ABSTRACT

Simplification on the structural analysis is often done to avoid the complexity of the problems. The structural analysis is straightforward if the building is assumed to be fixed at their column bases (Fix structure). This analysis ignores the effect of the soil on the structural response. In this analysis, the soil is assumed to be supported by the structure and transferred in terms of kinatic, strain, viscous and hysteretic energy. However, soil is not an infinitely rigid material, so it has flexibility. When the soil-flexible pile interaction is considered, its interaction may also modify the vertical seismic propagation and impose vertical, horizontal and rotation vibration modes. In this analysis, part of the seismic imparted energy will be reflected back to the soil media in terms of radiation damping (Flex structure). The structural analysis becomes more realistic when the soil-pile interaction is considered.

Research on the effect of pile-foundation interaction on the inelastic Flex building and response of Fix inelastic building has been conducted, and the result is presented in this paper. In this research, the structural model was 12-storey fully ductile frame building, located at Indonesian earthquake region-3 and designed according to the SK-SNI 1991 Codes. The building model was excited by the 1940 El Centro North-South component. Four member hysteretic models Le Bilinear, Clough, Takeda and Q-Hyst models have been considered.

The inelastic seismic response of Fix and Flex structure then be compared. The Flex structure exhibits higher in the most inelastic structural response than the Fix one. The faster hysteretic model (such as the Bilinear model) implies that the structure becomes more stiff and causes smaller in most structural response. The capability of the member hysteretic model to dissipate energy is not always affected by its stiffness but more dependent on the unloading, reloading stiffness and amplitude of motions. Since its relationship is relatively strong, the inter storey drift and beam curvature ductility demand can be used to predict the member damage index.

Keywords: Pile-foundation interaction, Fix structure, Flex structure, hysteretic model, inelastic seismic response

INTRODUCTION

The assumption that the building structure is fixed at its column bases is a common assumption in the structural analysis. In this paper those structural system is called Fix structure. In this condition, the structural analysis is straightforward, because the analysis more emphasized on the superstructure, ignoring the present-effect of the soil. The seismic energy is directly transmitted to the superstructure. All of the inertial seismic energy then fully accommodated by the building structure and transferred in term of kinetic, viscous, strain and hysteretic energy.

As an engineering material, the soils can not be defined as an absolutely rigid medium. Depending on the site condition, the soil may be soft or firm, but it is not infinitely stiff. The soil, in general, possesses flexibility. Accordingly, the fixed base assumption as mentioned above can not be fully performed by the soil respect to the foundation. More realistic of structural analysis may be achieved when the soil is modeled as a flexible material and incorporated in the analysis of structural system. In this condition the building termed as a Flex structure.

The building structure may be supported by either direct shallow foundation or pile foundation. In this paper, the pile supported building is assumed. Under vertical propagating seismic waves, pile-caps of the pile foundation systems might undergo vertical, horizontal and rocking vibration modes as reported by Gazetas et al.(1991, 1993). If the piles are extremely flexible, the piles might move simply to follow the seismic motion of the ground. In reality, anyhow, the piles are not extremely flexible, the pile may resist the motion of the ground and hence will modify the soil deformation. Accordingly, the pile will experience bending, axial and shear deformation as well as the rotation of the pile caps (Pan et al., 1991). Under seismic excitations, accordingly, the building structure supported by pile foundation may rock at their foundation.

The Lumped Parameter Method was used in this research because of its simplicity. In this method, interaction between soil and pile foundation is represented by the presence of the stiffness and the damping coefficients. The seismic response of pile supported multi storey building has been conducted.

5) Department of Civil Engineering, Faculty of Civil Engineering and Planning
Islamic University of Indonesia, Yogyakarta, Indonesia, Ph.: (0274) 895 042
by El-Hefnawy and Novak (1986). After all, this research was limited only for a very simple structural model, structural response and the results were more emphasized for the academic purposes. A continuation of this research is using a more realistic structural model, structural response and earthquake excitation needs to be carried out.

The main aim of this paper is to compare the seismic response of inelastic Fix and Flex building structure by considering the different types of member hysteretic model.

