Implication of Soil-Structure Interaction on Deteriorate Existing Frames in Penang

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Abstract. Soil-structure interaction (SSI) is often disregarded to reduce difficulties in analyses. Thus, most of analyses adopted rigid foundation despite ignoring SSI could lead to inaccurate response. Current study investigates the influence of SSI on low- to medium-rise existing frames considering non-seismic loading. A multichannel analysis of surface wave (MASW) is performed at several locations in Penang to obtain shear wave velocity of local site conditions. The frames are modelled with rigid and flexible (soil flexibility) and analyzed using nonlinear static analysis. Each of the frames is subjected with seismic zone factor to predict the seismic response using Acceleration-Displacement Response Spectra (ADRS) concept. A flexible base elongated the period mainly under soft soil (soil E), increasing by up to 6.27%, 9.44%, and 4.12% for 3-, 6-, and 16-story frames, respectively. The frames that considered SSI experienced degradation of their capacity curve, strength, and stiffness. Under a dissimilar seismic zone factor, low-story frames achieved high demand, whereas high-story frames delivered maximum displacement is observed.

1. Introduction

Earthquakes may cause damages within a 100–200 km radius from the epicenter [1]. A high intensity earthquake, such as the one that occurred in Mexico in 1985, may deliver an impact of up to 700 km [2]. Malaysia is situated close to two of the most seismically active plate boundaries, namely, the inter-plate boundary between the Indian-Australian and Eurasian-Sunda plate on the west and the inter-plate boundary between the Eurasian and Philippines-Pacific plate on the east. Omar and Jhonny [3] revealed that Peninsular Malaysia has been experiencing increasing deformation due to earthquake threats since the 2004 Indian-Ocean earthquake. The west coast areas of Peninsular Malaysia (i.e., Penang, Johor Bahru, and Kuala Lumpur) experience far-field earthquakes originating from Sumatra. The two large earthquakes that occurred near Sumatra in 2003 and 2004 created cracks on a few buildings and triggered panic among the people in Penang, even if no casualties were reported [4]. Penang is located at the northern part of the Malaysian west coast and is recognized for its historical buildings, tourist spots, and rapid modern urbanization with second population density growth. It is situated approximately 350 km away from the Sumatra fault and has experienced tremors due to strong far-field earthquakes [4–7]. Therefore, quantitative research on the local geological condition in Penang is necessary to evaluate seismic hazard on the non-seismic existing structures.
Anand and Kumar [8] stated that soil-structure interaction (SSI) is beneficial to seismic response. Ignoring SSI in design practice leads to a conservative design. Design codes either evaluate SSI to reduce overall seismic coefficients or ignore the interaction completely. Studies have shown that analyzing SSI likely increases frame periods. However, SSI has often been omitted to reduce difficulties in analysis. Structures that consider SSI may differ from restrained foundation response [9, 10, 11]. Given the significance of SSI in structural design, SSI is amalgamated in seismic codes. Some codes, such as ATC 40 [12] and FEMA-356 [13], introduce the influence of foundation behavior in terms of stiffness and strength of geotechnical components in a structure. Most studies on SSI are restricted to shallow foundations and surface foundation for simplicity [14]. The foundation characteristics (i.e., the footing size in shallow foundations), pile size, and load bearing mechanism of pile foundations are significant to SSI responses [15, 16]. The importance of site conditions may contribute to different SSI responses [17, 18]. Aydemir [19] examines single degree of freedom (SDOF) founded on stiff and soft soil with the stiffness degrading system delivering various SSI responses. Past studies suggest that superstructure geometry, characteristics of the foundation, soil modulus, and shear wave velocity profile in stratified deposits affect the seismic response [8]. To study SSI, a multichannel analysis of surface wave (MASW) is performed at several locations in Penang to obtain shear wave velocity of local site conditions. Frames founded on fully restrained and flexible (soil flexibility) bases with degrading behavior are analyzed using nonlinear static analysis. The frames are examined under low, medium and high of Seismic Zone Factor to estimate the seismic behavior. The rationale of the study is to determine the importance of SSI effects on the performance of the non-seismic existing frames.

