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KINEMATIC INTERACTION IN PILE FOUNDATION UNDER DIFFERENT LATERAL SPREADING EVENTS

A. Sahare[(1)], K. Ueda[(2)], R. Uzuoka[(3)]

[(1)] PhD Student, Graduate School of Engineering, Kyoto University, sahare.rahul.84a@st.kyoto-u.ac.jp
[(2)] Assistant Professor, Disaster Prevention Research Institute, Kyoto University, ueda.kyohei.2v@kyoto-u.ac.jp
[(3)] Professor, Disaster Prevention Research Institute, Kyoto University, uzuoka.ryosuke.6z@kyoto-u.ac.jp

Abstract

Lateral spreading due to liquefaction induced mechanism in piled foundations has been the cause of major failure of many structures in the past earthquakes, which represents a complex loading scenario involving a soil-pile-structure interaction. Piled foundations are subjected to the lateral kinematic and inertial loading generated due to an earthquake shaking event leading to lateral spreading of soil in liquefiable soil strata which in turn exerts large pressure on the geotechnical structures. Though most of the past research on kinematic interaction of piled foundations focuses on the mild slope conditions so as to induce limited amount of lateral spreading in order to study the soil-pile interaction. However, the pile foundations may be subjected to completely different amount of lateral spreading under different ground sloping conditions inducing non-identical loading to the pile system. In this paper, an effort has been made to study the kinematic interaction in pile group foundation due to the mechanism of liquefaction induced lateral spreading events under different ground sloping conditions as the dynamic properties of soil changes significantly during and after the shaking event. In the present paper, numerical analysis is carried out for 4 different cases of pile foundations considering single and 2X2 pile group conditions for the kinematic interaction under 5 and 10 degrees inclined ground surface. A strain space multiple mechanism model incorporated in the finite element program “FLIP ROSE” is used for the numerical analysis. The soil used for the present analysis is Ottawa F-65 sand having relative density of 50%. The constitutive model parameters for the liquefiable soil layer were derived from cyclic torsional shear tests (carried out by Uemura et al. 2018) at a relative density of 50%. The results are represented in terms of horizontal acceleration response, excess pore pressure response, lateral displacement and bending moment along the pile depth. Excess pore pressure ratio readings indicated the condition of full liquefaction achievement throughout the depth of soil model. The results obtained from all the cases are used to study the amount of lateral stresses induced by the surrounding soil onto the pile surface leading to different amount of lateral displacement and bending moment under the different spreading conditions. The response of the pile system under different sloping conditions is found to differ significantly. The residual lateral displacement and the bending moment is found to be significantly different for single and group pile conditions under kinematic interaction for a 10 degrees ground slope. However, this difference is much lesser for a 5 degree inclined ground surface. The single pile is found to be highly susceptible under an inclined ground surface of 10 degrees among all the cases with the estimated values of residual lateral displacement and residual bending moment being the largest among all the cases studied. It is found that under larger lateral spreading events, higher lateral stresses occur during the initial period of shaking which could lead to much early formation of plastic hinges along the pile length prior to failure.

Keywords: Piled Foundation, Liquefaction, Lateral Spreading, Kinematic Interaction, Effective stress analysis

1. Introduction

The phenomenon of soil liquefaction represents one of the most challenging issues in geotechnical community which has been the cause of failure of foundations, bridges and other structures in the past earthquake. Pile foundations in liquefiable sloping ground represents a complex soil pile interaction problem which could lead to the failure of foundation. Various case histories document the extensive damage to the pile foundations in liquefied soil due to the inertial loading and the lateral ground movement (Hamada 1992; Hamada and O'Rourke 1992; Ishihara 1997 and Japanese Geotechnical Society (JGS) 1996, 1998). Over the years, various methodologies including centrifuge experiments in order to study the soil pile interaction under lateral spreading events (e.g., Abdoun and Dobry 2002, Abdoun et al. 2003, and Brandenberg et al. 2005) have been carried out. Shake table tests (e.g., Hamada 2000, Tamura and Tokimatsu 2005, Cubrinovski et al. 2006 and Ebeido et al. 2019) were also used to study the response of piles under inertial loading and lateral ground movement). Numerical analysis based on two-dimensional and three-dimensional finite element models (e.g. Uzuoka et al. 2007 and Li and Motamed 2017) provide good insights to the response of pile subjected to lateral spreading but this models are very complex and requires huge amount of time for processing.

