EFFECT OF IRREGULARITY AND NONLINEARITY OF THE SOIL ON THE DAMAGE OF PILE FOUNDATIONS DURING AN EARTHQUAKE

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ABSTRACT

Due to the 2011 Tohoku Earthquake, a number of buildings have suffered from damage to pile foundations. Among those, a characteristic damage pattern was found in that only one of many similar size buildings in the same site has suffered from pile damage, while other buildings have seemingly survived. Since these sites are situated in the middle of narrow river valleys, the effect of so-called alluvial valley was suggested. Based on this hypothesis, a series of three-dimensional finite element analyses have been carried out. It was found from the study that due to this irregular ground condition there is a possibility of a building located at the center of a site experiencing larger pile response compared with surrounding buildings when the site is situated in the middle of a narrow river valley. It was also found that this phenomenon is more evident in the case of shaking in the direction parallel to the longitudinal direction of the valley. The effect of soil nonlinearity plays a fairly important role in the case of shaking in this direction.

Keywords: Pile damage; 2011 Tohoku Earthquake; Effect of geological irregularity; Equivalent linear analysis; Three-dimensional finite element analysis

1. INTRODUCTION

The 2011 Tohoku Earthquake with the magnitude of 9.0 has inflicted enormous damage to the eastern part of Japan on March 11. The damage due to tsunami, liquefaction and nuclear failure are well known. Although less presented just after the quake, however, it was revealed by the survey conducted afterwards that a number of pile foundations have been damaged due to this earthquake. Some damage was serious in that the superstructure was heavily tilted to the extent that it caused a health disturbance to its residents. Among these damages, it is worthy of note that there are cases in which only one of a group of similar size buildings in a single site has suffered from pile damage, while other buildings were not seemingly damaged. A closer look at these sites indicates that a characteristic landform is common to all sites, that is a narrow river valley that penetrates deep into terrace. All of the aforementioned sites are located in the middle of such river valleys. This survey result strongly suggests that the effect of an irregular ground, a so-called alluvial valley (Sanchez-Sesma 1988, Kawase 2008) in this case, may have caused a non-uniform distribution of ground motions, hence responses of buildings, in the valley during an earthquake. The authors have conducted a preliminary study on this subject and pointed out that there is a possibility of the response of a building situated in the central location of a group of buildings becoming larger compared to the surrounding ones when the site is located in the middle of a river valley (Nakai and Nakagawa 2017).

The objective of this paper is to further extend the study and to examine the detailed characteristics of the locality of the damage to piles due to the effect of an irregular ground. In the study, a simplified irregular ground consisting of a two-dimensional alluvial valley (soft soil) surrounded by a bedrock (stiff soil) with vertically incident shear waves is considered. The effect of soil nonlinearity due to strong

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ground shaking is also considered. Although the geological condition is two-dimensional, the problem is inherently three-dimensional because of the existence of buildings supported by piles that are installed down to the stiff soil. The analysis method used in the study is basically the same as the one the authors have presented previously (Nakai and Nakagawa 2014, Nakagawa and Nakai 2014), except that soil nonlinearity is considered by way of equivalent linear analysis. A key difference from existing similar studies (e.g., Mitsuji et al. 2017) is that this study is based on a pure three-dimensional analysis with the aid of a substructure technique instead of two-dimensional finite elements.

2. OUTLINE OF PILE DAMAGE DUE TO 2011 TOHOKU EARTHQUAKE

Right after the 2011 Tohoku Earthquake, the ministry of land, infrastructure, transportation and tourism, or MLIT, of Japan initiated a two-year survey about the damage to foundations of buildings, specifically targeted at piled foundations. One of the authors has been involved in this project and reported the outline of the survey (Nakai et al. 2014). According to this report, pile foundation damage was found at a total of 41 sites across eastern Japan, including the Tokyo metropolitan area, as shown in Figure 1a. In most cases, buildings which suffered from pile damage are old, dating back to 1970's and 80's, but a few are fairly new, dating back to early 2000's. Most damaged piles were precast concrete piles. Due to the pile damage, some buildings were forced to undergo major renovations and some were demolished even though buildings themselves were not heavily damaged.