2. Methodology

2.1 Site Selection
Penang consists of two parts, the island and the mainland, with a total area estimated at approximately 1048 km². Penang is abundant with pre-quaternary granite, covered with unconsolidated sand, silt, and clay from the Pleistocene and Holocene Periods. No sedimentary rocks are present, and most of the island lies on a type of granite [20]. To determine the dynamic properties of the soil, a multichannel analysis of surface wave (MASW) was performed in Penang. The MASW apparatus consists of cross-hole test, down-hole test, suspension logging, seismic reflection, seismic refraction, and surface wave or existing layer to access shear wave velocity, as shown in Figure 1. Shear wave velocity is an effective indicator to investigate the physical characteristics of sediments [21, 22]. Shear wave velocity within a 30 m depth, $V_{S30}$, is adopted in several earthquake regions to estimate ground shaking for surficial geology and potential ground motion amplification effect [23]. Three local sites were chosen based on the availability of borehole records for SSI study. Two sites situated at the south-western and north-eastern areas (Lorong Kenari and Bandar Jelutong and one site located on the mainland, Bukit Minyak) are presented in Figure 2. $V_{S30}$ is estimated using Equation (1). The $h_i$ and $v_i$ denote thickness and shear-wave velocity of the $i$ formation or layer, respectively, with a total of $N_{existing}$ at 30 m.

![Figure 1. Shear wave velocity using multichannel analysis of surface wave (MASW)](image-url)
Figure 2. Local site investigation in Penang

\[ V_{s,30} = \frac{30}{\sum \frac{F_i}{\nu_i}} \]  

(1)

2.2 Correlation for Shear Wave Velocity (\(V_s\)) and Standard Penetration Test (Nspt)

Tan et al. [20] conducted a total of 51 field sites using MASW to establish statistical empirical correlations for local site classes in Penang. The current study has adopted correlations by Tan et al. [20] and the Nspt to estimate the three local site classes with the availability of site investigation reports. The empirical correlations of \(V_s\) and standard penetration (Nspt) are correlated using simple regression following Equation (2). The estimated \(V_{s,30}\) correspond to the soil profile and site class referring to UBC [24], as shown in Table 1. For the fixed base, \(V_{s,30} > 1500\) m/s was assumed. For the flexible base, the estimated \(V_{s,30}\) in the range of 179–448 m/s is classified as soil C (very dense soil), soil D (stiff soil), and soil E (soft soil).

\[ V_s = 128.05 N^{0.4081} (r^2 = 0.73), \text{ for Class C} \]
\[ V_s = 128.71 N^{0.2833} (r^2 = 0.65), \text{ for Class D} \]
\[ V_s = 101.34 N^{0.2364} (r^2 = 0.83), \text{ for Class E} \]  

(2)

| Site Class | Soil Profile Name | Parameters | Estimation |
|-----------|------------------|------------|------------|
| Site Class | \(V_{s,30}\) (m/s) | \(V_{s,30}\) (m/s) |
| A          | Hard Rock        | > 1500     | >1500      |
| B          | Rock             | 760-1500   | N/A        |
| C          | Very Dense Soil  | 360-760    | 448        |
|            | and Soft Rock    |            |            |
| D          | Stiff Soil       | 180-360    | 271        |
| E          | Soft Soil        | < 180      | 179        |

Table 1. Site Class Definitions [24]
2.3 Modeling Reinforced Concrete Frames

This paper examines non-seismic existing reinforced concrete (RC) denotes low- to medium-rise frames in two-dimensional (2D) models under SSI effects. In 3-story frames, the structural plan and elevation (with a setback) are irregular. The frame consists of four bays with an estimated total length span of 16.9 m, and the height of the frame is 10.2 m. A 6-story frame is symmetrical in plan and elevation. The estimated total length span is 18.2 m consisting of five bays with a total height of 18 m. On the other hand, a 16-story frame is regular in plan with a ground opening. The frame height is equal to 45.48 m and consists of three bays with a total length span of approximately 18.3 m. Details of the frames are presented Figure 3 and Table 2. The concrete strength for each frame is 24 MPa with yield for longitudinal and transverse reinforcement assumed to be 500 MPa. The strength for the main reinforcement and stirrup are 460 and 250 N/mm², respectively. Each frame adopted gravity loading designed according to EC2 [25], a typical design used in Malaysia. The estimated gravity loading for a 3-story frame is 35kN/m on the first floor, 23kN/m on the second floor, and 19kN/m on the third floor. For a 6-story frame, gravity loading on the outer bay (left), intermediate bay, and outer bay (right) consist of 44.5kN/m, 1.9kN/m, and 15.5kN/m, respectively. For a 16-story frame, the estimated gravity loading on the outer bay and intermediate bay is 29.44kN/m and 4.84kN/m, respectively. For the foundation, the frames are analyzed using fixed and spring supports signifying hard soil, soil C, soil D, and soil E. The analysis option of the models is set into a XZ plane when 2D frames are considered. The mass source of the frame was defined as an element with additional masses and diaphragms assigned on the floor systems.

