Analysis the effects of soil-structure interaction on the seismic behaviours of a 5-stories reinforced concrete building with basements

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Abstract. The paper presents analysis results of structural behaviour with and without soil-structure interaction on a five-story reinforced concrete building with basements due to seismic loads. Two numbers of basements were considered namely the building with one basement floor (M1 model) and two basement floors (M2 model). Each of the M1 and M2 model has three variations with and without the soil structure interaction namely the model with the fixed supports (MJ1 and MJ2 models), the model with solid element of the soil (MSo1 and MSo2 models), and the model with lateral soil support of spring elements (MSp1 and MSp2 models). The Soil parameters of modulus elasticity, poisons ratio, reaction modulus and spring stiffness for the MSo and MSp models were obtained from soil investigation. All six models having loads combination of gravity and earthquake loads were analysed using a finite element software package program. All loadings and design codes follow Indonesian codes. Earthquake loads were evaluated using two methods namely equivalent static loads and spectrum response analysis. The results show that the roof-floor displacements of the soil-structure interaction model (MSo and MSp) are greater 2% to 3% than that of the non-soil-structure interaction models (MJ). The roof drift and natural fundamental period of the MSo and MSp models is greater 1% to 2% than that of the MJ model. The axial force of the columns in the MSo and MSp models is less 1% to 3% than the MJ model. The addition of basement floors to the building and modelling with soil structure interactions can minimize the roof floor displacement, the natural fundamental period of the structure, and axial force of the column by 1% to 2%.

1. Introduction

The building structural system in general can be divided into three groups, namely the superstructure above the ground surface, the foundation as the successor of the load from the structure to the ground, and the substructure that is below the soil surface and is known as the basement. Basements are usually used as a vehicle parking lot and put mechanical-electrical equipment such as: Water Treatment Plant, Sewage Treatment Plant, and so on. The position of the basement located underground can affect the behaviour of the superstructure because the basement will receive loads directly from the soil. Furthermore, the modeling of civil building structures generally considers the structure to have support on a non-deformed support. But in reality, the support of the structure which is soil will always be deformed when subjected to the loading due to soil-structure interaction.

Several studies have been conducted to investigate the effects of soil and structure interactions. Lu et al. [1] carried out a nonlinear finite element analysis to study soil behaviour around a structure and
found that there is a permanent lateral displacement of the soil surface after vibration. Hoedajanto and Surono [2] conducted a study on the dynamic behaviour of high tower structures in soft soils and concluded that soil-structure interactions affect the dynamic behaviour of the superstructure. García [3] investigated the effect of soil-structure interaction on the structure of six-story and one basement reinforced concrete building and obtained that the interaction of soil-structure increases the vibration’s period of the structure which approaches the actual behaviour of the structure. Li et al. [4] conducted a study on the effect of soil-structure interaction on the resistance of the collapse of a super high building, namely the Shanghai Tower and concluded that the natural fundamental period of the structure increased significantly and there were several impacts on structural failure due to the influence of soil-structure interaction. Putra [5] investigated the soil-structure interaction in the structure of a five-story reinforced concrete building with a spread footing foundation and found that soil-structure interaction increased roof-floor displacement and natural fundamental period but reduced the internal forces. Numerical analysis of the effect of soil on the collapse of the Hanshin Expressway during the 1995 Kobe earthquake carried out by Mylonakis et al. [6] and found that the frequency of surface movements on site increases the natural fundamental period, influences the collapse of structure and contradicts with the perception of the influence of soil-structure interaction which is always beneficial.

The soil-structure interaction is important to be included in analysing the behaviour of the building structure especially the building with basement floor. This paper compares the analysis results of the behaviour of the five-story reinforced concrete structure of an office building with one and two basement floors with and without considering soil-structure interaction.

