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Continuous Wall Pile Supporting Base-Isolated Building on the Reclaimed Ground

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SUMMARY

A large base-isolated building was planned to be constructed upon liquefiable reclaimed subsoil in Japan bay area. When constructing a building on the reclaimed ground is the dependence in the conditions of the soil. In order to penetrate to the firm gravel/clay layer and to establish rigidity to the soft soil layer to prevent liquefaction, a continuous wall pile system was adapted.

This examination shows the differences of response properties and seismic effectiveness of the foundation system and the superstructure arising from use of continuous wall piles and use of cast-in-place concrete piles.

For seismic analysis, seven types of seismic waves were used. The seven waves consisted of, 1 site-specific, 3 for observation purposes, and 3 artificial waves. The results illustrated a prominent response in the structure for the higher modes for the site-specific wave function. In order to reduce this response, viscous wall dampers were installed in the middle floors of the building.

As for the foundation system, a continuous wall pile foundation is chosen for the large-scale seismic isolated building to be constructed on the reclaimed ground. Even if shear force caused by ground drift during earthquake becomes larger compared to a cast-in-place concrete pile foundation, it can be expected to reduce the force acting on the long period structure like this seismic isolated building.Thus the safety of the structure and the realization of the project was achieved by the application of various structural means such as, continuous wall piles, base isolators, viscous dampers and by conducting thorough seismic analysis.

1. Introduction

This paper reports the structural design of a large seismic isolated telecommunications building. Because the site is reclaimed land with soft soil, the foundation system and structural system need to be designed considering conditions of the soil. Also, design criteria for a building are established to be elastic even for the biggest earthquake expected in the construction site. To satisfy these criteria, the building has a seismic isolation system and damping devices are installed in its middle stories, and the continuous wall pile was chosen as foundation system.

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2. Project Outline

2.1 The Building

This is a 12-story building with 54.25 m in eaves height, with a telecommunications facility. The building plan, with unit span of 6.4 m, is a rectangle measuring 116.8 m in the X-direction, by 43.2 m in the Y-direction, total floor area is 60993.42 m^2.

A seismic isolation system is applied on this building in order to guarantee sufficient safety and to maintain building functions in the event of a disaster like a major earthquake. The framework has Concrete Filled Tube columns and steel beams, rigid frames with bracing. Also, viscous damping walls are arranged in the building's middle stories. Fig. 1 shows the typical framing plan; Fig. 2 illustrates the framing elevation.

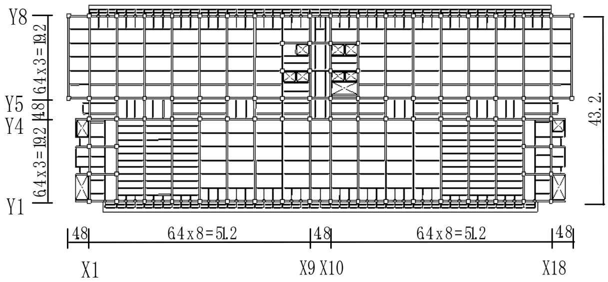


Fig. 1 Framing plan

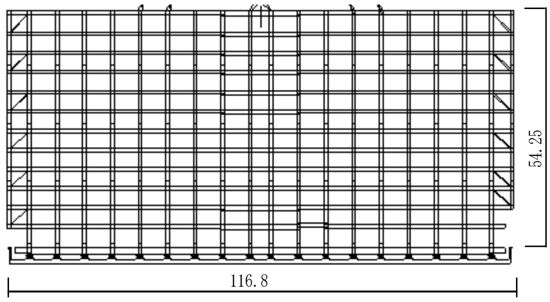


Fig. 2 Framing elevation

2.2 The Site Stratum and the Foundation System

The site stratum consists of in-filled land for the first 20 m, another 20 m of alluvium to 44 m below the surface, and further dense gravel and clay diluvium below it. Because the reclaimed layer is soft and likely to liquefy during a severe earthquake, a stiff continuous wall pile system, having a short natural period in foundation-ground system, was applied against liquefaction and for increasing seismic performance significantly. The pile's bottom level was set on a firm sand-gravel layer of diluvium (Dg1) encountered at 45 m below the surface. The stratum composition is shown in Fig. 3; the arrangement of continuous wall piles is shown in Fig. 4.