Figure 3. Low to medium rise existing RC frames
### Table 2a. Section dimensions of RC for 3-storey frames

| Frame  | Floor   | Beam | A   | B   | C   | D   |
|--------|---------|------|-----|-----|-----|-----|
|        | 3rd floor |      | (230 x 600) | (230 x 600) | (230 x 600) | 2012 | 2012 | 2012 | -   |
|        |          |      | 2012 | 2016 | 2016 |     |     |     |     |
|        | 2nd floor |      | (230 x 600) | (230 x 600) | (230 x 600) | 2012 | 2016 | 2016 |     |
|        |          |      | 2025 | 2016 | 2016 |     |     |     |     |
| 3-story| 1st floor |      | (230 x 600) | (230 x 600) | (230 x 600) | 2012 | 2016 | 2016 | 2012 |
|        |          |      | 2025 | 2016 | 2016 |     |     |     | 2025 |

#### Floor Column

| Floor   | Column |
|---------|--------|
| 3rd floor | 1 | 2-4 | 5 |
|          | (230 x 300) | (230 x 300) | 4012 | 4012 |
| 2nd floor | (230 x 600) | (230 x 450) | 8012 | 6016 |
| 1st floor | (230 x 600) | (230 x 450) | 8012 | 8012 |

### Table 2b. Section dimensions of RC for 6-storey frames

| Frame   | Floor   | Beam | A   | B   | C   | D   | E   |
|---------|---------|------|-----|-----|-----|-----|-----|
| 2nd - 6th floor |          |      | (230 x 600) | (230 x 600) | (125 x 600) | (230 x 600) | (230 x 600) |
|          | 2012 | 2012 | 2012 | 2016 | 2016 | 2025 |     |
|          | 2016 | 2012 | 2012 | 2016 | 2016 | 2025 | 2025 |
| 1st floor | (230 x 600) | (230 x 600) | (125 x 450) | (230 x 600) | (230 x 600) |     |
|          | 2012 | 2020 | 2012 | 2020 | 2020 | 2016 | 4025 |
|          | 4025 | 2012 | 2012 | 2012 | 2012 | 4025 |     |

#### 6-story Floor Column

| Floor   | Column |
|---------|--------|
| 2nd - 6th floor | 1 | 2-4 | 5 |
|          | (230 x 450) | (230 x 600) | (230 x 300) | (230 x 600) | (230 x 600) | (230 x 600) |
|          | 6020 | 8020 | 6016 | 10025 | 8020 |     |
| 1st floor | (230 x 600) | (230 x 850) | (230 x 450) | (230 x 1000) | (230 x 850) |     |
|          | 10025 | 16025 | 8025 | 1025 | 12025 |     |
Table 2c. Section dimensions of RC for 6-storey

| Frame     | Floor       | Beam          |          |          |          |
|-----------|---------------|---------------|----------|----------|----------|
|           |             | A             | B        | C        |          |
| 16th floor| 16th floor  | (125 x 450)   | 2016     | 2025     | 2016     |
|           | 16th floor  | (125 x 600)   | 2016     | 2025     | 2016     |
|           | 16th floor  | (125 x 700)   | 2016     | 2025     |          |
| 2nd-15th  | 2nd-15th    | (125 x 450)   | 2020     | 2020     | 2020     |
| floor     | floor       | (125 x 600)   | 2020     | 2020     | 2020     |
| 1st floor  | 1st floor   | (125 x 700)   | 2020     | 2020     | 2020     |
| 16-story   | 1st floor   | 4020          | 4020     | 4020     |          |
| Floor 1   | Floor 2-3   | Column        |          |          |          |
| 14th-16th | Floor 2-3   | (300 x 300)   | 4016     | 8016     | 4016     |
| floor     | Floor 2-3   | (300 x 700)   |          |          |          |
| 13th-11th | Floor 2-3   | (300 x 375)   | 8020     | 14016    | 8020     |
| floor     | Floor 2-3   | (300 x 800)   |          |          |          |
| 8th-10th  | Floor 2-3   | (300 x 450)   | 8025     | 16020    | 8025     |
| floor     | Floor 2-3   | (300 x 900)   |          |          |          |
| 5th-7th   | Floor 2-3   | (300 x 525)   | 10025    | 18025    | 10025    |
| floor     | Floor 2-3   | (300 x 1000)  |          |          |          |
| 1st-4th   | Floor 2-3   | (300 x 600)   | 10025    | 025      | 10025    |
| floor     | Floor 2-3   | (300 x 1100)  |          |          |          |

2.4 Modeling Soil-Structure Interaction
A flexible base (SSI) is performed using direct analysis and a substructure approach referring to FEMA-356 [13]. An uncoupled spring model is employed to denote the stiffness of a pile foundation where the footing represents the pile cap with respect to the size and type of the foundation presented in Figure 4. Hence, the present study defines the flexibility of soil using translation in horizontal, vertical and rotational flexibilities.

