Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0039

Geological and geotechnical considerations for seismic hazards for Penang Island, Malaysia

Considérations géologiques et géotechniques sur les risques sismiques pour l'île de Penang, Malaisie

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ABSTRACT: This paper presents a summary of a desk study to evaluate ground conditions and seismic hazards in Penang Island, Malaysia. It presents the local geology, topography and the geotechnical aspects of alluvial and marine deposits of the Island. The tectonic setting of the island and earthquake risk from near-and far-field seismic sources and the Malaysian National Annex to Eurocode 8 are discussed. Seismic hazard risks related to local ground motion amplification effects, liquefaction along the developed coastal areas, the coseismic landslides and tsunamis are reviewed.

RÉSUMÉ: Cet article présente le résumé d'une étude géotechnique visant à évaluer les conditions du sol et les risques sismiques sur l'île de Penang, en Malaisie. Il présente la géologie locale et la topographie de l'île et les aspects géotechniques des dépôts alluviaux. Le cadre tectonique de l'île et le risque de tremblement de terre provenant de sources sismiques en champ proche et éloigné et de l'annexe nationale malaisienne à l'Eurocode 8 sont discutés. Les risques d'aléa sismique liés aux effets d'amplification locale du mouvement du sol, à la liquéfaction le long des zones côtières développées, aux glissements de terrain et aux tsunamis sont examinés.

Keywords: Malaysia; earthquake, seismic hazard; site response; liquefaction

1 INTRODUCTION

The State of Penang is situated on the north west of the Peninsular Malaysia. It consists of Penang Island (*Pulau Pinang* in Malay) and Seberang Perai (formerly known as Province Wellesley) which is the coastal region located on the west of the Peninsula and separated from the island by the Penang Strait. The Malacca Strait is located to the west. The island covers an area of 285 km^2 (Figure 1). The closest distance from the island to the Peninsular Malaysia is approximately 3 km.

Penang is one of the most economically active and urbanised regions in Malaysia with highest GPD per capita. The population of the island only is over 700,000. The historical capital city George Town is also located at the north east of the island.

Penang is affected by the seismically active Sumatran Subduction Zone and the Sumatran Fault. Strong earthquakes occurred at the Sumatran Subduction Zone, e.g. the 2004 Great Sumatra-Andaman (Mw=9.3), the 2005 Nias–Simeulue (Mw=8.7), and the 2007 Sumatra earthquakes (Mw=8.4). The 2004 earthquake triggered a devastating tsunami along the coastal areas bordering the Indian Ocean which also caused loss of life on the island.

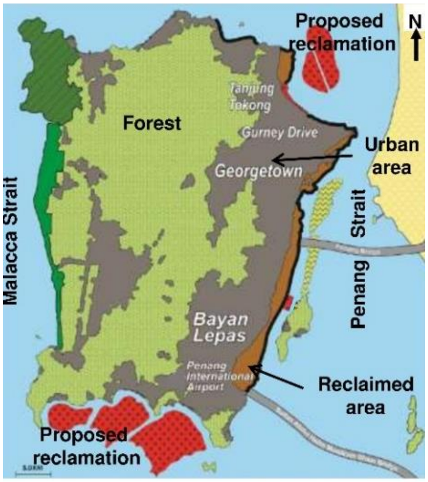

Figure 1. Penang Island and proposed reclamation (modified after Su et al., 2017)

Long-period structures such as high-rise buildings, major bridges and oil and gas storage tanks are affected by far-field large magnitude earthquakes. Such earthquakes, primarily consisting of surface waves, can lead to large amplitude, long period and long duration ground motion. Ground motion amplitude usually decreases with distance of propagation to less severe levels on rock sites. Due to lack of historical recorded ground motions, there are limited studies to investigate the characteristics of far-field earthquakes in Malaysia, except seismic hazard studies carried out for the preparation of the Malaysian seismic design code.

The purpose of this paper is to present an overview of geological and tectonic settings of Penang Island and to summarise ground conditions from various resources in relation to their impact on various seismic hazards such as ground motion amplification, liquefaction and coseismic landslides. The paper also briefly discusses the implications of the new Malaysian National Annex to Eurocode 8.

2 GEOLOGICAL SETTINGS

Peninsular Malaysia is an integral part of Sundaland (Sunda Plate) which is a tectonic entity that moves differently than the Eurasian Plate (Simons et al., 2007). The geological settings of the Peninsula and the Island are discussed below.

