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SEISMIC RESPONSE OF SOFT-FIRST-STORY BUILDINGS SUPPORTED BY YIELDING FOUNDATIONS

Takuya NAGAE[1], Shizuo HAYASHI[2]

SUMMARY

In 1995 Hyougoken Nanbu Earthquake, the soft-first-story buildings suffered significant damage because the buildings had to consume most of energy by the soft-first-story columns. For the preventative measure of this type of failure, it is well-known that making the soft first story stronger (i.e., increasing the column size) is efficient. But, in this case, the strength of super structure becomes large and the inertial force from the superstructure significantly influences the design of the foundations, especially in soft soil sites. In the traditional design, it is thought that the foundation should be stronger than the superstructure, i.e., the foundation should not suffer damages during great earthquakes. In this research, an alternative is proposed that reduces the reinforcement of foundation members and forces yielding in the foundation. To consider the effect of the yielding foundation on the seismic response of the superstructure, soft-first-story buildings supported by pile foundations were analyzed. The yielding of grade beam and the yielding of pile were defined as the yielding of foundation, and the strengths of grade beam and pile were changed as the parameters. For the model of the analysis, a 2-D frame structure model was connected with a free ground column by nonlinear soil (*p-y*) springs. The results from the dynamic analyses showed that the yielding of grade beam and the yielding of pile can reduce the seismic response of the soft first story during the great earthquake. And also it was indicated that the energy consumption of the soil in the vicinity of pile decreases the total energy consumption of the structure, and the yielding of foundation derive not just the energy consumption of the foundation members but also the extra energy consumption of the soil in the vicinity of the pile.

INTRODUCTION

Architecturally, soft-first-story buildings are favored, especially in the city which is short of spaces. And mostly the soft-first-story building has the multi-story wall (the residential sections) over the first story columns (the parking lot or the stores). In 1995 Hyougoken Nanbu Earthquake, the soft-first-story buildings suffered significant damage because the buildings had to consume most of energy by the soft-first-story columns. For the preventative measure of this type of failure, it is well-known that making the soft first story stronger (i.e., increasing the column size) is efficient. But, in this case, the strength of super structure becomes large and the inertial force from the superstructure significantly influences the design of

[1] Postdoctoral Fellow, Tokyo Institute of Technology, Yokohama, Japan. Email: nagae@serc.titech.ac.jp
[2] Professor, Tokyo Institute of Technology, Yokohama, Japan. Email: hayashi@serc.titech.ac.jp

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NUMERICAL MODEL AND ANALYSIS PROCEDURE

Analysis Procedure

Analysis is based on the calculations of ground response, soil-pile interaction, pile-building interaction, and building response all in one numerical calculation. Figure 1 shows the cross section of the building supported on piles with *p-y* connection between the pile and free ground motion. The free field soil was represented by a 1-D soil-column which was assigned a very large mass so that the mass of the building