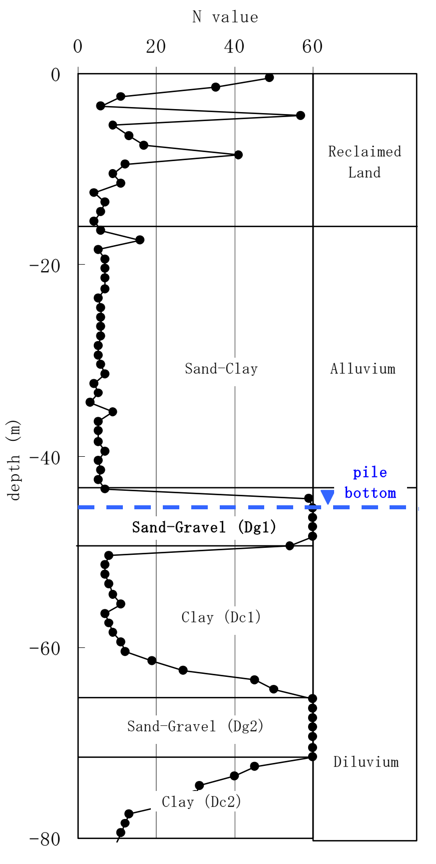


Fig. 3 Stratum composition

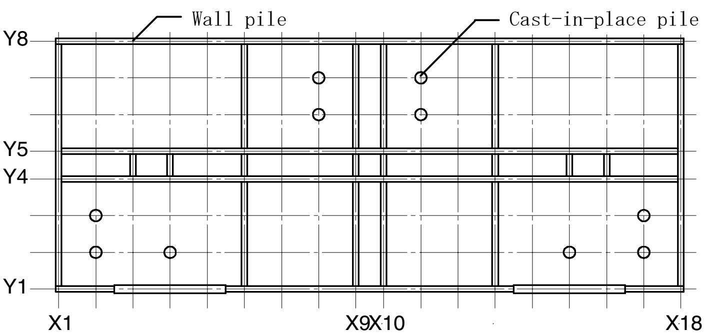
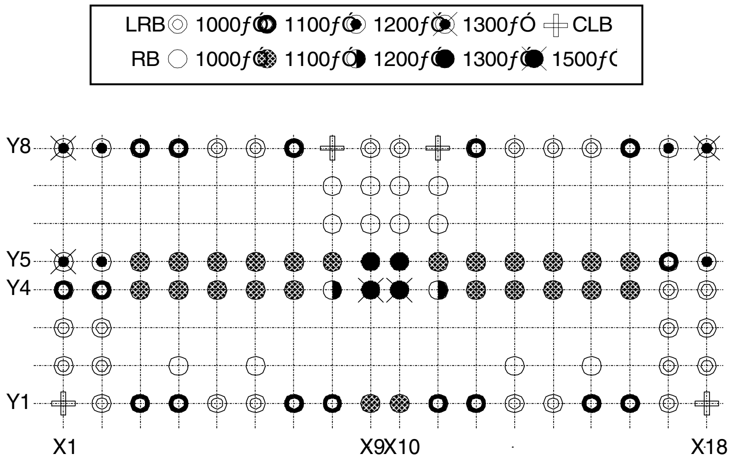
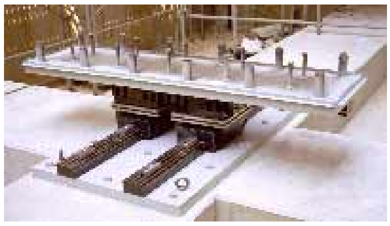


Fig. 4 Arrangement of continuous wall piles

2.3. Isolator Device

The isolator system comprises 46 lead rubber bearings (LRB), 42 rubber bearings (RB), and 4 cross linear bearings (CLB) which comes to 92 isolators in all, LRB and RB are 1000 ϕ - 1500 ϕ in diameter and 280 mm in total thickness of the rubber portion. The LRBs are arranged in the building periphery, with RBs in the central part to reduce eccentricity of the seismic isolated story as much as possible and secure torsional stiffness necessary for the isolated story. To prevent the building from up-lift, CLBs are arranged right beneath the columns, where lateral force causes high axial compression and tensile force. The device arrangement is shown in Fig. 5.





Cross Linear Bearing

Fig. 5 Arrangement of isolators

2.4. Damping Device

Viscous damping walls are used for damping devices, of which 24 and 22 are arranged in the X- and Y-directions, respectively, between 3 to 8 story. The damping walls are proportionally and symmetrically arranged around the building core and periphery to expect effective performance even when torsional vibration occurs to the superstructure and not to become obstacles in planning the building. The device arrangement is shown in Fig. 6.