2.1 Peninsular Malaysia

The Peninsula lies in north-northwest to south-southeast direction with a maximum length of 750 km and width of 330 km. The geological history of the Peninsula is of continuous orogenesis such that a long period of subsidence and sedimentation were followed by a very long cycles of mountain building with predominance of erosions and weathering. The Peninsula has been influenced by climate and sea level changes during the Quaternary period. It was exposed as a land during low sea levels of the late Pleistocene (Bird et al., 2005). During this period, particularly in the coastal areas, denudational and depositional terrains of unconsolidated alluvium were formed (Raj, 2009). Changes in sea level along the coast of Peninsular Malaysia were estimated between 60 m and 90 m during the Holocene (Kamulidin, 2001). Such change had an impact on the depositional environment of the alluvium. Today the coastal plains along the western coast of the Peninsula are typically a few metres above sea level and were formed through accumulation of fluvial, coastal and/or marine deposits.

Granitic rock typically outcrops over 40% of the land surface at the Peninsula and forms the bedrock. Weathering can be substantial and several tens of metres thick, but possibly exceeding 30 m (Stauffer, 1973). Residual soil that consists of predominantly fine-grained material can be up to 15 m thick.

Since major sedimentary control systems were regional, a similar stratigraphic Quaternary sequence is observed in Malaysia and Indonesia (Batchelor, 1988). Previous studies using deep boreholes divide the Alluvium into older Boulder Beds and Old Alluvium, and Young Alluvium (Holocene), in the vicinity of present streams, with a transitional unit in between. Later research based on studies of sediments from surface outcrops and coastal lowland areas of the Peninsula divided the Quaternary sediments into three main stratigraphic units and identified the marine deposits. Within the old marine deposits, the upper marine clay is at least from Holocene and the lower clay is likely to be Pleistocene. New sediments overlying Holocene upper marine clay can be found along the west coast of the Peninsula (Kamulidin, 2001).

2.2 Penang Island

Penang Island is mountainous with a centrally located granitic range running in a north-south direction. Low lying plains are situated on both the east and west coasts (Figure 2).

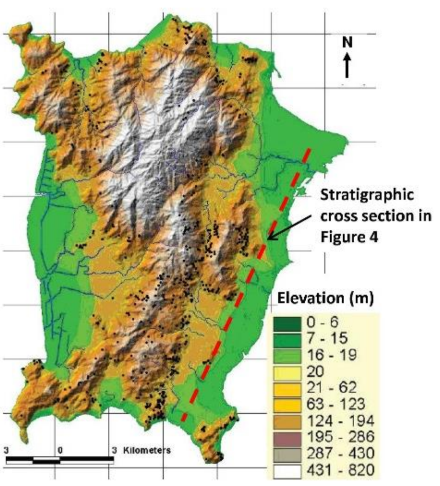

Figure 2. Topographic map of Penang Island (after Lee and Pradhan, 2006)

The island experienced major tilting and uplift during the Oligecene/Miocene periods which exposed the formerly buried granite (Raj, 2009). The Quaternary coastal deposits of the Malaysian Peninsula are typically marine clays and sands, sand beach ridges and woody peat, noting local occurrences of commonly mottled stiff clays under marine clay sequences along the west coast and Penang Island (Kamaludin, 2001), as shown in Figure 3.

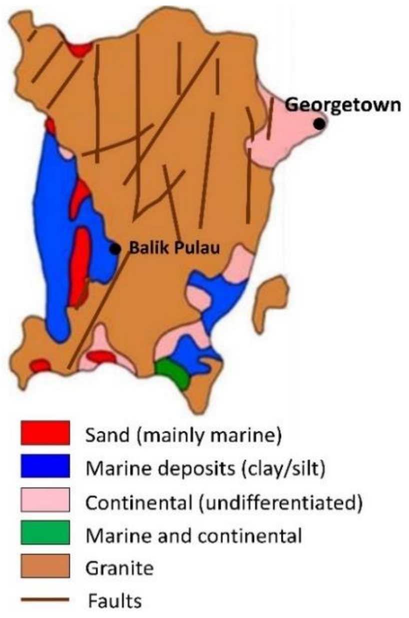

Figure 3. Geology map of Penang Island based on 1:500 000 scale 2007 GMGDM geology map and Tan et al. (2014)

Based on high-resolution seismic profiling and vibrocoring in the Straits of Malacca, the soft marine clays have been shown to overlie the now-submerged late to middle Pleistocene sedimentation (Kudrass and Schuluter, 1994). Sediments can also found in the Penang Strait due to rivers flowing to it.