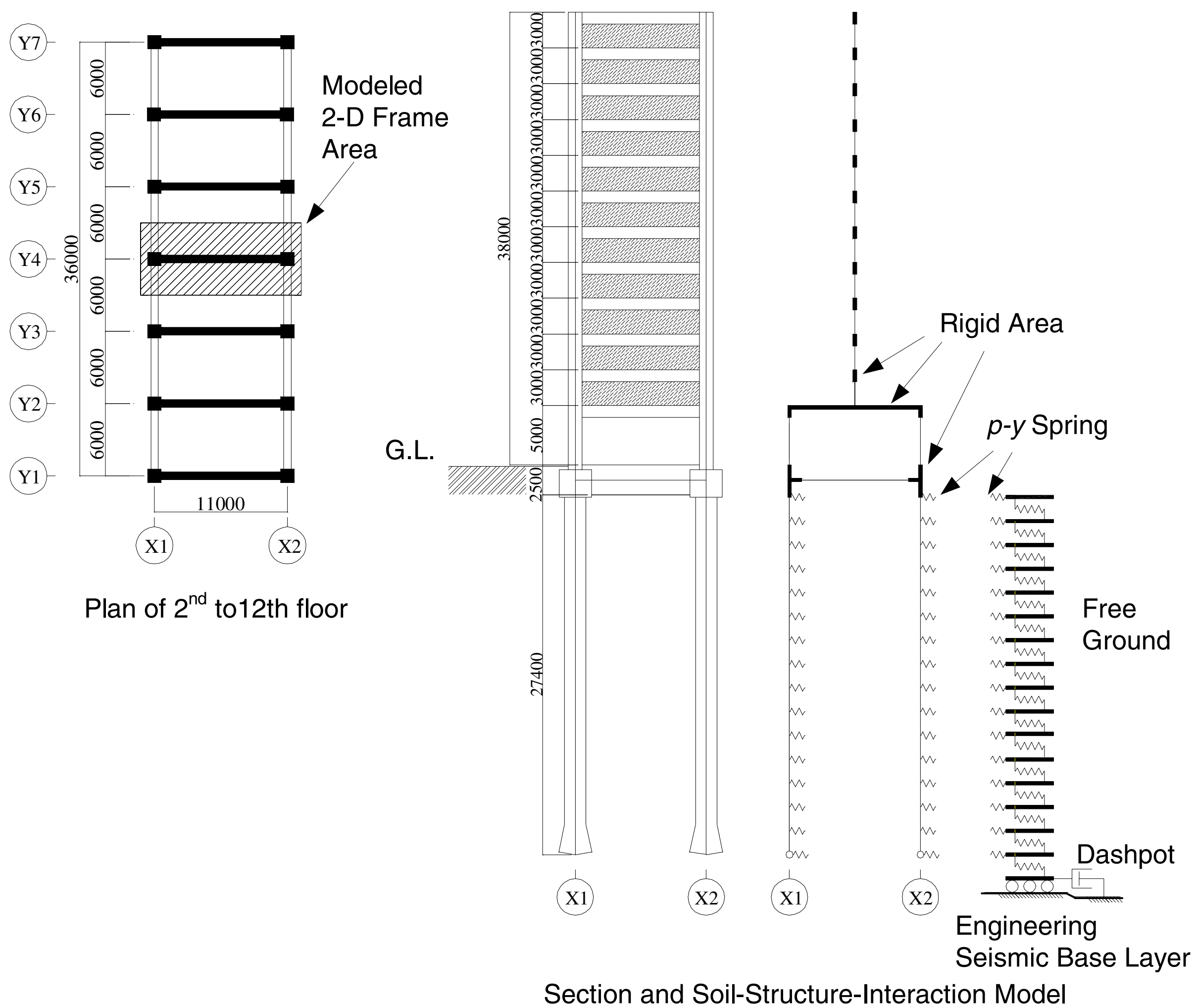


Figure 1 Soft-First-Story Building Supported by Pile Foundation

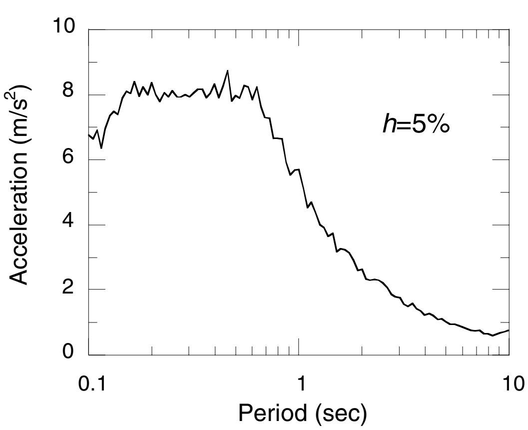
and piles had negligible effect on the soil column response. The soil column was connected to the piles by *p-y* springs, and the piles were rigidly connected to the base of the grade beam, and the building was modeled as a nonlinear 2-D frame structure.

Ground Motion

Table 1 shows the soil profile of the site located in Daiba Area of Tokyo. The soil is very soft and the shear velocity of Yuurakutyou Clay at the depth of 7.5m is only 80m/s. The free ground was modeled as a soil column using a multiple degree of freedom lumped mass nonlinear shear beam. The soil column was represented by a Ramberg-Osgood model, with Masing hysteretic damping [1]. Edogawa Gravel was defined as an engineering seismic base layer which is negligibly affected by the existence of the surface ground motion, i.e., the subsoil above the engineering seismic base layer. A ground motion of engineering seismic base layer which is defined by Japan Code was used as the input motion to the base of the nonlinear soil column. As shown in Figure 2, the input motion was fitted to the acceleration spectrum which is shown in the code and can be thought that the annual mean frequency is approximately 500years. The phase characteristics of the motion were fitted to El Centro 1940 NS. The acceleration time history of the input ground motion is shown in Figure 3. The elastic half space under the soil column was represented using a dashpot [2] because the ground motion is defined as a free-surface ground motion.