2. Literature Review and Methods

2.1. Soil Structure Interaction

The response of a structure to seismic loads is influenced by the interaction between the three connected systems, namely the structure, foundation, and soil around and under the foundation [7]. Earthquake loads cause the ground to move first and then propagate through the foundation to the structure. Hereafter, the structure experiences vibrations so that inertial forces are channelled back into the soil. In this case the soil was deformed due to the building movement. If the soil deformation is considered, it means that it has considered soil-structure interaction in evaluating the structural response.

Some available methods to evaluate the effects of soil-structure interaction can be categorized into direct analysis and substructure approaches. In the direct analysis method, soil and structure are included in the same model and analysed as a complete system. In this approach, the soils can be modelled in finite
element methods and boundary conditions are implemented around the soil. The schematic of the direct analysis method is shown in figure 1. In the indirect analysis or the substructure approaches, the soil-structure interaction effects are partitioned into different parts that are then combined to formulate complete results. The schematic of the substructure approaches is shown in figure 2.

2.2 Elastic properties of soil

Elastic properties of soil in the form of soil modulus of elasticity \( E_{\text{soil}} \), modulus of subgrade reaction \( k_s \), and Poisson's ratio \( \mu \). Modulus of soil elasticity and modulus of subgrade reaction used in this study were taken from the results of soil investigation in the form of \( N \) values from the standard penetration test (SPT). The \( N \) value of the SPT test must be further corrected to consider the energy efficiency of the equipment used and the operator implementing the test. The corrected \( N \) value is then correlated to obtain the modulus of elasticity of the soil by using the equation given by Sosrodarsono & Nakazawa [8].

\[
E_{\text{soil}} = 28.N \tag{1}
\]

where \( E_{\text{soil}} \) is the modulus of soil elasticity in kg/cm\(^2\) and \( N \) is the number of blows from the SPT test. Modulus of subgrade reaction is defined as the ratio between ground stress and deformation or deflection of the soil due to the load. Vesic [9] developed the modulus equation of subgrade as follows.

\[
k_s = \frac{E_{\text{soil}}}{B(1-\mu^2)} \tag{2}
\]

where \( k_s \) is the subgrade reaction coefficient in kg/cm\(^3\), \( E_{\text{soil}} \) is the modulus of soil elasticity in kg/cm\(^2\), \( B \) is the foundation width in centimetre, and \( \mu \) is the Poisson's ratio. The value of subgrade reaction coefficient \( k_s \) is correlated in modelling as stiffness of spring element to represent lateral soil bearing capacity. The basis of this modelling theory is that the foundation is above an elastic medium, where the foundation is influenced by the stiffness of the soil beneath it. Gazetas [10] provides an equation for calculating the spring stiffness in the \( x, y \) and \( z \) directions of \( x, y \), on the shallow foundation above the soil surface as follows.

\[
K_{z,\text{sur}} = \frac{2GL}{1-\mu} \left[ 0.73 + 1.54 \left( \frac{B}{L} \right)^{0.75} \right] \tag{3}
\]

\[
K_{y,\text{sur}} = \frac{2GL}{2-\mu} \left[ 2 + 2.50 \left( \frac{B}{L} \right)^{0.85} \right] \tag{4}
\]

\[
K_{x,\text{sur}} = K_{y,\text{sur}} - \frac{0.2}{0.75 - \mu} GL \left[ 1 - \left( \frac{B}{L} \right) \right] \tag{5}
\]

For foundations that are in the soil as deep as a certain depth, the values of \( K_{z,\text{sur}}, K_{y,\text{sur}}, \text{dan} \ K_{x,\text{sur}} \) are then multiplied by the correction factor given by Gazetas [10] as follows.