The variation in the lateral load subjected on the pile due to differences in the lateral spreading events caused by the different sloping ground is not yet clearly understood. The large lateral loads transmitted on the pile due to lateral spreading events caused by steeper sloping ground (e.g. for waterfront structures) may result in significantly large bending moments and shear forces in the piles and the response for such structures might be completely different than under mild slope conditions. The inability of the pile to resist such large bending moments and shear forces may result in extensive damage of the foundation along with the structure. Hence in this paper, an effort has been made to study the response of a single pile and a 2X2 pile group under lateral spreading induced by 5 degrees and a 10 degree sloping ground respectively. The numerical analysis is carried out using a 2D finite element program called as Finite Element Analysis Program for Liquefaction Process (FLIP). The constitutive model parameters were initially estimated by simulating the results of cyclic torsional shear test carried out at a relative density of 50% (by Uemura et al. 2018). The nonlinear spring elements were used to represent the soil pile interaction and the pile was modeled as a nonlinear beam element.

2. Numerical Model

The two dimensional effective stress model called as FLIP ROSE (Finite element analysis program of Liquefaction Process/Response of soil-structure systems during Earthquakes) based on finite element theory is used for the present numerical analysis. The model is widely used to study the degree of damage suffered by the structure resting on liquefiable ground. It is also commonly used to carry out the large deformation analysis for the soil-structure system under seismic loading. The soil element is modeled using a strain space multiple mechanism model (Iai et al. 2011) which represents the nonlinear stress-strain relationship. The pile element is modeled as nonlinear beam element. The response of soil-structure interaction during the seismic loading is highly nonlinear and FLIP ROSE can simulate the soil nonlinearity, the material nonlinearity of piles and the nonlinearity at the soil structure interface in a more efficient way. This allows to study the soil pile interaction during the lateral spreading in a much better way with mechanisms like separation and sliding being considered in the analysis using a soil-pile interaction spring element (Ozutsumi et al. 2003) which incorporates the gap which may form between the pile and the surrounding soil during the lateral spreading event. The numerical analysis is carried out in two stages. Initially the static or self-weight analysis is carried out in order to obtain the initial stress conditions followed by the dynamic analysis to capture the soil-system response during the lateral spreading event under the seismic loading applied at the base of the soil model. The initial static and dynamic analysis are based on the same constitutive equations for soil structure interaction.

3. Different Cases considered in the Numerical Analysis

Four different cases as shown in Figure 1 for single pile and 2X2 group pile were studied under different sloping ground conditions so as to induce different kinematic interactions between the pile and the surrounding soil. Uniform Ottawa F-65 Sand having relative density of 50% is used for all the cases. The water table is considered at the surface throughout the analysis. An end bearing circular steel pipe pile having 1 m diameter and 12 mm thickness is used for all the cases. The elastic modulus of the pile material is 2.0x10^5 MPa whereas the bending stiffness of the pile estimated to be 909000 kN m^2. In case of pile group, the pile spacing is considered as 5m. Figure 1 shows the location of nodes for estimating accelerometer, pore pressure and lateral displacement response for all the cases. The accelerometer and pore pressure transducers were deployed on both sides of the pile shaft in order to assess the soil response in upslope and downslope conditions subjected to different lateral spreading events. The accelerometer is also deployed along the pile shaft in order to compare the pile response with the free field response. The pile response to the lateral spreading for the kinematic interaction is represented in terms of maximum bending moment along the pile depth, shear forces along the pile depth and pile deformations along the depth. Lateral displacements are also measured at the free surface in both upslope and downslope direction and an effort has been made to compare the free field displacements with the pile head displacement in all the cases.