Table 1 Soil Profile of Site (Daiba Area in Tokyo)

Class of Soil	Depth (m)	Length (m)	Shear Velocity (m/S)	Density (tf/m^3)	SPT N value
Filling 1	-3.0	3.0	110	1.80	3
Filling 2	-5.5	2.5	110	1.52	3
Yuurakutyou Clay	-7.5	2.0	80	1.52	1
	-14.5	7.0	130	1.50	2
Tokyo Soil	-17.5	3.0	170	1.70	10
	-20.5	3.0	260	1.70	34
Tokyo Clay	-28.1	7.6	190	1.52	7
Tokyo Gravel	-32.5	4.4	370	2.05	>50
Edogawa Gravel	-46.5	14.0	370	1.84	>50



$$S\mathrm{a} = (3.2 + 30T)Z \quad T < 0.16$$
$$S\mathrm{a} = 8.0Z \quad 0.16 \le T < 0.64$$
$$S\mathrm{a} = (5.12/T)Z \quad 0.64 \le T$$

Sa : acceleration response spectra

T : period

Z : coefficient for zone

Acceleration Response Spectra of Engineering Seismic Base Layer for Great Earthquake (from Japan Code)

Figure 2 Acceleration Response Spectra of Engineering Seismic Base Layer

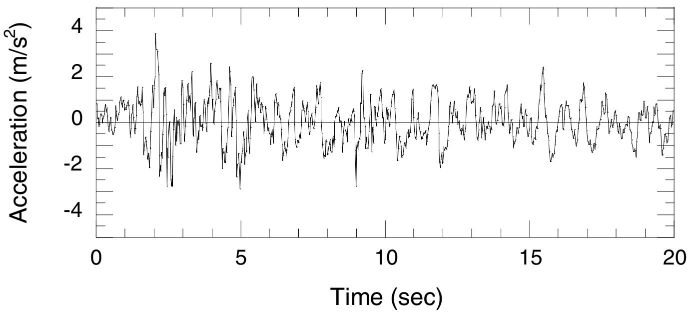


Figure 3 Acceleration Time History of Input Ground Motion

Building Frame

Multi-story wall

The wall of each story was modeled as an elastic line element. The bending deformation (curvature ϕ) and the shear deformation (shear strain γ) are given by

$$\phi = \frac{M}{E \cdot I_W} \ , \quad \gamma = \frac{Q}{G \cdot A_W} \tag{1}$$

E: Young's modulus of concrete
I_W: moment of inertia of gross section of wall including side columns
G: shear modulus of concrete
A_W: gross section of wall

Grade beam and first-story column

The grade beam and first-story columns were modeled using a line element and 2 rotational springs at the end of the line element. The relation between the end moment and the rotation was represented by the degrading tri-linear model [3]. The initial stiffness of the rotational spring K_1 was calculated by

$$K_1 = \frac{6E \cdot I}{L} \tag{2}$$

E: Young's modulus of concrete
I: inertia moment of gross section
L: clear span

The yielding strength was calculated using section analysis. The second stiffness after bending crack was calculated using the equation by Sugano [4]. However the axial force of the first-story column is significantly affected by the overturning moment from the multi-story wall over the soft first story. Thus the hysteresis of the rotational spring of the first-story columns was modeled to reflect the effect of this fluctuation of axial force. For the axial force changing by the step in the analysis, the tri-linear skeleton was renewed following to the interaction diagram for the column strength in combined bending and axial load which was defined by the results of section analysis, as shown in Figure 4.

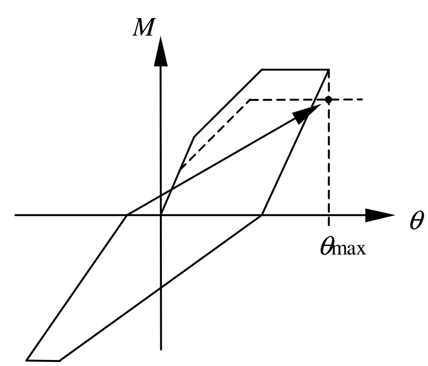


Figure 4 Effect of Axial Force Fluctuation on Column Hysteresis

Piles

The piles were modeled as line elements and divided to the axis of member. The lengths of the pile elements were a half of the pile diameter 0.5D at the top and the pile diameter D for others. The bearing layer for piles was Tokyo Gravel and the vertical displacement of the node of the pile tip was fixed. The relation between flexural moment and curvature of each element was represented by the degrading tri-linear model. The degrading tri-linear model reflects the effect of the fluctuation of the axial force as well as the columns.

