Seismic ground motion induced lateral earth pressures on basement walls

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Abstract. Research on the dynamic lateral earth pressures acting on basement walls induced by seismic ground motions has appeared in the literature in the last few years to examine the apparent inconsistency between the theoretical pressures and the pressures suggested by basement wall good performance of during large earthquakes. This inconsistency suggested that the current methods would yield excessive lateral earth pressures. In this paper, a two dimensional plane strain finite element model of a 2-story concrete basement wall was used to examine the dynamic lateral earth pressures. The seismic ground motion was the N-S component of the 1992 Erzincan earthquake motion record. The assumed soil profile was a sands deposit overlying a reflecting bedrock layer. The observed time history outputs were the wall acceleration in horizontal direction, the lateral earth pressures, and the associated lateral thrust. The outputs were examined further to evaluate the amplification of wall acceleration, the different time history pattern of wall acceleration and lateral thrust, the influence of limiting soil tensile strength, the time difference for peak wall acceleration and peak lateral thrust, and a discussion on phase difference. The results suggested that the complex interaction could not be represented by typical simple peak input acceleration – soil pressure relationships.

1. Introduction
Basement walls are to be designed against the increase in the lateral earth pressures induced by seismic ground motions, as required by the Indonesia seismic building code [1]. Although the code does not require any specific estimation methods, many design estimation methods can be found in the literature (e.g., [2]). It is noted that the typical estimation methods are based on relatively simple peak input acceleration – soil pressure relationships. At the international level in recent years (e.g., [2-6]), basement walls appeared to perform well during relatively larger-than-expected earthquakes. This observation has raised a major concern, not about the actual good performance, but about the apparent over-designed nature of the current estimation methods. This over-designed nature might consequently lead to unnecessary construction costs.

Sitar and his colleagues (e.g., [2, 4]) have shown through a series of laboratory tests and numerical studies that the actual lateral earth pressures induced by seismic ground motions were not as high as those estimated by the current estimation methods. Prakoso and his colleagues have built upon this suggestion by conducting a series of numerical analyses. Winner and Prakoso [5] found that, for basement structures without embedded walls, the peak value and frequency of the input acceleration would affect the earth pressures and wall bending moments. The limiting soil tensile strength provided by the soil cohesion would also affect the lateral pressures, but it would not have a significant effect on the wall bending moments. Prakoso et al. [6] found that the increase in horizontal wall acceleration and
wall pressures was not linearly proportional to the increase in the peak input acceleration, and the embedment wall depths had a minor effect on the wall acceleration and wall pressures. It is noted that [5, 6] employed harmonic ground motions.

The paper objective is to examine numerically further the increase in dynamic lateral earth pressures acting on basement walls due to an actual earthquake ground motion record. This paper is an extension of [6]; the basement considered is a 2-level, 8 m deep basement without any pile foundations typically constructed in Jakarta area. The finite element model used and the case evaluated are described in the beginning, while the horizontal wall acceleration and lateral earth pressures are discussed in the latter part of the paper.

2. Research method
This research assumed that a concrete basement with dimensions of 8 m deep and 18 m wide was constructed in a 25 m thick sands deposit ($\phi = 35^\circ$) overlying a reflecting engineering bedrock. The thickness of the basement concrete wall was 0.6 m, while the embedment depth was 6 m (total wall length 14 m). Two-dimensional, finite element models were used to examine the increased lateral earth pressures as shown as figure 1. The model used fifteen-node triangular finite elements for the soils and concrete walls; the total number of elements was 1,018 elements. To better capture the increased earth pressures and wall bending moments, finer elements were used for the soil directly behind the walls and the basement walls. Beam elements were used to model the basement structural elements (e.g., columns and beams). The Mohr-Coulomb constitutive soil model was used for all the soil elements, while the elastic model was used for basement wall elements and structural elements; details of the soil, wall, and structural element properties were given in [6]. Absorvent boundaries were specified on the both sides of the model to avoid spurious reflection during dynamic analyses, and the Rayleigh damping parameters adopted from [7] was used. The software used was Plaxis 2-D version 8 [8].

The input seismic motion used for this paper was the N-S component of the 1992 Erzincan earthquake motion record [9]. The considered record had a peak ground acceleration of 0.387 g and was 20 second long. The acceleration was applied using the prescribed displacement option at the base of the mesh representing the reflecting engineering bedrock. The number of dynamic calculation steps was 1,000 steps ($\Delta t = 0.02$ s). The dynamic calculation was performed after the static construction phases (excavation of basement, installation of wall and structure). The observed outputs include the lateral earth pressure behind wall and the wall acceleration.

Static and dynamic model verification results were reported in [6]. The static lateral earth pressures behind the basement wall at the end of construction stage were examined. In general, the pressures were about the same as the Rankine active pressures in the upper wall part, then increased to about the same as the at-rest pressure, and subsequently decreased to the Rankine active pressure at the wall tip level. The observed dynamic wall acceleration was compared to the peak input acceleration directly; for lower acceleration values, there was amplification of the ground motions, but for higher values, there was de-amplification of the ground motions, similar to the general trend shown in [10]. It is noted that a related dynamic model verification for a soil retaining system has been given in [11].

Figure 1. Finite element mesh.
3. Results

3.1. Horizontal wall acceleration

The time history of the basement wall acceleration in horizontal direction is shown in figure 2. The time history was monitored at three locations: 0.67 m (about top floor slab level), 4.0 m (middle floor slab level), and 8.0 m (bottom floor slab level). The peak wall acceleration values at these locations (> 0.6 g) were greater than the peak input acceleration (0.387 g). The amplification factors could subsequently be evaluated by calculating the ratio of peak wall acceleration to peak input acceleration; the factors for the three locations were 1.899, 1.658, and 1.570, respectively.