MODELING OF THE SOIL AND PILE FOUNDATION

Previously research indicated that the effect of soil properties even more significant than effect of soil or foundation modeling (Widodo, 1999). However, it is necessary to define or to model the soil because the state of the soil in general is not regular. In this paper the soil is assumed as a homogeneously isotropic elastic materials. Therefore, the available stiffness and damping soil-pile interaction derived by Novak and El Sharnouby (1983) can be used. Because of the complexity of the problem, some assumptions must be taken. Homogeneously soil profile with different distributions of soil elastic modulus was used by Gazzeta et al.(1991) and Fan et al. (1991) in similar discussion. The homogeneously isotropic soil medium with parabolic distribution of elastic modulus was used in this research. The combination between friction and point bearing rectangular reinforced concrete piles is also used. The c-p soil assumption is also taken.

Several factors will affect on the stiffness and the damping soil-pile interaction. Those factors are influenced by pile model and soil model. Modeling of the pile includes member modeling (stiff or flexible pile), the pile-pilecap modeling (fixed or pin head) and load transfer modeling (floating or point bearing pile). In this research relatively flexible piles are used to reduce the strong dependency to the loading frequency. Relatively slender pile and far pile-to-pile distance are also used. The fixed pile-pile cap connection model is also considered.

STIFFNESS AND DAMPING OF SOIL-PILE INTERACTION

In this research, the stiffness and damping in the vertical, horizontal and rocking vibration modes of the soil-foundation interaction are considered. Soil-foundation interaction formulas according to Novak (1977), Novak and El Sharnouby (1983) are used. Three explicit formulas for the vertical, swayng and rocking stiffness and damping as presented by Prakash and Puri (1988) and Prakash and Sharmna (1990), respectively are expressed in the form,

\[ K_\delta = N \frac{E_A}{r_s} \left( \sum_{P_i} \frac{E_A}{P_{P_i} + P_{C_i}} \right) \]

\[ C_\delta = N \frac{E_A}{r_s} \left( \sum_{P_i} \frac{E_A}{P_{P_i} + P_{C_i}} \right) \]

where \( K_\delta \) and \( C_\delta \) respectively are the dynamic stiffness and damping of pile group at j mode of vibrations, N is number of pile, \( E_A, \delta_i \) respectively are the elastic modulus, area and corner moment of inertia of the pile, \( V_i \) is the shear wave velocity, \( f_j \) is a function, \( S_{P_i}, P_{P_i}, P_{C_i} \) respectively are soil pile, pile tip and pile cap models, \( r_s \) is pile radius, \( G_i \) is soil shear modulus, \( n \) is constant depends on the mode of vibration and \( f_j \) is group factor. For a single pile, \( N = 1 \) and the value of \( f_j \) is equal to 1.

Several graphs and tables involve in the calculation of stiffness and damping of the soil-pile foundation interaction. However, because of the limitation of space, these graphs and tables are not presented herein. Several inelastic responses are considered include the member damage index. The member damage index according to Park and Ang (1985) such as follows is adopted.

\[ DI = \delta_m + \frac{\beta}{\delta_s} \]

where \( DI \) is damage index, \( \delta_m, \delta_s \) respectively are the maximum and the ultimate deformation, \( P_s \) is member yield strength, \( \beta \) is a strength deterioration factor and \( dE \) is an incremental absorbed hysteretic energy.

RESEARCH METHODS

The Building Model and Material Properties

In this research the 12 storey Fix and pile supported (Flex) RC frame building are being used as building models. Two dimensionless inelastic analysis of the structure is considered. The elevation of the building model have symmetric 2-bays of beam with 5.20 meters beam span as shown in Fig.1a. The typical height of the storey is 3.95 meters with 5.20 meters of first storey height is also considered. The design concrete compressive strength fc = 25 Mpa and the steel bar yield strength fy = 400 Mpa are used in the design of the building model. The building model is assumed to be located on soft soil at Region-3 of Indonesian Seismic Region Map and is designed according to the full ductile principle as suggested in The 1991 SK-SNI Code. The normal occupancy of the building is also taken into account.
a) Frame Section
b) Outer Pile Foundation
c) Inner pile foundation
   \( d = 0.45 \text{ m}, s = 1.5 \text{ m} \)
d) Lumped Parameter Model
e) The 1940 Earthquake, North South Component

Fig. 1 Frame Section, Pile Configuration, Lumped Par. Model and Earthq. Excitation
In this analysis, the structural members have to be modeled to simulate its inelastic flexural behavior under cyclic loading. The hysteretic model is commonly used to simulate its behavior. Four member hysteretic models are considered i.e., the Bilinear, Clough, Takeo and Q-Hyt models. The Bilinear model is the most fat model, followed by the Clough, Takeo and Q Hyst. The unloading and reloading stiffness will control the degree of the fatness of those models. The value of 6% initial stiffness is assumed to include the effect of member strain hardening. The value of B = 0.05 is used and the maximum ductility of 30 is also adopted.