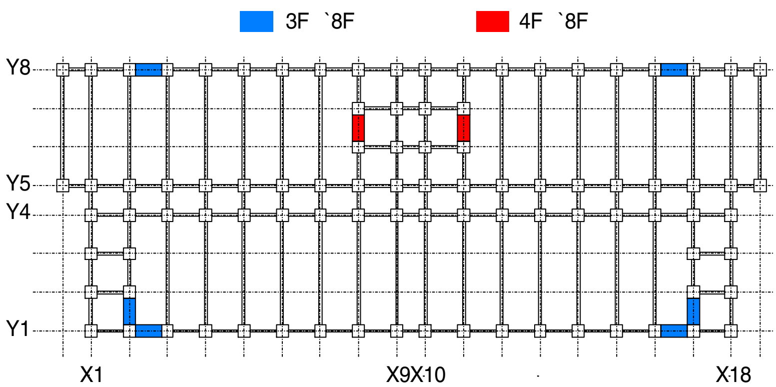
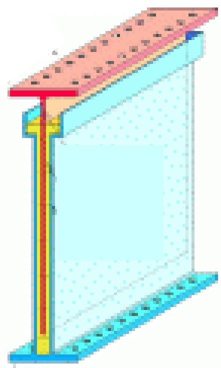


Fig. 6 Arrangement of viscous damping



Viscous Damping Wall

3.The Outline of structural Examinations

3.1 Examination about the effect of the foundation system over the superstructure

This examination shows differences in response properties and seismic effectiveness of the foundation system and the superstructure arising from use of continuous wall piles (hereafter, "wall pile") and use of cast-in-place concrete piles (hereafter, "cast-in-place pile"). The Penzien model, continuous series of subsoil-pile-superstructure, is used as an analytical model. Each cast-in-place pile is arranged directly beneath each isolator. (Refer to Fig.13)

For the superstructure, the building is modeled as an equivalent shear model with 13 masses; the pile structure is modeled as a flexural shear model. Wall piles are constructed on Dg1 as the pile bottom level; cast-in-place piles are constructed on Dg2. The seismic wave for the analysis is two simulated waves in consideration of soil conditions. (Refer to 3.4.2)

As the analytical results of both models, maximum response drift in the X-direction is shown in Fig.7, maximum response of interstory shear force in Fig. 8, and maximum response of seismic isolated story in Fig. 9.

Because of wall pile's high stiffness, the drift of wall pile is one-fifth of that of cast-in-place pile. This may be constraining effects on surrounding soil's deformation and soil behavior is similar to the wall piles.

Regarding to the shear force of the superstructure, difference due to foundation forms is significant, but difference due to earthquake waves is negligible and the response on continuous wall pile is small. Both models show the similar results that the response on the site wave is largest in the middle stories, which is obviously seen in continuous wall pile. This may depend on earthquake ground motion characteristics and building vibration characteristics.

As for the isolated stories, in regards to both drift and shear force, the continuous wall pile response value is smaller than the cast-in-place pile's response. That means the continuous wall pile with high stiffness is effective for isolation performance.