Table 1 shows the Quaternary deposits encountered on the island and their descriptions. Kamaludin (1990 and 2001) states that differentiation between younger and older Alluvium is difficult due to lack of clear changes in lithology and that some parts of the older Alluvium may be from the late Tertiary.

Table 1. Quaternary deposits of Penang Island (after Kamaludin, 1990). Note that geological ages are not differentiated on the 1:500 000 scale 2007 geology map of the Peninsula by GMGDM

Stratigraphic Group	**Subgroup**	**Description**
Recent Marine Deposits		Very soft to locally soft high plasticity clay with seashells along the coast and Penang Strait.
Young Alluvium	Gula Formation	Marine deposits of estuarine-to-shallow marine, mangrove and beach environment deposited during Holocene. Predominantly silt, sand, clay, gravel and sometimes peat. Well exposed in low lands and coastal areas.
	Beruas Formation	Fluvial origin deposited in a continental environment during the Holocene. Predominantly clay with a lesser amount of sand, gravel, silt and peat.
Old Alluvium	Simpang Formation	Fluvial origin deposited in a continental environment during low sea level during the Pleistocene. Silt, clay, gravel and sand locally with peat. Typically occurring above bedrock or boulder beds which are basal deposits of very coarse gravel.

3 SEISMOTECTONIC SETTINGS

Peninsular Malaysia is situated on stable Sundaland which is located at the zone of convergence between the Indian–Australian, Philippine and Eurasian plates. It is surrounded by tectonically active and complex convergent boundaries below which the Indo-Australian plate is being subducted under the Eurasian Plate along the Sunda Trench. Since Penang Island is tectonically part of the Peninsular Malaysia, the same regional tectonic settings also apply to the island.

The zone where these two tectonic plates are converging is called the Sumatran Subduction Zone (SSZ) which is very active and accounts for most of the megathrust earthquakes in the area. The other far-field source is the Sumatra Fault Zone (SFZ), an approximately 1900 km long trench-parallel dextral strike-slip fault running in a northwest-southeast direction, accommodating an oblique convergence along the plate boundaries. SF transverses the hanging wall of SSZ along its entire length (Sieh and Natawidjaja, 2000). The fault can trigger lower magnitude earthquakes because of its highly segmented structure with irregularities along its length, producing earthquakes with rupture lengths of approximately one hundred kilometres.

The majority of earthquakes affecting Peninsular Malaysia and Penang Island are large-magnitude far-field events triggered at the SSZ and SFZ. The closest distance to a potential earthquake epicentre is over 300 km from the Peninsula. The 2004 earthquake and the 2005 Nias earthquakes were approximately 540 km and 490 km, respectively, from the Island.

Major intraplate faults and some minor faults, located within the Peninsular Malaysia, run mostly in northerly-southerly direction. The earthquake records from local intraplate events are scarce and sporadic (Looi et al., 2018). Recent studies using GPS and remote sensing technology suggest that there has been distortion of plates due to intraplate stress build up in the north west part of the Peninsula (Shariff et al., 2014) following the mega earthquakes which may have activated the major local faults. However, a quantitative review of intraplate faults which may trigger near-field earthquakes of M>5 is still lacking.

The closest fault, the intraplate Baubak fault, is approximately 80 km from the island. The authors could not find any studies suggesting that this fault can trigger any earthquakes. The 80 km-long Bukit Tinggi fault is located approximately 200 km west of the island. No records were found suggesting that 2007-2008 small events triggered by this fault were felt in Penang Island.

The earthquakes from subduction zone, as mentioned in section 1, were all felt in the Island. USGS's ShakeMap and descriptions from locals suggest that the likely intensity observed on Penang Island appears to MMI<IV rather than typically reported VI.

Although the earthquake was felt in high-rise buildings by the public, there were no records of earthquake damage in the Island or Malaysian Peninsula.

The recorded peak ground acceleration (PGA) values at a station (KUM on Type B rock site) located in the Peninsula but relatively close to the island are small, e.g. 0.0080 m/s^2 for the 2004 earthquake and 0.0117 m/s^2 for the 2009 earthquake (Shoustari et al., 2015). The PGA values should be similar to what would have been recorded on the island with expected modification of the acceleration levels on soft/loose soil sites at the island.