***p-y* springs**

The initial stiffness of p-y spring K_h was based on Recommendation for Design of Building Foundation (Architectural Institute of Japan AIJ) [5]. The initial stiffness of p-y spring K_h was defined as a product of the coefficient of lateral subgrade reaction k_h, the diameter of the pile D and the element length of the pile l. The coefficient of lateral subgrade reaction k_h is given by

$$k_h = 80E \cdot D^{-\frac{3}{4}} \qquad (\mathrm{kN/m^3}) \qquad (3)$$

E: modulus of soil deformation (=700N, N: N value)
D: pile diameter

The ultimate lateral reaction of p-y spring P_{max} was calculated from the equation by Broms [6].

$$P_{max} = 3\sigma \cdot K_p \cdot D \cdot l \text{ (Sand)}, \quad P_{max} = 9c_u \cdot D \cdot l \text{ (Clay)} \qquad (4)$$

σ: vertical pressure
K_p: coefficient of Rankine passive pressure
c_u: undrained shear strength
D: pile diameter
l: element length of the pile

The hysteresis rule of p-y spring was represented by the hyperbolic model [7], with Masing hysteretic damping as shown in Figure 5. The internal viscous damping c was defined so that the damping ratio h at the natural period of the superstructure which is fixed at the base becomes 3%. However, the internal viscous damping c was changed linearly to the instantaneous stiffness of p-y spring.

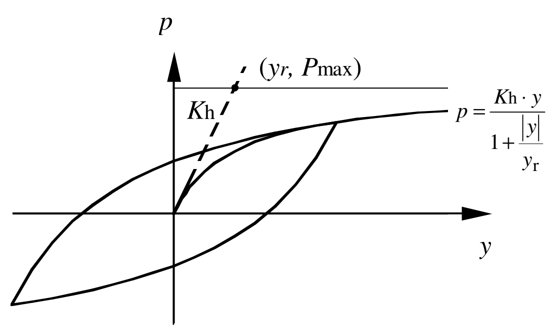


Figure 5 *p-y* Spring Hysteresis

Parameter of Numerical Simulations

Table 2 summarizes the conditions and parameters for considering the effect of the yielding foundations on the seismic response of the soft-first-story building. In this paper, the yielding foundation means the yielding of grade beam and the yielding of pile. The mechanisms of the yielding of grade beam and the yielding of pile are depicted in Figure 6. The prototype is G13P25 which has enough amount of reinforcement to the yielding of grade beam and pile. For G85P25, G0775P25 and G07P25, the amounts of reinforcement of the grade beams are decreased by the same difference to consider the yielding of grade beam. For G13P10, the amount of reinforcement of grade beam is much enough to the yielding, but the amount of reinforcement of the piles is decreased to consider the yielding of pile. The result of eigen value analysis showed the natural period of the superstructure fixed at the base was 0.49 sec and the natural period of the structure supported on piles with p-y connection between the pile and free ground was 1.25 sec, i.e., the lengthening ratio of the natural periods was 2.6. This result indicates the soft-first-story building at the soft soil site is very susceptible to the soil-structure-interaction effect. Second, the result of static pushover analysis for SSI model is shown in Figure 7. The lateral load for the superstructure was based on the uniform distribution. Figure 7 demonstrates that the yielding of grade beam decreases the stiffness of the first story. On the other hand, the yielding of pile (G13P10) didn't affect on the relation between shear force and deformation of the first story because the elastic grade beam could behave as a barrier. The strength ratio λ between superstructure and foundation in Table 2 was calculated as a ratio of the base shear corresponding to the yielding of the foundation to the horizontal ultimate strength of the soft first story. However, the base shears corresponding to the yielding of the ends of grade beam or the tops of piles did not occur at the same time because the column and pile were incorporated the effect of fluctuation of the axial force. Thus the base shear corresponding to the yielding of foundation was taken an average of 2 different values (For the grade beam, it means the average corresponding to the yielding of 2 rotational springs at the ends. For the piles, it means the average corresponding to the yielding of 2 elements at the tops of piles).

Table 2 Conditions and Parameters of Numerical Model

Case	Width of Grade Beam (mm)	Depth of Grade Beam (mm)	Pt (%)	Diameter of Pile (mm)	Pg (%)	λ
G13P25	900	2500	1.3	1600	2.5	-
G085P25	900	2500	0.85	1600	2.5	0.96
G0775P25	900	2500	0.775	1600	2.5	0.87
G07P25	900	2500	0.7	1600	2.5	0.81
G13P10	900	2500	1.3	1600	1.0	0.90

Pt : Tension reinforcement ratio of grade beam (double reinforcement ratio is one) Pg : Reinforcement ratio of pile λ : Strength ratio between superstructure and foundation