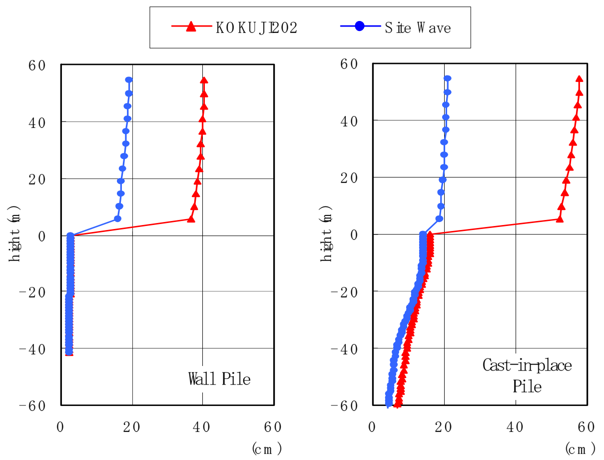


Fig. 7 Maximum response drift

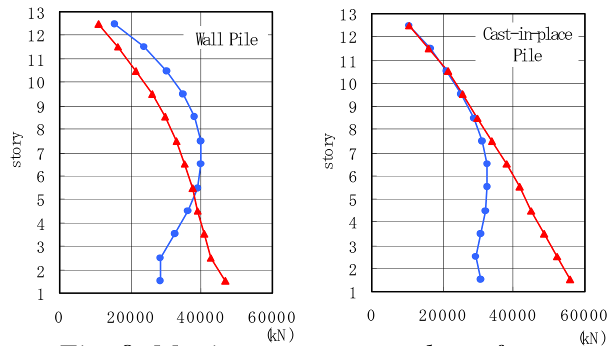


Fig. 8 Maximum response shear force

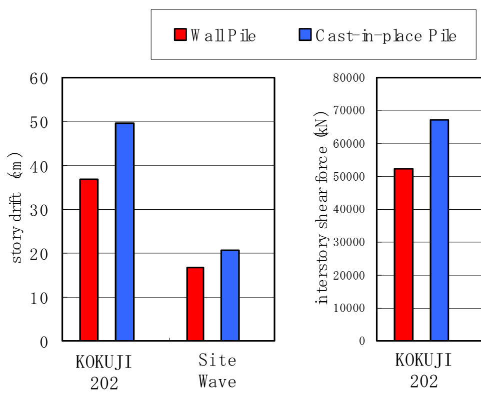


Fig. 9 Maximum response of isolated story

3.2 Examination about the liquefaction of the ground

This examination shows the liquefaction of the ground when continuous wall pile arranged in the shape of a lattice. The analysis method is two-dimensional total stress analysis considering the nonlinear characteristics of the soil by the equivalent linearization. The discrimination of liquefaction based on the shear stress of the soil element surrounded in continuous wall pile. The model of superstructure is the equivalent shear model with 13 masses, and the lowest layer is isolated story. The analytical model is shown in Fig. 10. The seismic wave for the analysis is site wave. (Refer to 3.4.2)

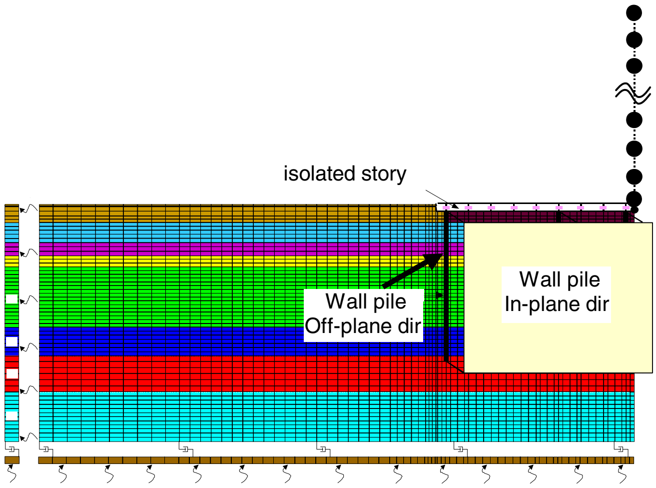


Fig.10 Analytical model

As the analytical results of both directions, the contour of the effective shear strain of the ground is shown in Fig.11 and the contour of the liquefaction resistance is shown in Fig.12. The liquefaction-range is FL value is less than 1 in Fig.12.

As for the shear strain, the displacement is restricted by the stiffness of the continuous wall pile, and it is smaller than the outside of continuous wall pile. As for the liquefaction resistance, the liquefaction-range of X direction is smaller than Y direction. It is considered that the wall pile's stiffness of the in-plane direction of X direction is higher than the Y direction. The high-stiffness wall pile moves approximately as one-body in the earthquake. And, the ground-deformation of inside and circumference of wall pile restricted by the pile's stiffness, and the prevention of the liquefaction can be expected.