One of the interesting facts found even during the survey is that in some sites, more specifically at 4 sites out of 41 pile damage sites, only one building among a number of similar buildings in the same site has suffered from pile damage, while other buildings were not seemingly damaged. A closer look at the landform of each location reveals that all of 4 sites are situated in the middle part of a narrow river valley and that one of the buildings located in the central part of the site has suffered from pile damage. Figure 1b shows the damage distribution map of the eastern part of the Tokyo metropolitan area, located more than 300 km away from the hypocenter of the 2011 Tohoku Earthquake, along with the landform classification. As can be seen, the landform of this area consists of 4 categories, i.e., terrace, lowland (river valley), reclaimed ground and slope. Also, it is of note that there are 6 pile damage sites in this area and that a half of them are situated in narrow river valleys and the other half are situated in the reclaimed ground. Soft soil conditions are expected in all of these sites. According to the literature, it is well known that the central part of a so-called alluvial valley, a soft soil deposit surrounded or enclosed by a stiff bedrock, becomes large when compared to the edge part of the soft soil (Sanchez-Sesma 1988).

Figure 1a. Distribution map of damage sites  Figure 1b. East of Tokyo metropolitan area
3. TARGET SITE

Site A shown in Figure 1b is taken as the target site for this study. As shown in Figure 2a, this site is situated in the middle of a narrow river valley and there are a total of six similar size buildings in the site, as shown in Figure 2b. One of the buildings painted in red color has suffered from pile damage. Figure 3 shows an elevation view of the building and a plan view of its foundation. The damage to the pile was concentrated on the left-hand (southwest) side of the building. The building is a five-story residential building supported by a total of 140 prestressed concrete piles with the diameter of 30 cm installed to a fairly stiff bearing layer located about 20 m below the ground surface. The surface soil is mostly silty with the SPT-N value of 0 ~ 2 and is underlain by the bearing soil with the SPT-N value over 50.

4. ANALYSIS

4.1 Method of Analysis

The method of analysis used in this study is basically a three-dimensional finite element method. Since the problem under study is classified as a wave propagation problem, the substructure technique has been utilized in which the total system is divided into two: a near field that consists of buildings and
surrounding soils, and a far field that consists of a two-dimensional alluvial valley. It is of note that the far field ground already involves a geological irregularity. The detail of the methodology is described elsewhere (Nakai and Nakagawa 2014, Nakagawa and Nakai 2014) and is not repeated here. It is briefly summarized as follows. The near field is modeled by usual three-dimensional finite elements, in which the far field is considered by the combination of an impedance matrix and a driving force vector at the boundary of the near field. The impedance matrix of the far field is simplified by dashpots and the driving force due to an incident wave is computed by the combination of 2.5-dimensional thin layer elements and the theoretical solution to a wave propagation problem of elastic layered media. Analysis was done in the frequency domain. Soil nonlinearity is considered by way of equivalent linear analysis based on one-dimensional soil nonlinear properties found in a literature (Koyamada et al. 2003). Strain dependent stiffness and damping were considered instead of constitutive relations of the soil.

4.2 Analysis Model

Figure 4a shows the finite element mesh layout of the near field. As shown in the figure, the ground consists of a soft soil and a stiff soil. The soft soil part is considered of infinite length in its longitudinal direction that corresponds to the longitudinal direction of the buildings as well. There are three buildings in the analysis model with the same dynamic properties, each has a natural period of 3 Hz in the longitudinal direction and 9.5 Hz in the transversal direction of the building. The foundation is modeled by solid elements, the superstructure is modeled as a lumped mass-beam system and the pile is modeled by beam elements. The building-pile system is separately shown in Figure 4b.

In the model, a total of 10 prestressed concrete piles with 30cm diameter are represented by a single beam. In the following discussion, the response of a pile is computed as one tenth of the response of this beam element. The pile layout is shown in Figure 4c.

As can be seen from the figure, the analysis model is a simplified model and is not intended for detailed simulation, rather it is to examine the effect of alluvial valley on the seismic response of a group of buildings, more specifically targeted at the response of piles during an earthquake. In order for the comparison, a parallel layer model consisting of the surface layer and the bedrock and a single building model instead of three have also been considered in the analysis. In addition, a massless foundation model that consists of the soil, piles and massless foundations but without buildings were considered.

4.3 Input Ground Motion

Figure 5a and 5b show the input ground motions defined as outcrop motions at the bottom of the analysis
model. These ground motions were obtained by a deconvolution analysis of the ground motions recorded during the earthquake at a site situated on terrace located 3 km southeast of the target site, as shown in Figure 1b (denoted as “accelerometer”). The north-south (N-S) component was used as an input for shaking in the longitudinal direction of the alluvium, whereas the east-west (E-W) component was used as an input for shaking in the transversal direction of the alluvium. Hereafter, the former case is referred to as the SH wave incidence case and the latter case is called the SV wave incidence case, respectively, as shown in Figure 4a.