\[
K_{z,\text{emb}} = K_{z,\text{sur}} \left[ 1 + \frac{D}{21B} \left( 1 + 1.3 \left( \frac{B}{L} \right) \right) \left[ 1 + 0.2 \left( \frac{A_w}{4BL} \right)^{2/3} \right] \right] \tag{6}
\]
where \( K_{sur} \) is spring stiffness above the ground surface (kN/m), \( K_{emb} \) is the stiffness of spring in the ground (kN/m), \( G \) is the shear modulus (kN/m²), \( B \) is \( \frac{1}{2} \) the width of the foundation (m), \( L \) is \( \frac{1}{2} \) the length of the foundation (m), \( \mu \) is the Poisson's ratio, \( D \) is the depth of the foundation of the subgrade (m), \( A_w \) is the area of the foundation side contact with the ground (m²) i.e. the thickness of the foundation \( (d_w) \times \) perimeter of foundation, and \( z_w \) is distance of the center point of the foundation from the ground face (m).

Poisson's ratio \( (\mu) \) is the elasticity constant that is possessed by each material which is defined as the ratio of the lateral strain to the longitudinal stress produced by a stress occurring. A proper Poisson's ratio value in partially saturated soils is 0.40 [11]. NIST and NEHRP [7] give \( \mu \) values in general for sand is 0.30 and for clay is 0.45.

2.3 Structure properties and model

In this study, the superstructure of all models are based on properties of a five-story reinforced concrete structure for an office building which were first designed properly a ductile moment frames according to Indonesian concrete code [12] to withstand gravity and earthquake loads calculated according to [13] and [14], respectively. The basic model (Model M0) has fixed supports at the ground and no basement floors. Once the upper structure of Model M0 obtained, then the structural model was expanded to add one and two basement floors (MJ1 and MJ2 Models). To include the effect of soil-structure interactions, two approaches for modelling the soil are considered such as modelling the soil as solid element (MS01 and MS02 models) and modelling the soil as equivalent spring element (MSp1 and MSp2 models). Solid and spring models are used in accordance with the theory of approximation methods to evaluate the effects of soil-structure interaction, namely the direct analysis and the substructure approaches.

### Table 1. Soil elastic properties

| No | Soil description   | Soil depth (m) | \( N_{(60)} \) SPT | \( E_{soil} \) (kg/cm²) | \( \mu \) |
|----|--------------------|----------------|---------------------|--------------------------|----------|
| 1  | Silty clay         | 0.0 - 2.5      | 2                   | 56                       | 0.45     |
| 2  | Sandy rock         | 2.5 - 4.0      | 51                  | 1428                     | 0.40     |
| 3  | Sandy rock         | 4.0 - 6.0      | 46                  | 1288                     | 0.40     |
| 4  | Sandy rock         | 6.0 - 8.0      | 44                  | 1232                     | 0.40     |
| 5  | Sandy rock         | 8.0 - 10.0     | 34                  | 952                      | 0.40     |
| 6  | Sandy rock         | 10.0 - 12.0    | 36                  | 1008                     | 0.40     |
| 7  | Sandy rock         | 12.0 - 14.0    | 33                  | 924                      | 0.40     |
| 8  | Sandy rock         | 14.0 - 15.0    | 30                  | 840                      | 0.40     |

The concrete properties used in the structural models have a compressive strength and elastic modulus of 30 MPa and 25.74 MPa, respectively. The yield strength of the longitudinal and transversal rebars is 400 MPa and 240 MPa, respectively, with elastic modulus of 200 GPa. The members structural dimensions are 600 x 600 mm for columns, 400 x 650 mm for floor main beams, 350x550mm for roof main beams and 300 x 450mm for floor and roof secondary beams. The floor and roof slab thickness are 120mm and 100mm, respectively. All basement walls are 300 mm.
The structure is a ductile reinforced concrete frame having a regular plan with floor-to-floor height of 3500 mm. Figure 3 shows the structure plan and figure 4 and 5 are the structural sections for the models with one floor basement (M1) and two floors basement (M2) respectively. Two analysis methods were considered for earthquake loads namely equivalent static and dynamic response spectrum.