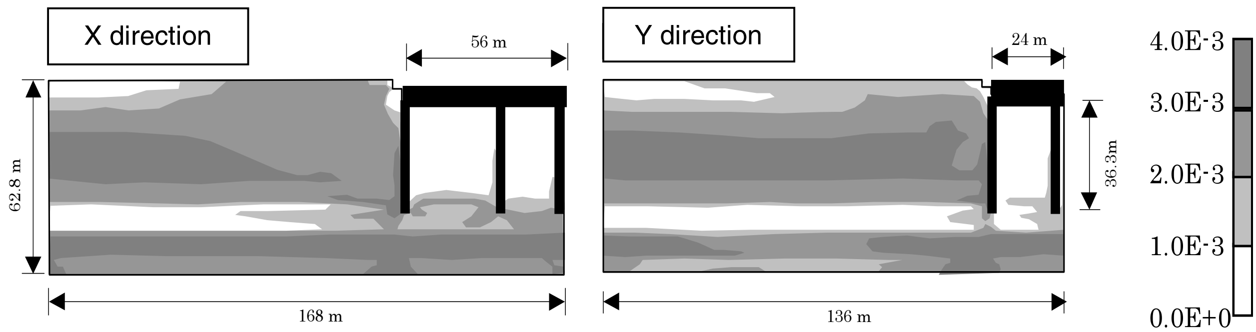


Fig. 11 Shear strain

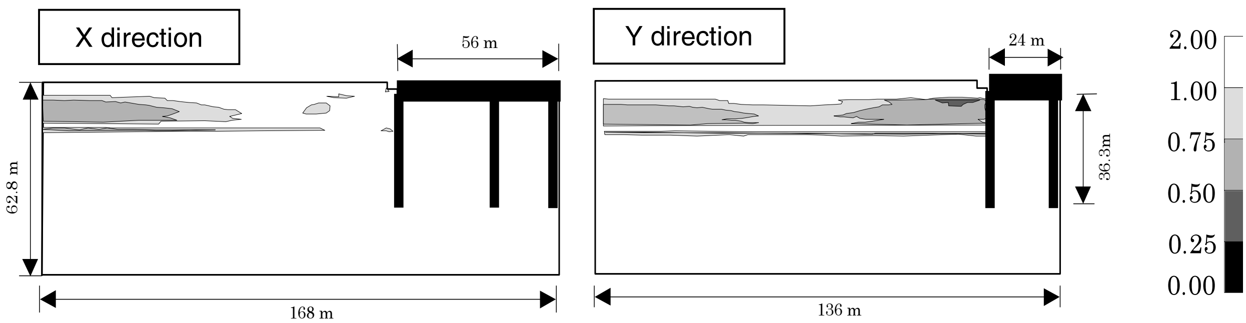


Fig. 12 Liquefaction resistance (FL value)

3.3 Examination about the effect of the difference of foundation system on settlement

This examination shows differences of settlement using continuous wall piles and using cast-in-place concrete piles. The arrangement in using the cast-in-place pile is shown in Fig.13. (Wall pile's arrangement refers to Fig.4.) The thickness of the wall pile is 1.0m, and the diameter of the cast-in-place pile is 1.8～2.3m It was analyzed by three-dimensional nonlinear FEM.

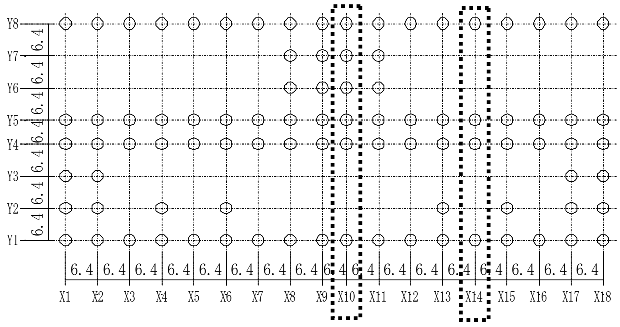


Fig.13 Arrangement of cast-in-place pile

The result of immediate settlement and consolidation settlement is shown in Fig.14. The underground soil stresses of Dc1 and Dc2 layer are shown in Fig.15. In case of continuous wall pile, the consolidation settlement of the X10 frame is 4.8～6.5cm, but in case of the cast-in-place pile, the dispersion is big . In case of the cast-in-place pile, the underground soil stress of Dc1 is over consolidation yield stress in the building central part. Therefore, it is necessary that the bearing stratum to be Dg2 (refer to Fig.3) in case of the cast-in-place pile. In the meantime, underground soil stress of the Dc1 layer is smaller than the consolidation yield stress in case of continuous wall pile, and the distribution is gentle. The reason is that the stiffness of continuous wall pile is high and it is possible to disperse the upper load of the pile.