As mentioned before that the c-s soil is used. The soil is assumed to be a good enough with undrained shear strength \(c_u = 5.5 \, \text{kN/m}^2\) and at the bearing point \(c_u = 120 \, \text{kN/m}^2\) are considered. The E/C, ratio of 500 is also taken. The soil unit gravity of 1800 \(\text{kg/m}^3\) and the Poisson ratio of 0.40 are also used. The square ordinary reinforced concrete pre cast pile is assumed. The pile has 0.45 cm square section, 19.0 m length and rigidly connected to the pile cap. With these configurations, a slender or flexible pile behavior is expected. The number and arrangement of the pile to support the super structure, internal column shown in Fig. 1b, and 1c. The representation of Lumped Parameter Model is soil foundation stiffness and damping is shown in Fig. 1d.

Method of Analysis

To determine the number, configuration and soil-pile stiffness and damping, a computer program called PILESTIF has been written. The outputs of the program are the stiffness and damping coefficients for vertical, sway ing and rocking vibration modes based on the desire soil and pile foundation models. These stiffness and damping coefficients than to be connected to the standard input program for RUAUMOKO (Carr, 1998).

The main input program for the RUAUMOKO software consist of the geometry of the structure, the element properties, the material properties, the strength of the element, the element model, the hysteretic model, the damping model etc. Single Gilerson's element model and four hysteretic models such as mentioned above have been used. The Rayleigh damping model, short displacement model, and time step \(\Delta t = 0.01 \, \text{dt} \) are used. These data then to be composed in to the standard input program. The building model was excited by the 1940 El Centro NS component. The inelastic response of Fix

and Flex structure (pile supported building) for each member hysteretic model then to be compared. The equation of motion of the structural system can be found in several paper or textbooks (Widodo, 1999) and are not presented in this paper.

RESEARCH RESULT AND DISCUSSION

Top Horizontal Displacement and Base Shear

Top horizontal displacement of the structure is shown in Fig.2. The PegEPI and NegEPI shown in the figure relates to the directions of the vibration. It is necessary to remain one again that the term Fix and Fl as shown in all figures refer to Fixed and Flexible (pile supported structure) respectively. It shows that in all hysteretic model, the structure that is supported by pile foundation (Flex structure) exhibits higher horizontal displacement than the Fix structure. This is because the structures with pile foundation becomes more flexible than the Fix one. Note that the structural fundamental period of Fix and Flex structure is 2.12 s and 2.18 s respectively.

![Fig. 2 Top Horizontal Displacement](image)

The figure also shows that the horizontal displacement of the structure with Bilinear member model is the smallest one, because this structure is stiffer than Clough, Takeo and Q-Hyst Model. The effect of hysteretic models on the base shear of Fix and Flex structures is shown in Fig.3. It is shown in
Beams and Columns' Base Curvature and their Curvature Ductility Demand

The distribution of maximum beam curvature and curvature ductility along the building height is shown in Fig. 4 and Fig. 6 respectively. It shows that the structures supported by pile foundation tend to have higher maximum curvature and curvature ductility demand than the Fix one. Structural horizontal displacements as discussed before strongly affect the result. It is true that the high member curvature is not necessarily requires high member curvature ductility. The maximum value of the beam's curvature is $18.56 \times 10^{-3}$ rad/m and $18.31 \times 10^{-3}$ rad/m for Flex and Fix structure respectively. According to Watson and Park (1994), Booth (1994) the available curvature for ductile member may fall in the range of 60-120.10^{-3} rad/m. The maximum curvature demand, therefore, can be provided easily. As shown in Fig. 5 and Fig. 7 the structures with pile foundation undergo smaller column’s base curvature and curvature ductility demand than for Fix one. Rotations of the pile cap is the main reason.
The degree of inter storey drift along the building height is shown in Fig. 8. Similar to the previously result, the structures supported by pile foundation tend to have maximum storey-drift. The maximum storey drift for Fix and Flex structure are 0.8546 % and 0.9144 % respectively. Horizontal displacement of the structure clearly affect to this result. The structure with Q-Hyst member hysteretic model (the most flexible structure) exhibits maximum storey drift. Fig. 9 and Fig. 10 show the plot between storey drift and curvature and curvature ductility demand respectively. Even though the relationship is scatter (especially plot between drift and curvature ductility in Fig. 10) however, in general the relationship has consistent in trend i.e the more the drift tend to have the more curvature or curvature ductility demand.