The soil properties used in this study were taken based on the results of the soil investigation conducted by the Soil Mechanics Laboratory, Civil Engineering Department of Udayana University for Canggu area, Badung, Bali with a medium (SD) site class. For the results of soil investigations correlated to obtain the value of soil elastic properties in the form of N SPT values, modulus of soil elasticity and Poisson's ratio are shown in table 1.

2.4 Modelling procedures
The superstructure of the five-story reinforced concrete building is modelled with fixed support (M0 model). The loadings consist of gravity load and seismic load. The seismic loads are analysed with two methods namely equivalent static and spectrum response. In accordance with Indonesian earthquake code [14] the minimum dynamic base shear is 0.85 of the equivalent static base shear.

After the M0 model meet the design requirements, the model were expanded to be a one basement floor (M1) and a two basement floors (M2). The structural models without soil-structure interaction are
considered with fixed support (MJ1 and MJ2 models). The basement wall is modelled with shell elements and given a lateral soil pressure according to the results of calculations as shown in table 2.

Table 2. Result of lateral soil pressure calculation

| No  | Wall depth (m) | Active lateral soil pressure, $\sigma_a$ (kN/m$^2$) |
|-----|----------------|-----------------------------------------------|
| 1   | 0.00 – 1.99    | 0.000                                         |
| 2   | 1.99 – 2.50    | 8.083                                         |
| 3   | 2.50 – 3.00    | 25.110                                        |
| 4   | 3.00 – 3.50    | 29.295                                        |
| 5   | 3.50 – 4.00    | 33.480                                        |
| 6   | 4.00 – 4.50    | 37.665                                        |
| 7   | 4.50 – 5.00    | 41.850                                        |
| 8   | 5.00 – 5.50    | 46.035                                        |
| 9   | 5.50 – 6.00    | 50.220                                        |
| 10  | 6.00 – 6.50    | 54.405                                        |
| 11  | 6.50 – 7.00    | 58.590                                        |

The model with soil-structure interaction was modelled by two methods; those are solid elements (MSo1 and MSo2 models) and spring elements (MSp1 and MSp2 models). In these four models the foundation was modelled directly and the shallow footing foundation were used with dimensions of 2.5 x 2.5 x 0.6 m with 1 m depth (D) below the basement slab. The column foundation was modelled using frame elements and spread footing uses shell elements.

Table 3. Modulus of subgrade reaction values.

| No  | Soil description | Soil depth (m) | Value of ks (kg/cm$^3$) |
|-----|------------------|----------------|-------------------------|
| 1   | Silty Clay       | 0.0 - 2.5      | 0.28                    |
| 2   | Sandy Rock       | 2.5 - 4.0      | 11.33                   |
| 3   | Sandy Rock       | 4.0 - 6.0      | 7.67                    |
| 4   | Sandy Rock       | 6.0 - 8.0      | 7.33                    |

Table 4. Values of spring foundation stiffness.

| Model    | $D$ (m) | $K_x$ (kN/m) | $K_y$ (kN/m) | $K_z$ (kN/m) |
|----------|---------|--------------|--------------|--------------|
| MSp1     | 4.50    | 614,044,29   | 614,044,29   | 554,562,22   |
| MSp2     | 8.00    | 587,346,71   | 587,346,71   | 530,452,73   |

In the MSo1 and MSo2 models, the modulus of soil elasticity and Poisson's ratio are needed as shown in table 1. The soil material was assumed to be massless. The length and width of the soil to be modelled was 1.5 times the radius of the building foundation for the length of the soil towards x and y direction, which is 30 meters from the edge of the building parallel to the longitudinal direction of the building and 13.5 meters from the edge of the building parallel to the shortening direction building. In the model given the boundary condition at the lowest depth is the joint, which is not allowed to deform in z direction and translate horizontally in the direction of x and y. Whereas the soil boundary conditions in the x and y directions are the basis of rollers [15].
In MSp1 and MSp2 models the lateral soil support is modelled as a spring element. The spring stiffness value is related to the modulus of subgrade reaction in accordance with equation (2) for basement walls and slabs as shown in table 3. The results of multiplication between \( k_s \) and tributary area of the wall and basement floor can be obtained lateral spring stiffness \( K \). As for the shallow footing foundation has the value of spring stiffness in accordance with equation (3) through equation (8) and the results of the calculation are shown in table 4.