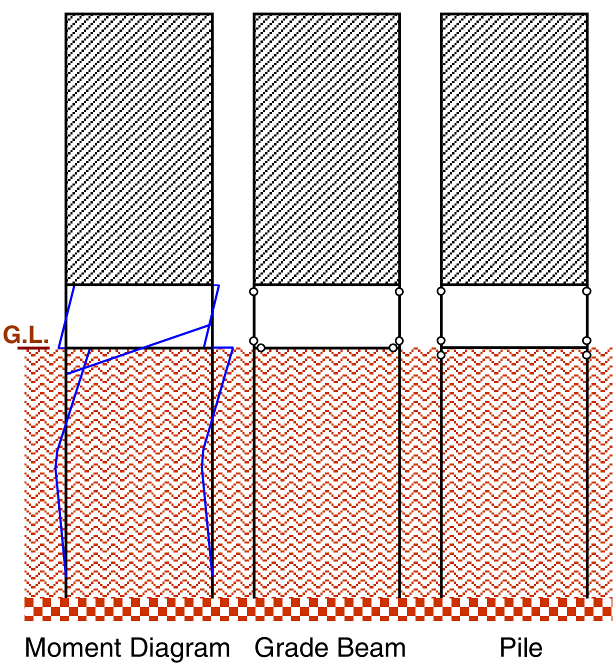
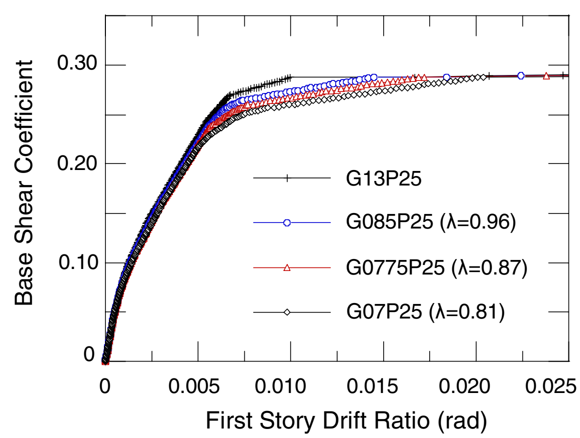


Figure 6 Mechanisms of Yielding Foundation



* Base Shear Coefficient : Ratio of 1st story shear force to the total weight from 1st story to 12th story

Figure 7 Results of Pushover Analysis

RESULTS OF DYNAMIC ANALYSIS

Response of Free Ground

Figure 8 shows the response of free ground in the numerical model. For the maximum acceleration, the amplification of the ground surface to the base of soil column is small. For the maximum displacement, the nonlinearity is significant at Yuurakutyou Clay layer around the depth of 7.5m which is relatively soft and has the shear velocity of 80 m/s. The maximum relative velocity at the level of the grade beam was 0.55m/s.

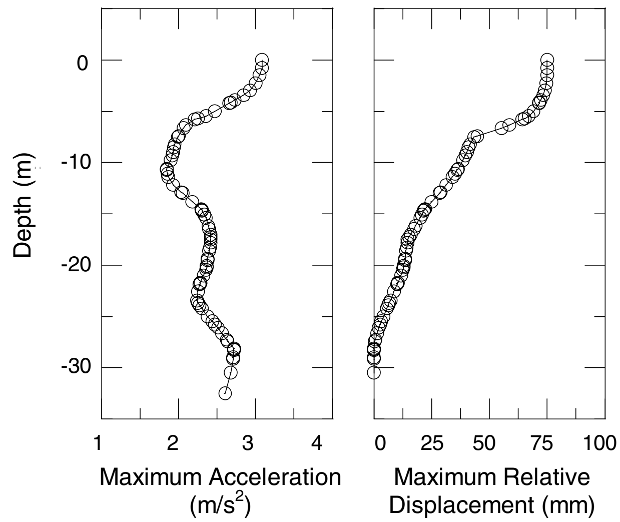


Figure 8 Response of Free Ground

Response of Structure

For G13P25, the first-story columns only yielded. For G085P25, G0775P25 and G07P25, the first-story columns and the grade beam yielded. For G13P10, the first-story columns and the top of piles yielded (the other portions of the piles did not yield). Figure 9 shows that the hysteresis of the