Inter Storey Drift and Plastic Hinge Rotation

Fig. 6 Curvature Ductility Demand

Fig. 7 Column's base Curv. Ductility

Fig. 8 Interstorey Drift (%)

Fig. 9 Drift vs. Curvature Ductility
Energy Dissipation and Damage Index

Fig. 12 shows that the viscous and hysteretic energy dissipation for the Flex are greater than the Fix one for all used hysteretic models. The amplitude of motion will affect the hysteretic energy dissipation. The more horizontal displacement of the structure tend to dissipate the more hysteretic energy such as the Flex structures. The hysteretic energy dissipated by the Clough and Takeda model even greater than yielded by the Bilinear model. This is because the results of the combination of the unloading, reloading stiffness and small amplitude of motions. At the small amplitude of motions, the smaller reloading stiffness such as the Clough and Takeda model will dissipate hysteretic energy more effectively than the Bilinear model.

The distribution of the member damage index along the building height of Fix and Flex structures is presented in Fig. 13. The distribution is quite similar to the distribution of curvature ductility demand as shown in Fig. 6. Later on, it will clearer that its relationship is strongly linear. The Flex structure seems to have higher member damage index rather than the Fix ones.

Plot between drift ratio and member damage index is depicted in Fig. 14. It is clear that even though the data looks scatter, but in general, the relationship between drift and member damage index can be categorized relatively strong.
relationship is presented in Fig. 15 i.e. plot between curvature ductility demand versus member damage index looks linear. This relationship can be used to predict the member damage index. Combination among Fig. 10 and Fig. 14 also can be used to control the relationship in Fig. 15.

Fig. 15 Drift v. Element Damg Index

Fig. 13 Element Damage Index

Fig. 14 Drift v. Element Damg Index

Fig. 16 Column's Base Damage Index

Fig. 16 shows the column's base damage index. It clears from this figure that the column's base damage indexes of Flex structures are smaller than the Fix one. Rotation of the pile cap is the main reason. Rotation of the pile cap is not presented here because limitation of the space. Finally, the structural damage index is presented in Fig. 17. It is clear that the Flex
structures undergo higher structural damage index than Fix one, in all considered member damage index. This figure is similar to Fig. 2, means that structural damage index is strongly affected by top horizontal displacement. The stiffer structure (i.e. structure with Bilinear model) tend to yield smaller structural damage index.

CONCLUSION
Research of the inelastic seismic response of Fix and Flex structure (pile supported structure) has been conducted. The following items are the conclusion of this work:

a. Incorporated soil-foundation interaction (Flex structure) shifts the structural fundamental period, caused higher top horizontal displacement, higher viscous and hysteretic energy dissipation, smaller base shear and smaller column's base curvature than the Fix base structure.

b. In the inelastic behavior, the Bilinear member model made the structure becomes more stiff, caused smaller top horizontal displacement and higher base shear than other models.

c. The Flex structure and structure with the slender member hysteretic model (QHyst) exhibited higher inelastic structural response (such as beam's curvature, curvature ductility demand and inter storey drift) than the Fix and the structure with fatter hysteretic model.

d. The capability of the model to dissipate hysteretic energy was not always dependent on the farness of the model but also affected by the unloading, reloading stiffness and the amplitude of motions.

e. The Flex and the structure with stiffer hysteretic model (Bilinear) exhibited higher member and structural damage index than the Fix and the thinner model (QHyst), the beam curvature ductility demand and inter storey drift can be used to predict the member damage index.

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