5. RESULTS AND DISCUSSIONS

5.1 Linear Analysis

5.1.1 Comparison between single and triple buildings on a layered ground

Figure 6 shows the comparison of maximum bending moment distribution of a pile along its depth between single building case and triple building case both on a layered ground with SH wave incidence. The location of the buildings and the piles are shown in Figure 4c. From the figure, it is apparent that the bending moment of a pile is very large at its head and near its tip. Large value at the pile head is caused by inertia force of the superstructure, while large value near the pile tip (toe) can be considered
as a result of a constraint effect of the bearing layer since piles are embedded into it by 1m. When looking into the results of the triple building case, it is found that the bending moment in the center building is slightly larger than that for the single building case. Whereas, the response of the left and right buildings is a little smaller than the single building case, although the difference is small.

Figure 7. Distribution of bending moment of piles for layered ground with SV wave incidence

Figure 7 shows the similar comparison but with SV wave incidence. When compared with Figure 6 for the SH case, it is pointed out the followings: the bending moment of piles is a little smaller than the SH case although the ground motions are almost the same for both cases. The difference between center and left/right building responses is also a little different from the SH case in that the bending moment in the center building is larger than that of the single building and that the outer row piles of left/right buildings give larger values than those of the inner row piles due to the antisymmetric nature of the SV case.

Figure 8. Distribution of bending moment of piles for valley ground with SH wave incidence
5.1.2 Comparison between single and triple buildings on a valley ground

Figure 8 shows the comparison between single and triple building cases for an alluvial valley ground with SH wave incidence. In this case, the single building is located at the center of the valley. From the figure, it is found that the trend is a little different from the layered ground case in that the average value of bending moment in the center building is larger than that of left and right buildings.

Figure 9 shows the results for SV wave incidence. When compared with the SH case, the tendency is a little different in that the bending moment of outmost corner piles in the case of triple buildings is the largest and the overall bending moment of the triple building case is a little larger than that of the single building case. This phenomenon implies that all three buildings of the triple building case move in an integrated fashion.

5.1.3 Comparison between layered and valley ground

Figure 10 compares the pile bending moment of single building models: a building on a layered ground, a building located in the center of a valley ground and a building located in the left-hand side of the valley ground (the same location as the left building of the triple building case). This figure represents the SH wave incidence case. From the figure, it is understood that when the building is located in the center of the valley ground, the bending moment of the piles is almost the same as that of the layered case, and that when it is located off the center, the value in a row closer to the center becomes very large compared with other situations. This result implies that the response of buildings is different depending on the location in the valley ground and that it may become even larger.

Although not shown in the figure, the tendency of the results for the SV wave case is similar except that the difference is not very large.

5.1.4 Effect of ground deformation on the response of piles

It is well known that the behavior of the pile during shaking is governed by both building and ground behaviors. In order to examine which is influential, analyses have been carried out where the mass of the building is neglected. Figure 11 shows the results for the triple building case of the valley ground with SH wave incidence. It is possible to point out from the comparison between Figure 8 and Figure
that the bending moment of the pile is mostly governed by the ground deformation except the uppermost part of the pile. When looking at the uppermost part of the pile, it can be said that the pile bending moment in the center building is governed by the inertia force from the superstructure, but that of the left and right buildings are mostly determined by the ground deformation.

According to a similar comparison in the SV wave incidence case, which is the influential factor when compared between building and ground is a little different from the SH wave case in that the ground deformation is influential for most part except the outermost corner piles of the left and right buildings.

Figure 10. Comparison between layered and valley grounds for SH wave incidence

Figure 11. Pile response of massless foundations for a valley ground with SH wave incidence
5.1.5 Maximum bending moment at pile head

Figure 12 shows the maximum bending moment at the pile head. Each graph in the figure has 7 groups of columns. As shown in Figure 4c, each building has a total of 14 piles in two rows. In Figure 12, a legend "center-left", for example, reads as the maximum bending moment at pile head of left row piles of the center building. From the figure, it can be pointed out the following points:

- Maximum bending moment at pile head of corner piles is the largest for all cases compared to the piles in-between.
- Maximum bending moment of left and right row piles is the same in the center building, but that is different in the case of left and right buildings.
- The difference between left and right row pile bending moment tends to become large in the case of an alluvial valley ground.

More importantly, when compared among triple building cases, it is observed that:

- There are situations where the center building gives larger pile bending moment for corner piles.
- The above is clearly so for the SH wave incidence case.