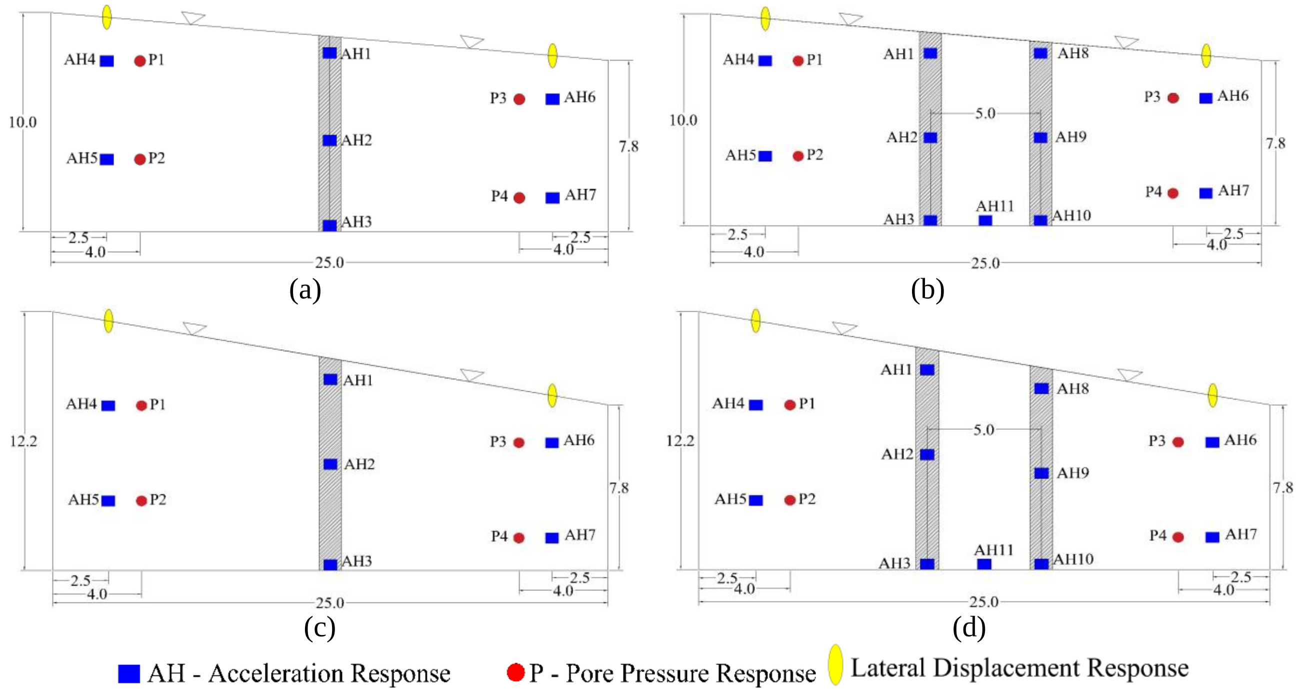


Fig. 1 – Different cases considered in the numerical analysis (a) Single pile with 5 degree ground slope (b) 2X2 pile group with 5 degree ground slope (c) Single pile with 10 degree ground slope (d) 2X2 pile group with 10 degree ground slope

The constitutive model parameters for the liquefiable soil layer were determined so as to reasonably simulate the results of cyclic torsional shear test. Figure 2 represents the numerically simulated liquefaction resistance curve and is compared with the measured liquefaction resistance curve obtained by torsional shear test, where the liquefaction resistance or the onset of liquefaction is defined as the number of loading cycles required to achieve 1.5% double amplitude shear strain. The numerically simulated liquefaction resistance curve is found to be in a good agreement with the measured response.

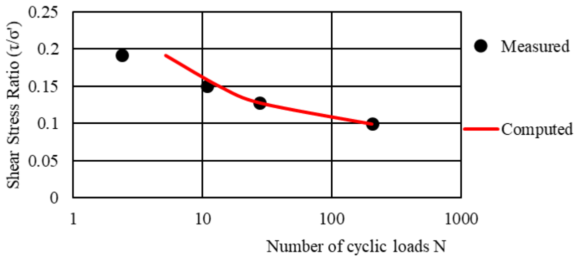


Fig. 2 – Numerically simulated liquefaction resistance curve

A ramped sinusoidal wave is used as an input motion for all the 4 cases as shown in Figure 3. The degrees of freedom for displacement at the base are fixed in the vertical direction whereas the lateral displacement at the side boundaries is allowed in order to simulate the conditions of a free field.