It can be observed clearly that there was a phase difference between the peaks of horizontal wall acceleration as shown in figure 2 (right) for the time window of 2.5 to 5.0 second. For the main peak (t = 3.1 – 3.5 s), the peaks at different depths occurred in slightly different patterns. However, for the subsequent local peaks, the peak at depth of 8.0 m (deepest monitoring point) occurred first, followed subsequently by that at depth of 4.0 m and 0.67 m (shallowest monitoring point). These different observed patterns suggest that, although it was of relatively high stiffness (t = 0.6 m, supported by 3 levels of floor slabs), the basement wall showed rather flexible behavior.

![Figure 2. Horizontal wall acceleration at different depths.](image)

3.2. Lateral earth pressures and thrust

The time history of the resulting dynamic lateral earth pressures (p_{AE}) acting on the basement wall is shown in figure 3. The time history of change in lateral earth pressures (= dynamic lateral earth pressure – static lateral earth pressure, Δp_{AE}) is also calculated and shown in figure 4. Note that a positive pressure is a compressive pressure. The earth pressures were monitored at five depths: 0.85 m (about ground surface level), 1.8 m (about midway between top and middle floor slabs), 4.0 m (middle slab level), 6.2 m (about midway between middle and bottom floor slabs), and 7.9 m (slightly above bottom floor slab). In all observation points, p_{AE} remained in compression due to limited soil tensile strength, consistent with observations reported in [5]. The p_{AE} and Δp_{AE} initially increased with an increase in the input acceleration. However, after the time window of the main peak (t = 3.1 – 3.5 s), p_{AE} and Δp_{AE} only decreased slightly, although the input acceleration was relatively small. Similar behavior was observed in centrifuge tests as reported in [12].

It can be observed clearly that there was a phase difference between the peaks of Δp_{AE} as shown in figure 4 (right) for the time window of 2.5 to 5.0 second. The peaks of Δp_{AE} for depths = 0.8 m and 1.8 m occurred earlier at dynamic time t of about 3.1 s, though at slightly different times. The Δp_{AE} subsequently decreased and then oscillated slightly (average of Δp_{AE}(t=8-20s) = 38.6 kPa and 19.5 kPa, respectively). The peaks of Δp_{AE} for depths = 4.0 m, 6.2 m, and 7.9 m occurred latter at t = 3.8 – 4.0 s,
though again at slightly different times. The $\Delta p_{AE}$ subsequently gradually decreased and then oscillated slightly (average of $\Delta p_{AE}(t=8-20s)$ = 86.2 kPa, 98.3 kPa, and 110.9 kPa, respectively). Furthermore, at times, the local peaks for the shallow observed points occurred when $\Delta p_{AE}$ for the deeper points reached their local minima, and vice versa. This different times for peaks at different depths suggest that the use of pressure envelope might lead to an excessively conservative design.

The $\Delta p_{AE}$ can be integrated to obtain the dynamic lateral thrusts ($P_{AE}$), and figure 5 shows the time history of $P_{AE}$. The general trend of $P_{AE}$ was similar that of $\Delta p_{AE}$; $P_{AE}$ reached its peak (803 kN) at $t$ about 3.8 – 4.0 s, then gradually decreased, and then oscillated slightly (average of $P_{AE}(t=8-20s)$ = 581 kN.

It is of interest to relate the wall acceleration time history to $\Delta p_{AE}$ and $P_{AE}$. It was observed that the time history of the wall acceleration had a different pattern compared to that of $\Delta p_{AE}$ and $P_{AE}$. Furthermore, the main peak of wall acceleration occurred at $t$ = 3.1 – 3.5 s. The main peaks of $\Delta p_{AE}$ for shallow depths occurred at $t$ about 3.1 s, while those for deeper depths occurred at $t$ = 3.8 – 4.0 s. The main peaks of $P_{AE}$ occurred at similar time as $\Delta p_{AE}$ for deeper depths. All these observations suggest a complex dynamic soil-basement interaction which could not be represented by a simple peak input acceleration – soil pressure relationship as found in typical design approaches.

**Figure 3.** Lateral earth pressure acting on basement wall.

**Figure 4.** Change in lateral earth pressure on basement wall.
4. Conclusions
A two dimensional plane strain dynamic finite element model was used to evaluate the wall acceleration and the lateral earth pressures induced by the N-S component of the 1992 Erzincan earthquake motion record. The basement was a 2-story concrete basement. The basement was embedded in a sands deposit overlying an engineering bedrock layer. The highlighted observations are as follows:

- The amplification of horizontal acceleration was observed at different wall depths, and the amplification factors tend to decrease with greater wall depths.
- The time history of wall acceleration had a different general pattern compared to that of $\Delta P_{AE}$ and $P_{AE}$.
- A phase difference was observed in horizontal wall acceleration and $\Delta P_{AE}$. The basement wall behavior was somewhat flexible, although it was of relatively high stiffness.
- The $\Delta P_{AE}$ is affected by the limiting soil tensile strength.
- The time of the peak wall acceleration was different from that of the peak $P_{AE}$.

The above observations suggested that a complex dynamic soil-basement interaction occurred and it apparently could not be represented by a simple peak input acceleration – soil pressure relationship as found in typical design approaches.

Acknowledgment
The authors gratefully acknowledge the partial support provided by Universitas Indonesia through the 2017 PITTA research grant.

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