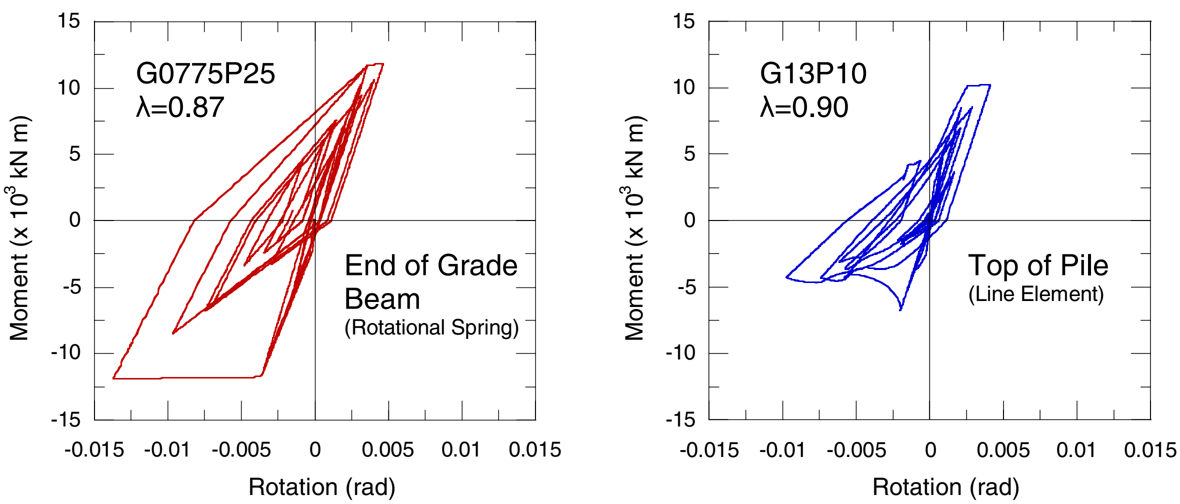


Figure 9 Hysteresis of Yielding Foundations

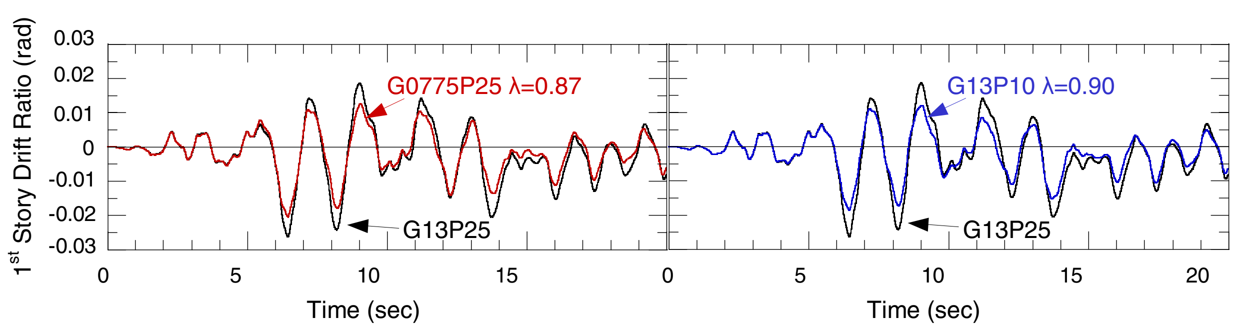


Figure 10 Time History of First-Story Drift Ratio

yielding grade beam (G0775P25) and the yielding pile (G13P10) which are equivalent in the strength ratio λ. For the hysteresis of the top of pile, the moment is the average moment of the element, and the rotation is the product of the average curvature of element and the length of element. The yield moment of the end of grade beam is bigger than the yield moment of the top of pile even if the strength ratios λ are equivalent, because the end of grade beam takes the moment not just from a pile but also from a column. For the yield strengths of pile, the plus is different from the minus because the pile was incorporated the effect of the axial force fluctuation. Figure 10 shows the time histories of the first-story drift ratio. Figure 10 compares the response of the case of yielding foundation (G0775P25 and G13P10) to the response of the case of no foundation yielding (G13P25). G0775P25 and G13P10 are equivalent in the strength ratio λ, and those maximum first-story drifts are similarly restrained comparing to G13P25. For considering the behaviors of members, Figure 11 shows the maximum rotations of the rotational springs at the end of the first-story column, the rotational springs at the end of the grade beam and the elements at the top of pile. The rotation of the pile element is the product of the average curvature of the element and the element length. For G13P25, the maximum rotations of the grade beam and the pile are small because the foundation members behave elastically. Comparing G13P25, G085P25, G0775P25 and G07P25, the maximum rotations of the grade beam gradually increase with the decrease of the reinforcement in the grade beam (i.e., the strength ratio λ). On the other hand, the maximum rotations of the columns gradually decrease with the decrease of the strength ratio λ. Especially, the maximum rotations of the base of column connected with the yielding grade beam decrease more significantly than the top of column. Likewise, for G13P10 of yielding pile, the maximum rotations of the columns decrease with the increase of the maximum rotation of the pile. However, the maximum ration of the top of column and the base of column are very close because the elastic grade beam behaved as a barrier. Comparing to G0775P25 which is equivalent to G13P10 in the strength ratio λ, the maximum rotation of the top of column is smaller in the case of yielding pile than in the case of yielding grade beam, but the maximum rotation of the base of column is bigger in the case of yielding pile than in the case of yielding grade beam.