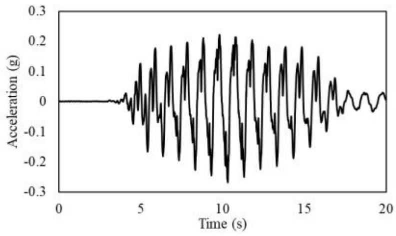


Fig. 3 – Input Motion considered for all the 4 cases

3.1. Case 1: Single Pile with 5 Degree slope inclination

Figure 4 represents the horizontal acceleration response at the free field and at the pile head. Liquefaction occurred during the shaking with the reduction in horizontal acceleration at the surface. Pore pressure response shown in Figure 5 shows the occurrence of liquefaction throughout the depth of soil model, with excess pore pressure exceeding the values of initial effective stress.

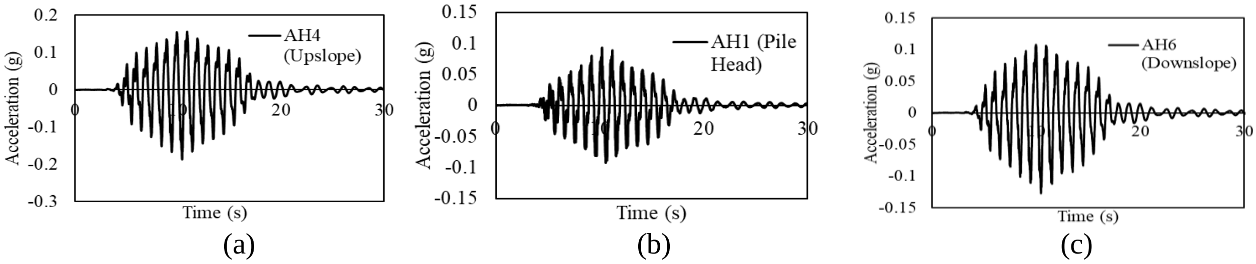


Fig. 4 – Horizontal acceleration response for case 1

The reduction in the maximum horizontal acceleration at the pile head as compared to the peak input horizontal acceleration is observed to be more as compared to the upslope and the downslope free field. The de-amplification ratio at the pile head is estimated to be 0.42 as compared to ratio of 0.90 and 0.70 estimated at the upslope and the downslope free field respectively.

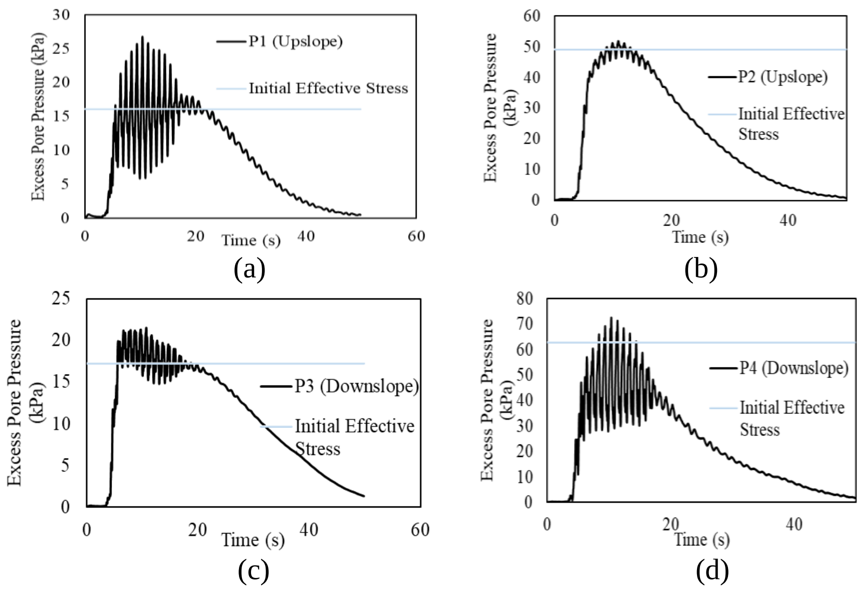


Fig. 5 – Excess pore pressure time history for case 1

The maximum lateral displacement at the pile head (107.92 mm), at the upslope ground surface (143.40 mm) and at the downslope ground surface (189.58 mm) is obtained at the point of occurrence of soil liquefaction (9.95 sec). However, the lateral displacement is found to be decreasing with time after the occurrence of liquefaction because of the increase in denseness of sand. Figure 7 represents the residual lateral displacement and bending moment along the pile length at the end of shaking. The maximum lateral displacement is estimated at the pile head. The maximum bending moment (16.9 kN-m) is estimated at a depth of 4.9 m.