![Figure 4](image)

Figure 4. Modeling soil according to FEMA-356[13]; (a) Uncoupled spring model for rigid footing, (b) Notation description for the pile cap (spring stiffness)

2.5 Degrading Frame Behavior
Moment-rotation relationship can be modeled using a bi-linear or tri-linear relationship [26] to develop an adequate structural model before strength deterioration. However, a tri-linear moment-rotation relationship of plastic hinge property seems to be more appropriate for the stimulation of low displacement demand [27]. Thus, tri-linear moment-rotation is adopted on the beams and columns in
the current study. CR is the cracking point of the concrete. Y is the yielding of the reinforcement. M is the maximum moment. NC is the near collapse limit state of the structure presented in Figure 5.

![Figure 5](image)

**Figure 5.** (a) Bi-linear moment-rotation relationship with softening and (b) tri-linear [27]

### 2.6 Acceleration-Displacement Response Spectra (ADRS)

This study utilizes the Acceleration-Displacement Response Spectra (ADRS) concept using pushover analysis in terms of capacity spectrum incorporated with a response spectrum. The ADRS concept allows the comparison of the structure capacity corresponding with demands (in the form of response spectra) from the intersection of the two curves approximates [12]. The performance point is attained based on the structural performance at a given seismic demand. The ADRS represents a plot of spectral acceleration versus spectral displacement (Sa vs. Sd). In addition, a reduction factor of 5% damping is applied on an elastic spectrum (i.e., reduced demand) for hysteretic energy dissipation.

### 3. Results and Discussions

#### 3.1 Capacity Curves

Figure 6 shows that the performance of the frames founded dissimilar soils delivers diverse capacity curve under dissimilar frame height and geometry. For low rise frames, a 3-story frame conveys high post-yield stiffness, whereas the capacity curve for a 6-story frame is abbreviated. The capacity curve for a 16-story frame is lower in terms of spectral acceleration with respect to a higher mode. Flexible base particularly in soil E is more likely to experience reduction of capacity curves at approximately −4.87% and −12.17% for 3- and 6-story frames, respectively. However, the capacity curves for 16-story frames under fixed and flexible bases are more likely to overlay. The comparison between fixed and flexible bases indicate that fundamental periods elongate under soil flexibility mainly for soft soil (soil E), as shown in Figure 7. The differences of frame periods between soil E with a fixed base intensifies up to 6.27%, 9.44%, and 4.12% for 3-, 6-, and 12-story frame, respectively. Furthermore, due to the influence of SSI, plastic hinge deforms from Immediate Occupancy (IO) to Collapse Prevention (CP) state mainly for 3-story frame. In this study, the frames evidently experience degradation of capacity, strength, and stiffness because of SSI effects compared with a fully restrained base.
3.2 Seismic Zone Factor, Z

The current study examines the performance of non-seismic existing frames considering SSI under Seismic Zone Factor (Z) effects presented in Figure 8. Frames are subjected with seismic zone factor intensity equal to 0.075, 0.2, and 0.4 which signifies low, medium, and high seismic zone factors, respectively. The present study has discovered that the intensity of seismic zones controls the demand with respect to soil conditions, frame height and geometry. Moreover, the reduced demand can be easily influenced under the seismic zone which contributes to the performance of the frames. Overall, the estimated demand and capacity corresponding with performance points are below 1 and 0.1, with low frames achieving high demand and high story frames delivering maximum displacement.
4. Conclusions
This paper examines the performance of existing non-seismic RC frames of local site conditions using multichannel analysis of surface wave (MASW). Frames consisting of 3-, 6-, and 16-story frames modeled in 2D are analyzed using nonlinear static analysis considering SSI in reference to FEMA-356. Comparison between fixed and flexible bases indicate that fundamental periods elongate under soil flexibility mainly for soft soil (soil E), increasing up to 6.27%, 9.44%, and 4.12% for 3-, 6-, and 12-story frames, respectively. A flexible base, particularly soil E, is more likely to experience reduction of capacity curves at approximately \(-4.87\%\) and \(-12.17\%\) for 3- and 6-story frames, respectively. For 16-story frames, fixed and flexible bases deliver a more likely overlay for capacity curves. Frames considering SSI effects tend to experience degradation of capacity, strength and stiffness compared with a fully restrained base. Under dissimilar seismic zone factors, low frames achieve high demand, whereas high story frames deliver maximum displacement with respects to SSI. The SSI procedure is outlined to emphasize the effect of SSI on the frame using simplicity and practical ADRS method through accuracy.

Figure 8. Predicted performance point of 3-story frame under seismic zone factor
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