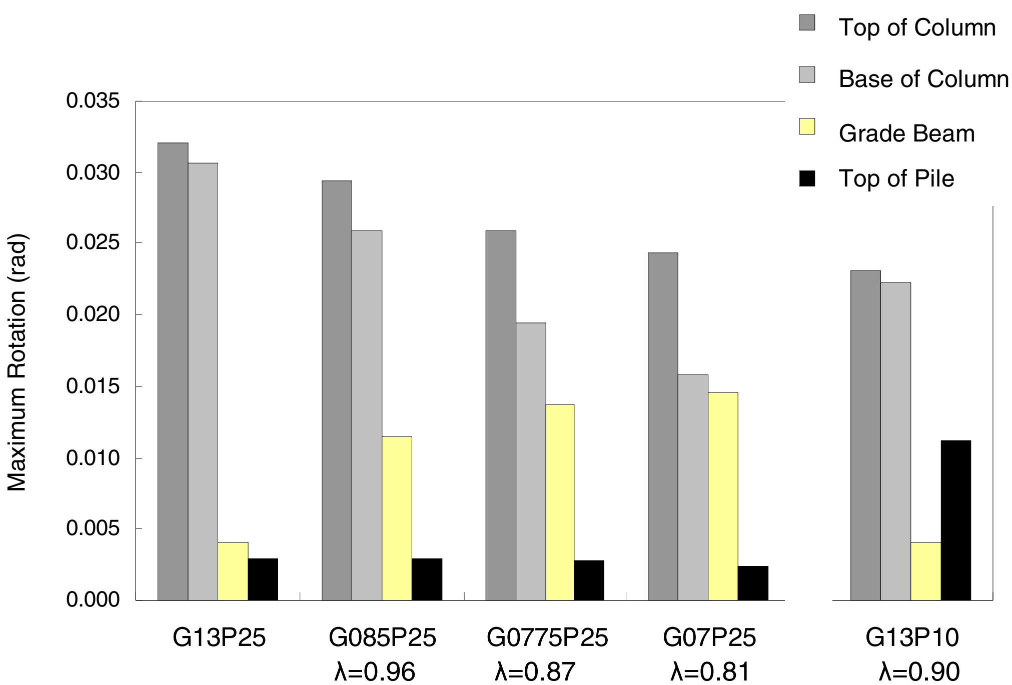


Figure 11 Maximum Rotations of Structural Members

Response of *p-y* spring

Figure 12 shows the maximum deformation of *p-y* springs. The maximum deformation of *p-y* spring can be thought the soil behavior in the vicinity of piles. Thus it is shown in Figure12 that the soils in the vicinity of the piles deform more in the case of yielding foundation (G0775P25 and G13P10) than in the case of no yielding foundation (G13P25). These increases of the deformation are because the rotational resistance of the top of pile significantly decreased by the yielding of grade beam or the yielding of pile. The change of the soil deformation in the vicinity of the piles means the change of the hysteretic damping of the soil as shown in Figure 13.

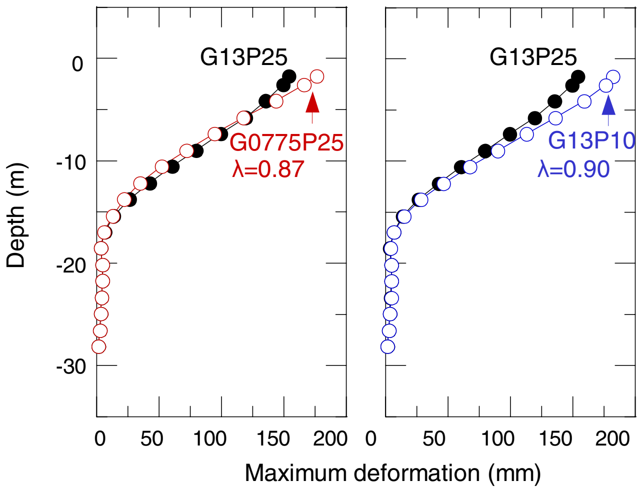


Figure 12 Maximum Deformations of *p-y* Springs

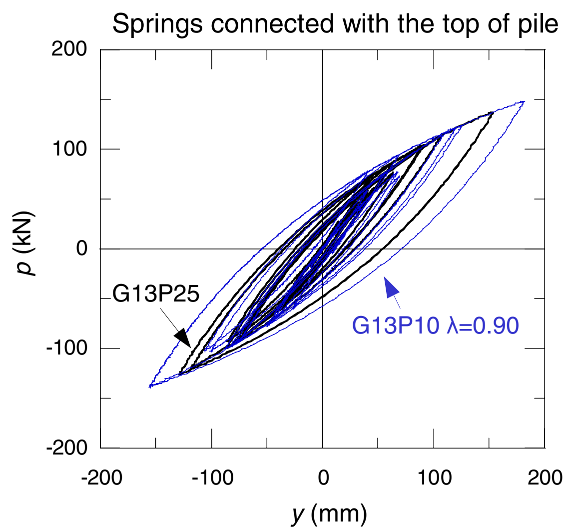


Figure 13 Hysteresis of *p-y* spring

Cumulative hysteretic energy consumption

Figure 14 shows the cumulative hysteretic energy consumption of the structure. The cumulative hysteretic energy consumption of the first-story columns decreases with the increases of the energy consumption of yielding foundation. However the total cumulative hysteretic energy consumptions of the structures are