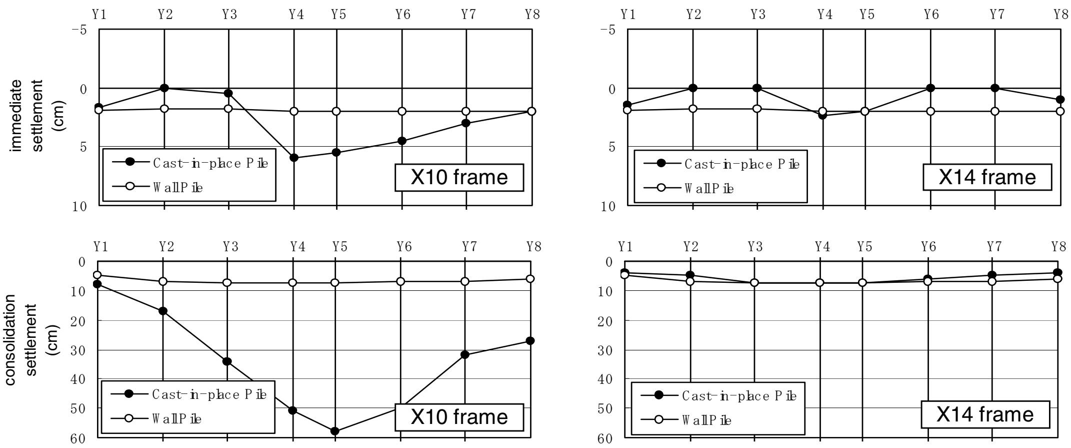


Fig.14 Settlement

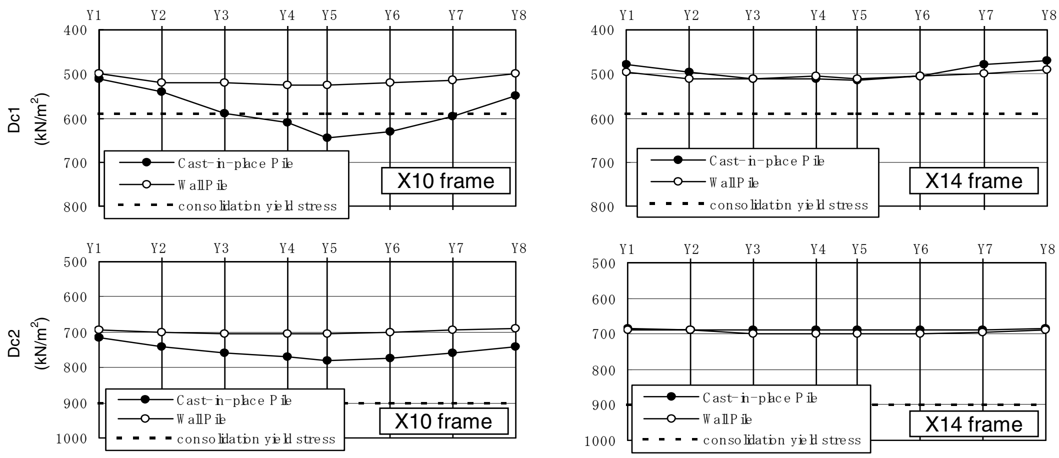
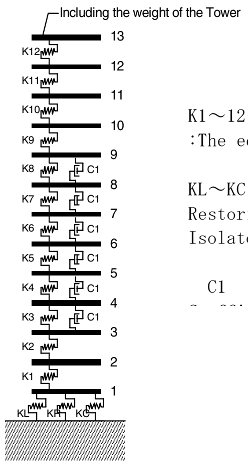


Fig.15 Underground soil stress

3.4 Superstructure

3.4.1 Analytical Model of building

The dynamic analytical model for the building is the equivalent shear model with 13 masses, the isolated story’s base fixed, while restoring force characteristics are supposed to be elastic. Damping is the stiffness proportional type of damping ratio h=2% for the first natural period of the building neglecting the isolated story, damping walls are modeled as a dashpot depending on interstory velocity. As restoring force characteristics of each isolator, LRB is Bi-Linear, RB is Linear and CLB is Bi-Linear. The dynamic analytical model is shown in Fig. Also, Table 1 shows natural period of building in each direction. The natural period of this building as the isolator deformation is 4～5 seconds.



K1～12
:The equivalent shear stiffness of the each story

KL～KC
Restoring force characteristics of the each Isolator

C1

Fig. 16 Dynamic analytical

Table. 1 Natural period

(second)

strain of Isolator	X-direction			Y-direction		
	1st	2nd	3rd	1st	2nd	3rd
0%	1.489	0.537	0.320	1.441	0.528	0.320
0.5%	2.216	0.720	0.404	2.184	0.717	0.400
10%	2.808	0.769	0.414	2.783	0.764	0.408
100%	4.540	0.805	0.420	4.525	0.804	0.416
200%	4.896	0.816	0.422	4.883	0.808	0.415

3.4.2 Earthquake Ground Motion for Analysis

The following waves are used as earthquake ground motion for analysis. Three earthquake waves are conventionally observed (hereafter, “observed waves”), three simulated waves in consideration of soil conditions at the designated site (“KOKUJI waves”), and one simulated wave in consideration of the fault and soil conditions which is expected to affect the site the most (“site wave”).

KOKUJI waves are input in the base of the isolated story. KOKUJI waves are simulated earthquake ground motions based on the spectra officially announced by the Ministry of Land, Infrastructure and Transport and calculated by non-linear earthquake response analysis in consideration of surface soil conditions. The maximum velocity of the observed waves on the ground level is set to be 70 cm/s. Fig. 17 and 18 show acceleration and velocity response spectra of KOKUJI waves and site wave. Characteristics of Site wave are greatly different from other seismic waves.

