{wc}{LL} > 0.80 \) and (ii) \( 12 < PI < 18 \) are moderately susceptible to liquefaction and further laboratory testing for fine-grained soils located in this range is recommended, whereas soils having \( PI > 18 \) are considered to be non-liquefiable.
Figure 8. Grain size distribution plot in liquefaction margin.

(a) West coast of Peninsular Malaysia

(b) East coast of Peninsular Malaysia
Figure 9. Liquefaction susceptibility margin.
Table 2. Input score for the shoreline zoning and soil liquefaction category.

| Liquefaction margin | Yes | No | – | – | – | – |
|---------------------|-----|----|---|---|---|---|
| Score               | 25  | 0  | – | – | – | – |
| SPT-N (m)           | 0–5 | 6–11| 12–17| 18–23| 24–29| 30–50|
| Score               | 25  | 20 | 15| 10| 5 | 0 |
| Saturated zone      | Yes | No | – | – | – | – |
| Score               | 25  | 0  | – | – | – | – |
| Seismic intensity (M)| 6  | 5  | 4 | 3 | 2 | 1 |
| Score               | 25  | 20 | 15| 10| 5 | 0 |

Table 3. Output 1 for the shoreline zoning and soil liquefaction category.

| Score | Shoreline zone | SL-0 | SL-1 | SL-2 | SL-3 | SL-4 |
|-------|----------------|------|------|------|------|------|
| 76–100| Z-5            | 20   | 40   | 60   | 80   | 100  |
| 51–75 | Z-4            | 16   | 32   | 48   | 64   | 80   |
| 26–50 | Z-3            | 12   | 24   | 36   | 48   | 60   |
| 21–25 | Z-2            | 8    | 16   | 24   | 32   | 40   |
| 0–20  | Z-1            | 4    | 8    | 12   | 16   | 20   |

**Risk assessment matrix of studied areas**

The general procedure in making hazard-informed evaluation is to highlight potential hazard zones along the shoreline areas in addressing authorities and local councils about soil liquefaction threat for future improvement, mitigation and remediation works. The quantification is subjected to contributing factors of hazard. Observation from available data which was made in the decision-making process results in addressing high possibility and uncertain situations in the most optimized manner in the context of Peninsular Malaysia. The wide use of resources is to ensure that appropriate action is taken quickly and efficiently in reducing unknown hazard in the location. Limited resources are prioritized accordingly in generating Table 2 for soil liquefaction hazard quantification.

The tables are summarized with a summation of the scores for the driving effect of hazard which is then concluded under respected zones and categories of hazard level. The zones are presented with a description of severity level ranging from low to high level. By using available mitigation in the wide scope of the present research, each category of hazard level is related to the mitigation aspect respectively.

Tables 3 and 4 summarize the hazard level at each studied location along with the hazard category in providing the mitigation information accordingly. This approach is to acknowledge individuals as well as the community about hazard information in the areas which could lead them in making safe decisions and effective planning of their surroundings. This information could trigger more detailed research to be carried out by local and also international governing bodies from research institution as well as engineering firms in shaping good measures in the near development of Peninsular Malaysia. Table 5 presents the liquefaction zoning for the 40 shoreline districts of Peninsular Malaysia.

Table 4. Output 2 for the severity level, action and mitigation.

| Zone | Severity level       | Category | Action                                | Mitigation            |
|------|----------------------|----------|---------------------------------------|-----------------------|
| Z-5  | Critical impact      | SL-4     | Forest restoration and rehabilitation | Abandon site          |
| Z-4  | Important impact     | SL-3     | Conduct site-specific investigation   | Special analysis for structure |
| Z-3  | Moderate impact      | SL-2     | Further analysis                      | Ground improvement techniques |
| Z-2  | Low impact           | SL-1     | Monitor                               | No action             |
| Z-1  | Insignificant impact | SL-0     | No action                             | No action             |

Table 5. Liquefaction zoning for the 40 shoreline districts of Peninsular Malaysia.
The paper reported on the susceptibility of soil liquefaction study from SPT-N data in shoreline region of Peninsular Malaysia through a series of graphical visualization information. The soil parameters which best represents the liquefaction hazard are extracted and produced using soil profile visualization software. In addition, the general information on studied location is tabulated to highlight the necessity of having such data in which the aim is to benefit future land use and development. Detailed conclusions are as follows:

(1) The results show that the soil layer composition in the west coast areas is mainly composed of silt and clay deposits. In contrast, the east coast areas looking the South China Sea are mainly consisting of sand deposits which can be vulnerable to liquefaction hazard.

(2) The hardness of layer is produced using the SPT-N blow count distribution. In general, deposits within 15 m depth have softer blow count number compared to deeper interval of soil layers mainly consisting of gravel which gives higher blow count.

(3) As for the zone of saturation, high distribution of saturated zone is found to be common at shoreline areas.
(4) The grain size distribution plot in liquefaction margin and liquefaction susceptibility plot present a critical soil in the east coast compared to the west coast.

(5) The fine content, FC < 20% is likely to liquefy. These indicators are presented in many literatures related to soil liquefaction phenomenon. In the tabulated information, it can be found that most of the areas are prone to liquefaction with densely sand concentration areas, high sand depth, uniform type of soil grading, FC < 20% and groundwater table near surface.

(6) There is obviously a critical need to adapt further liquefaction analysis in the shoreline region of Peninsular Malaysia to better understand liquefaction hazard and produced beneficial information of the liquefaction hazard. Besides that, the study presented serve as a catalyst in soil monitoring with further updating of database for more accurate soil presentation. Finally, the findings will be the key for the future studies and development in the regional context.

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