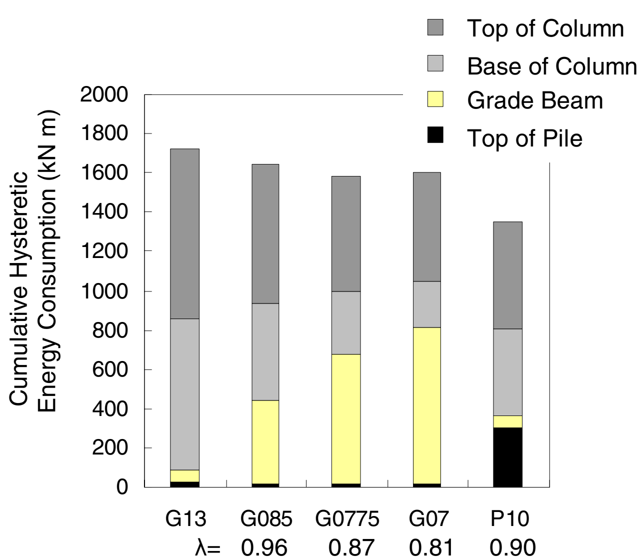


Figure 14 Cumulative Hysteretic Energy Consumption of Structure

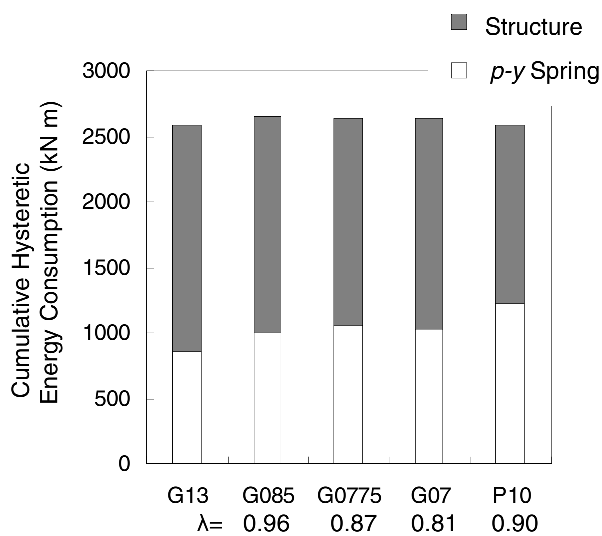


Figure 15 Cumulative Hysteretic Energy Consumption of Structure and *p-y* Spring

different, especially in the case of yielding pile. Figure 15 shows the sums of the cumulative hysteretic energy consumption including all the *p-y* springs. The sums of the energy consumption of the structure and the *p-y* springs are very close regardless of the yielding of foundation. The result indicates that the energy consumption of the soil in the vicinity of pile decreases the total energy consumption of the structure, and the yielding of foundation derive not just the energy consumption of the foundation members but also the extra energy consumption of the soil in the vicinity of the pile. Thus it can be thought that the total cumulative energy consumption of the structure supported on yielding piles is smaller than others in Figure 14 because the deformations of the *p-y* spring are bigger than others from the top to around the depth of 10 m, as shown in Figure 12, and derive the biggest extra energy consumption from *p-y* springs (i.e., from soil in the vicinity of piles).

CONCLUSION

12 story buildings supported by the pile foundation were analyzed for considering influences of the yielding foundation on the superstructure during the great earthquake. The yielding of grade beam and the yielding of pile were defined as the yielding of foundation, and the strengths of grade beam and pile were changed as the parameters. Those buildings were modeled as 2-D frame structures which have a multi-story wall over the first-story columns. Since the site is located in Daiba Area of Tokyo and the soil is very soft, the free ground and *p-y* springs exhibited nonlinear behaviors under the great earthquake. The results from the dynamic analyses under the conditions mentioned above showed that the yielding of grade beam and the yielding of pile can reduce the seismic response of the soft first story during the great earthquake. And also it was indicated that the energy consumption of the soil in the vicinity of pile decreases the total energy consumption of the structure and the yielding of foundation derive not just the energy consumption of the foundation members but also the extra energy consumption of the soil in the vicinity of the pile.

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