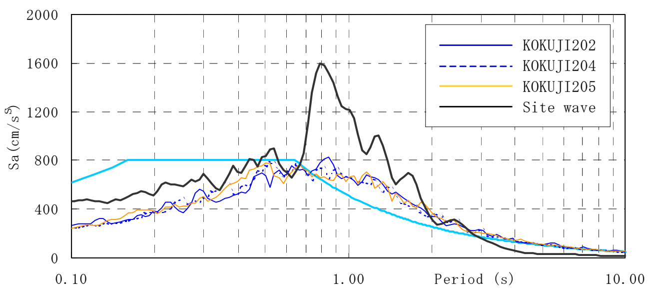


Fig. 17 Acceleration response spectra

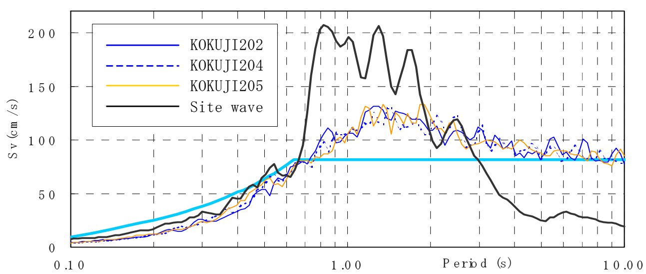


Fig. 18 Velocity response spectra

3.4.3 Dynamic Analysis Results

The original project did not have the installation of viscous damping walls to this building. Fig. 19 shows the maximum response interstory shear force of typical earthquake ground motion in the X-direction on the case not considering fluctuation of isolators' performance values (hereafter, the "standard case") without viscous damping walls.

According to analytical results, while all shear force is a less than the designed shear force, site wave response differs from those of other earthquake waves. This shows the fact that the second mode including the isolated story causes resonant vibration near the site wave's powerful period, as shown in Table 1 and Fig. 17, 18. Even if it could satisfy design criteria without installing damping walls in the standard case, it was difficult to satisfy criteria in considering fluctuation of isolators and other factors, so installation of damping devices was examined and determined to use. The building is seismic isolated structure and it's story drift is relatively small. Therefore, Viscous damping walls which were suitable for slight deformation were adopted.

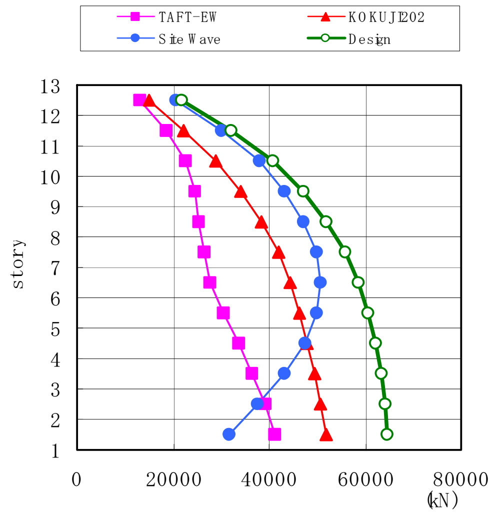


Fig. 19 Maximum response shear force

Figs. 20 to 22 show a comparison of analytical results in the X-direction with and without installing damping walls (maximum response acceleration, maximum response, story deformation angle, and maximum response shear force). We used KOKUJI202, which was prominent response among KOKUJI waves, and the site wave for seismic response analysis. Installation of damping walls shows reduced responses, by 20% in acceleration, 16% in story deformation angle, and 15% in shear force and satisfies the design criteria sufficiently even considering the fluctuation of each device's performance value.