3. Results and Discussion

3.1. Comparison lateral floor displacements and drifts

Comparison of floor displacements and drifts are done using a combination of equivalent static earthquake load and dynamic spectrum response in X direction. With each story level height is 3.5 meters, the analysed displacement must not be more than the inter-floor permit displacement according to [14] that is equal to 0.020 x 3500 mm = 70 mm. The value of the floor displacements and the drifts in X-direction due to equivalent static base shear (Sx) and due to the dynamic base shear (Dx) on the M1 and M2 models are shown in figure 6 to figure 9.

Figure 6. Floor displacements X direction M1 model.

Figure 7. Floor displacements X direction M2 model.

Figure 9 to figure 12 show that the floor displacements and drifts for all MJ, Mso and MSp models have met the requirements for allowed inter-floor displacement that is less than 70 mm. The model with soil-structure interaction (MSo and MSp) has a greater roof-floor displacement value and drift than the model without soil-structure interaction (MJ). This is due to the displacement that occurs on the basement floor due to a flexible support.

For the M1 model with the same earthquake load, the MSo1 model has a roof-floor displacement 3% greater than the MJ1 model. While the MSp1 model has a roof-floor displacement of 2% greater than the MJ1 model. For roof drift values, the MSp1 and MSo1 models show roof drifts of 1% - 2% greater than MJ1. As for the M2 model, MSo2 and MSp2 models have a roof-floor displacement of 2% greater than the MJ2 model. For roof drift values, the results of the MSp2 and MSo2 models show results of 1% - 2% greater than MJ2.

If it is compared to the floor displacement and drift between M1 and M2, the MJ2 floor displacement is 1% greater than MJ1. Whereas MSo2 and MSp2 show different results with a 1% smaller floor displacement than MSo1 and MSp1. But for the drift only MSo2 which shows a smaller value of 1% compared to MSo1 with other models shows M2 drift is 1% larger than M1. The use of static earthquakes and dynamic earthquakes as well as differences in the results obtained can also be compared. Obtained
the M1 model displacement due to dynamic earthquake is smaller 21% - 23% compared to the M1 model due to static earthquake. This is due to the large difference in earthquake force received by the structure in this study, where dynamic earthquake loads are at least 85% of the static earthquake loads.

3.2. Comparison of natural periods
The natural fundamental period of the structure is one of the parameters that can show the rigidity of a structure. The values and percentage of natural fundamental period comparison of the six models in this study are shown in Table 5. From Table 5, the structure natural fundamental period of the model with soil-structure interaction (MSo and MSp) is greater than the model without soil-structure interaction (MJ). The MSo1 and MSp1 models have a natural fundamental period value of 1.67% and 1.45% greater than MJ1. While the MSo2 and MSp2 models have a natural fundamental period value of 1.08% and 1.10% greater than MJ2.

| No. | Model | Natural Fundamental Period (seconds) | Difference (%) of MJ |
|-----|-------|-------------------------------------|----------------------|
| 1   | MJ1   | 1.12058                             | 0.00000              |
| 2   | MJ2   | 1.12318                             | 0.00000              |
| 3   | MSo1  | 1.13928                             | 1.66878              |
| 4   | MSo2  | 1.13532                             | 1.08086              |
| 5   | MSp1  | 1.13680                             | 1.44746              |
| 6   | MSp2  | 1.13559                             | 1.10490              |

This shows that the model with soil-structure interaction is more flexible than the model without the soil-structure interaction due to movement on the foundation.