4 MALAYSIAN SEISMIC CODE

Malaysia adopted Eurocode 8 for the design of structures for earthquake resistance. The draft Malaysian national annex (NA) to Eurocode 8 (NA-2017 to MS EN 1998-1:2015) includes a seismic hazard map indicating probabilistic PGA for a 475 year return period of seismic action for the no-collapse requirement based on probabilistic seismic hazard analysis (PSHA). This map recommends a PGA of 0.03g to 0.04g for Penang Island.

Malaysian NA uses the same elastic response spectrum as in Eurocode 8 with different corner frequencies. The ground type classification uses the same letter format, but it depends on the natural period of the site rather than $v_{s,30}$. For sites with deep geology (i.e. more than 30 m of sedimentation), different elastic spectrum is proposed.

5 LOCAL GROUND CONDITIONS

It is well known that local site conditions can lead to amplification and resonances of the strong ground motion as seismic waves propagate, near vertically, from the bedrock to the ground surface. The composition, thickness, stratification, stiffness and strength of alluvial deposits are the main factors affecting the amplification of the ground motion. Topography effects such as irregularities of the surface topography in addition to geometry of deep basins can also modify the ground motion.

In order to assess the impact of local site conditions on Penang Island, the authors carried out a literature and geotechnical database review.

5.1 Literature review

There are very few and reliable published works on the ground conditions of the island. Tan et al. (2014) undertook surface wave tests to determine the shallow shear wave velocity structure of the island, indicating lowest shear wave velocities on the Quaternary deposits of the west of the island. However, because of lack of areal coverage of field testing (particularly in highly populated coastal zones, Georgetown and the central west) their site characterisation based on $v_{s,30}$ gives crude areal interpretation with sometimes surprising $v_{s,30}$ values. Nevertheless, $v_{s,30}$ ranges indicate that the ground type in the island soil is typically Type B as per the Malaysian NA (areas with residual soil overlying possibly completely/highly weathered granite within the top 30 m and possibly Old Alluvium) and Type C (areas with Quaternary deposits but also surprisingly including areas which possibly include residual soil of unknown thickness). The authors No Type E soils were noted in the literature.

The logs of on- and off-shore boreholes carried out for the Second Penang Crossing indicated up to 105 m thick sediments overlying granitic bedrock between the Island and the Peninsula. The sediments comprise up to 24 m thick of very soft to soft marine clay (locally up to 38 m thick) overlying locally loose, typically medium dense becoming very dense sand of approximately 40 m (locally up to 65 m containing intermittent clay zones of up to 2 m).

On-shore and off-shore borehole shear wave velocity measurements undertaken for the same project show unexpectedly high values (130 m/s to 180 m/s) within the very soft mud/clay although average values derived from SPT N blow count numbers suggests v_s<80 m/s.

5.2 *Local ground investigation database*

The authors' assessment of stratigraphy along a north (Georgetown) to south (Teluk Kumbar) section (see solid line in Figure 2) show that the thickness of Alluvium is a minimum of 90 m at the North and at least 15 m over completely to moderately weathered granite throughout (Figure 4). The soil classification in the figure indicates predominant constituents only. In deeper alluvial zones the top 10 m to 20 m is typically very soft/soft to firm, becoming stiff when it overlies the predominantly coarse-grained soils. When it underlies the coarse-grained soils it is generally stiff. Similarly, the coarse-grained material (mainly sands) below ground level is generally loose within the top 5 m becoming medium dense with depth. The stratum with SPT N>50 is classified as very dense/hard in Figure 4. It predominantly consists of silty or gravelly sand or, to a lesser extent, sandy and gravelly silts and clays. These observations may conclude ground type typically Type B and C.

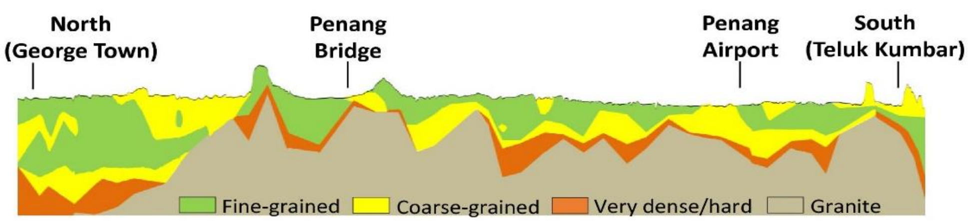

Figure 4. North-south stratigraphy (more than 15 km long) along the east coast of the island (distorted to fit). Location are indicative and do not necessarily represent borehole locations

The section shows 10 m to 15 m thick deposits over the areas where the geology map indicates granite. Such areas can be considered as Type A ground. Figure 4 indicates that there is substantially thicker very soft to soft marine deposits onshore. There is no information indicating that a similar thickness is encountered at the south and the north of the island where major reclamation works were proposed.