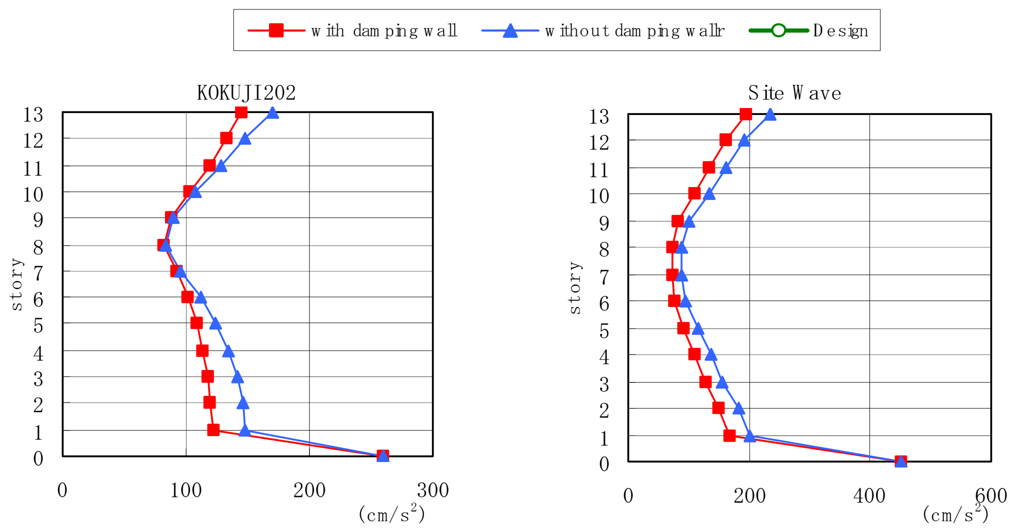


Fig. 20 Maximum response acceleration

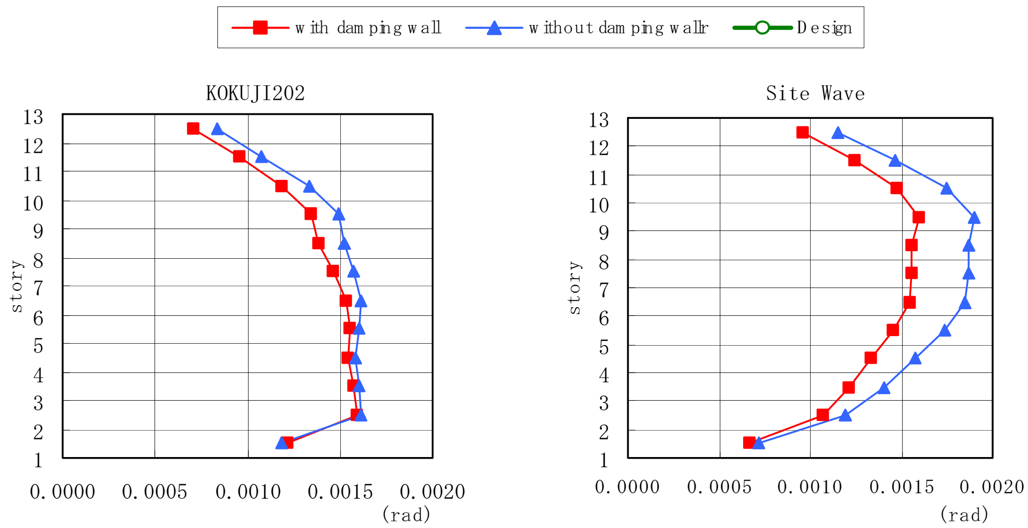


Fig. 21 Maximum response story deformation angle

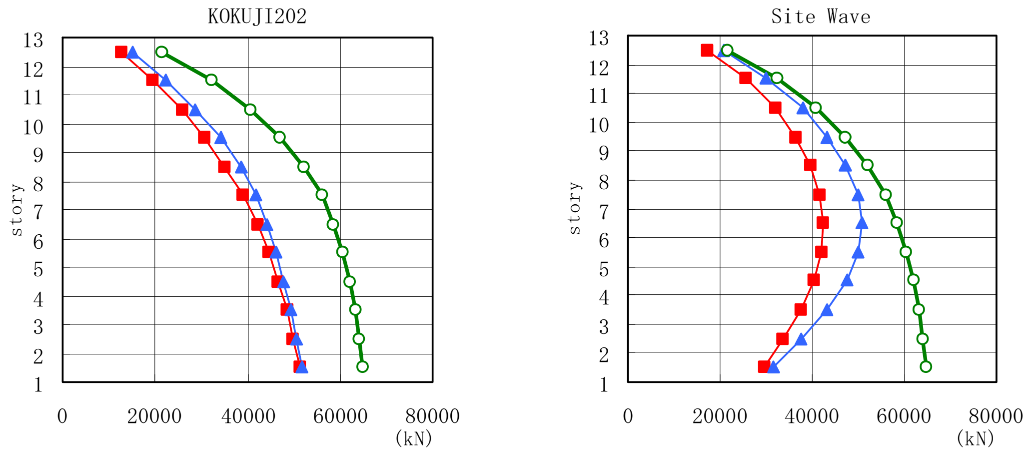


Fig. 22 Maximum response shear force

4. Conclusion

As for the foundation system, a continuous wall pile foundation is chosen for the large-scale seismic isolated building to be constructed on the reclaimed ground. Even if shear force caused by ground drift during earthquake becomes larger compared to a cast-in-place concrete pile foundation, it can be expected to reduce the force acting on the long period structure like this seismic isolated building. The deformation of the ground is suppressed by foundation stiffness, and the depression effect of the liquefaction can be expected. It is effective to suppress the differential settlement, and it is possible that the bearing subsoil is Dg1.

As for the superstructure, the response was greatly reduced by applying viscous damping walls on the isolated structure considering the site's soil conditions and the building's vibration characteristics. If earthquake ground motion characteristics coincide with the response of the building higher modes like this building, the reduction of response by damping devices is also effective.