If it is compared to the effect of adding basement floors on models with the same variation, the MJ2 model has a natural fundamental period greater than 0.2% compared to the MJ1 model. While the MSo2 and MSp2 models have a smaller natural fundamental period value of 0.3% and 0.1% compared to the MSo1 and MSp1 models. This shows that the model with soil-structure interaction and the addition of basement floors can reduce the natural fundamental period of the structure.

3.3. Comparison of internal forces
The internal forces will be checked on the entire beam and column in the six models, but the maximum value on each floor due to static earthquakes and dynamic earthquakes that will be compared. The load
combination used is $1.2D + 1.0L + 1.0E_{\text{Static}} + 0.3E_{\text{Static}}$ and $1.2D + 1.0L + 1.0E_{\text{Dinamic}} + 0.3E_{\text{Dinamic}}$. The value of beam internal forces on the M1 and M2 model are shown in figure 10 to figure 13.

Figure 10. Beam moments M1 model.

Figure 11. Beam moments M2 model.

Figure 12. Beam shear forces M1 model.

Figure 13. Beam shear forces M2 model.

Figure 10 through figure 13 shows the results of the beam internal forces in the M1 and M2 model where the moment and the shear force of the Mj and MSp models have values that are close to each other. Whereas the MSo model generally has a greater beam moment value but the beam shear force is smaller when compared to other models. The difference between the moment and shear force of the MSo and MSp models is $\pm 1\% - 6\%$ of the MJ model. If the results of the internal forces between the M1 and M2 models are compared, the beam moment and shear force of the M2 model are smaller than the M1 model with a ratio of 1\%. Furthermore, for the columns internal forces in the M1 and M2 model are shown in figure 14 to figure 19.

Figures 14 through figure 19 show the results of internal forces in the columns of models M1 and M2 where the moment, shear force, and axial forces of the columns of MJ and MSp models have values that are close to each other. Whereas the MSo model generally has a greater column moment and shear force value but the column axial force is smaller when compared to the MJ and MSp models. The difference in moment and shear force of the MSo and MSp models is $\pm 1\% - 6\%$ of the MJ model. Whereas for the axial force of the column in the MSo model and MSp is $1\% - 3\%$ smaller than the MJ model. If the results of internal forces between the M1 and M2 models are compared, the column axial force of the M2 model is smaller than the M1 model with a ratio of 1\% - 2\%. The use of static and dynamic analysis
for earthquake load results in slight differences in the internal forces. The moments and shear forces of the columns in M1 model due to dynamic analysis is smaller about 14%-17% than the M1 model due to static analysis. This is due to the contribution of higher structural modes in calculation the structural response, therefore the Indonesian seismic code requires the base shear obtained from dynamic analysis shall be at least 85% of the base shear obtained from equivalent static load analysis.

Figure 14. Column axial forces M1 model.

Figure 15. Column axial forces M2 model.

Figure 16. Column moments M1 model.

Figure 17. Column moments M2 model.

Figure 18. Column shear forces M1 model.

Figure 19. Column shear forces M2 model.
4. Conclusions
From the results of the structural analysis of the six models and previous discussions, the following conclusions are obtained.

- The roof-floor displacement in the model with soil-structure interaction (MSo and MSP) is greater 2% to 3% than the model without soil-structure interaction (MJ).
- The roof drift in the model with soil-structure interaction (MSo and MSP) is greater 1% to 2% than the model without soil-structure interaction (MJ).
- The natural fundamental period of the structure in the model with soil-structure interaction (MSo and MSP) is greater 1% to 2% than the model without soil-structure interaction (MJ).
- The axial force of the columns in the model with soil-structure interaction (MSo and MSP) is less 1% to 3% than the model without soil-structure interaction (MJ).
- The addition of basement floors in buildings and modeling with soil-structure interactions can minimize the roof-floor displacement, the natural fundamental period of the structure, and column axial forces by 1% to 2%.
- The moments and shear forces of the columns in M1 model due to dynamic analysis is smaller about 14% to 17% than that of the M1 model due to equivalent static load analysis.

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