This can be understood as the effect of geological irregularity, in this case the alluvial valley type ground condition. As mentioned earlier, amplification due to a soft soil over a stiff soil is larger in the alluvial valley soil condition compared to the horizontally layered soil condition. When considering the difference between symmetric (SH wave incidence) and antisymmetric (SV wave incidence) conditions as well as the difference of constraint effect of the surrounding stiff soil, the response of a river valley ground due to an incident SH wave becomes large at the center of the valley, while this phenomenon is less apparent in the SV wave case, the above discussion can be understood.

In Figure 12, the maximum bending moment at the pile head for the massless cases, i.e., masses of buildings and foundations are set to zero, is shown. In this situation, pile response is caused by the displacement of the ground. It is of note that:

- In the case of a layered ground, the maximum bending moment due to soil displacement is large in the central part of the building and becomes smaller toward its edge.
- In the case of an alluvial valley ground, however, the above trend is less distinctive and the corner pile gives a larger value in some cases.
5.2 Equivalent Linear Analysis

5.2.1 Comparison of pile bending moment distribution with the linear case

In order to examine the effect of soil nonlinearity, equivalent linear analyses were conducted by using a standard nonlinear relationship of shear modulus and damping factor with soil strain (Koyamada et al. 2003). The soil nonlinearity was assumed only for the surface soft soil, while the stiff bearing layer was kept elastic.

Figure 13 compares the pile bending moment distribution along its depth for the single and triple building models with the alluvial valley ground due to SH wave incidence. By comparing these results with the linear case shown in Figure 8, it is pointed out that the pile bending moment for equivalent linear analysis case is larger than the linear case. In addition, the maximum bending moment at pile head of the center building is far larger than that of the left and right buildings, which is different from the linear analysis case. Thus, regardless of soil nonlinearity, it is understood that there is a possibility that the center building gives larger pile response due to shaking compared with surrounding buildings when they are situated in the central part of an alluvial valley ground.

Although not shown in the figure, it is found that this characteristic is less obvious for SV wave incidence when compared to SH wave incidence.

![Figure 13. Distribution of bending moment of piles from equivalent linear analysis with SH wave incidence](image)

5.2.2 Maximum bending moment at pile head

Figure 14 compares the maximum bending moment at pile head between linear and equivalent linear cases for SH and SV wave incidence. What the legends in the figure represent is the same as in Figure 12. From this figure, it is seen that the overall maximum bending moment at pile head is larger in the case of equivalent linear analysis compared with linear analysis, possibly due to the stiffness degrading of the surface soil. It is of particular note that the center building gives very large bending moment at pile head for corner two rows of piles in the case of SH wave incidence with equivalent linear analysis. This analysis result is in consistency with the actual damage situation in which the end part of the central building has suffered from very heavy damage to pile foundations.
5.2.3 Distribution of shear strain in the ground

Figure 15 depicts the distribution of maximum soil strain that has developed in the ground during shaking. Here, the maximum strain means the maximum value of the average of three shear strain components. From the figure, it is understood that large strain develops near the bottom of the soft surface soil just above the stiff bearing layer. The large strain zone is concentrated in the central part of the alluvium in the case of SV wave incidence, whereas it is found in a wider area causing the strain distribution more or less one-dimensional in the case of SH wave incidence. This difference of the strain distribution reflects the fact that confining effect of the surrounding stiff soil is stronger in the case of SV wave incidence compared with the case of SH wave incidence.

6. CONCLUSIONS

Among a number of damages to pile foundations caused by the 2011 Tohoku Earthquake, there was a characteristic damage pattern in which only one of many similar size buildings in the same site has
suffered from pile damage, while other buildings have seemingly survived. Since this phenomenon strongly suggests the effect of so-called alluvial valley, a series of three-dimensional finite element analyses were carried out. From the analysis, the followings have been pointed out:

(1) When the ground is horizontally layered, the pile bending moment varies depending on the configuration of the building layout or the shaking direction. In the case of an alluvial valley ground, however, the bending moment of the pile of a center building tends to become larger than that of surrounding buildings.

(2) This phenomenon is noticeable for shaking in the longitudinal direction of the valley compared to the transversal direction in the case of equivalent linear analysis.

(3) Soil strain due to shaking mainly concentrates in the bottom part of the soft surface soil. Its distribution pattern is different between longitudinal and transversal shakings with respect to the direction of the alluvial valley ground.

7. ACKNOWLEDGMENTS

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8. REFERENCES