6 SEISMIC HAZARDS

A discussion on seismic hazards on the island is provided below.

6.1 *Seismic hazard analysis*

For PSHA both the area and background source modelling approach was adopted such that random earthquakes without mapped faults and small earthquakes with mapped faults were represented in the model (Shoushtari et al., 2018). However, there are insufficient studies on intraplate faults in Malaysian Peninsula. Compared with the measured low acceleration values at rock sites in the Peninsula (Section 3), the PGA values in the Malaysian National Annex demonstrate a degree of conservatism. Low seismic activity and a small number of events by interpolated faults might have resulted in large uncertainties in ground motion prediction equations. This is due to difficulties in identifying and characterising near-field seismic sources (Ake, 2008). This risk awareness related to areas with low intraplate seismicity (Shoushtari et al., 2018) possibly has affected the design response spectrum at low periods in the (draft) Malaysian National Annex. Considering no structural damage was reported on the Island, it can be assumed that the well designed and built engineered structures had sustained earthquake loads from recent far-field earthquakes without code ductility requirements.

6.2 Site response

The 1985 Michoacan earthquake resulted in severe amplification of the ground motion when it reached Mexico City. This very well-known earthquake has been cited by many researcher in Malaysia in order to emphasise the likelihood of ground motion amplication from far-field earthquakes (e.g. Tan el al., 2014; Shoushtari et al., 2015). However, the current research findings demonstrated unique conditions in Mexico City: anomalously high energy (at around the period of 2 sec) and very long duration of shaking, amplification at longer periods due to the very long natural period of lake deposits underlying Mexico City and unique (high moisture content, very low v_s and damping) soil properties (e.g. Singh et al., 1988). For the Island, local site conditions (despite the presence of marine deposits onshore) are, by and large, not similar to those present in Mexico City. Without further research, suggestions of major far-field events causing a similar site response in Malaysia are considered to be unfounded. However, ground motion amplification is expected through the Alluvium deposits on the Island. Particularly for structures in reclaimed areas site response analysis may need to be undertaken.

6.2.1 Liquefaction hazard

No liquefaction evidence was reported during the strong earthquakes of 2004 and 2005 in Peninsular Malaysia. It is known that saturated loose Holocene predominantly coarse-grained soils are usually more susceptible to liquefaction. Based on borehole log descriptions, particle size distributions and SPT N values, there are soil zones in the island which match the criteria for liquefaction potential. However, historical liquefaction effects are limited by epicentral distance and moment magnitude (Ambraseys, 1988). For a typical epicentral distance between a far-field event and Penang Island being greater than 350 km, likelihood of liquefaction is very small and limited by very large earthquake events. There is uncertainty of probability of occurrence on intraplate earthquakes in the Peninsula with sufficient magnitude to cause liquefaction. However, at epicental distances greater than 100 km to the Island, the likelihood of liquefaction by small-to-medium magnitude intraplate earthquakes is also considered to be very small. However, a site-specific desk study to evaluate the risk of liquefaction should be carried out for high rise buildings or structures for greater ‘Importance Factors’ as per Eurocode 8.

6.3 Coseismic landslide and tsunami

Although landslides within residual soils are common on the Island, there are no reported seismically induced landslides. Considering earthquake main sources being far-field the likelihood of such landslides can be considered very low. Near-field earthquakes with M>5 may lead to landslides but there is further research needed to assess the risk.

Tsunamis which can be caused by a very large far-field earthquake appear to be the main seismic hazard on the Island. Establishing a tsunami early warning system (TWS) appears be the most cost-efficient mitigation measure.

7 CONCLUSION

A desk study summary to assess the valid seismic hazard risks for Penang Island by reviewing published geological, geotechnical and seismotectonic information together with our expeirence in local geology is presented. For any major civil engineering works in the island, regardless of low seismicity consideration, it is strongly recommended that a detailed desk study should be carried out to assess seismic hazard.

8 ACKNOWLEDGEMENT

Support to prepare this manuscript was provided by a grant through Tony Gee and Partners Technical Development Programme.

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