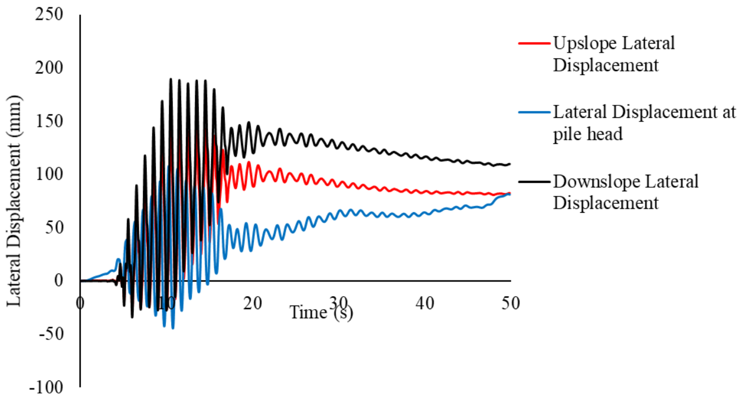
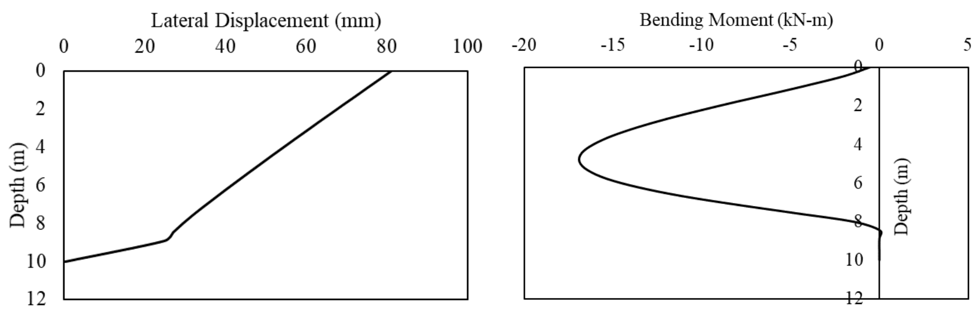


Fig. 6 – Lateral Displacement profile for case 1



(a) (b)

Fig. 7 – Residual Lateral Displacement and bending moment along the pile length (estimated at end of shaking)

3.2. Case 2: 2X2 Group Pile with 5 Degree slope inclination

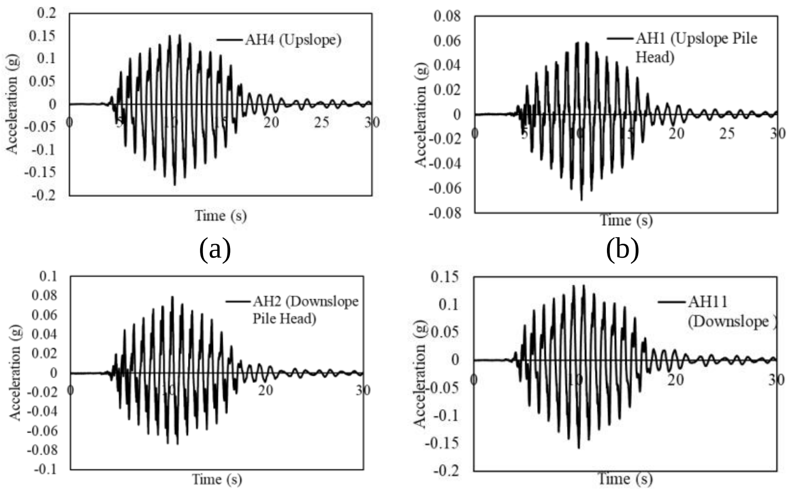


Fig. 8 – Horizontal acceleration response for case 2

A state of full liquefaction was achieved throughout the depth of soil model. Figure 8 represents the horizontal acceleration response for case 2 at the ground surface (upslope and downslope) and for the upslope and downslope piles. The horizontal acceleration response is found to be similar at the upslope and downslope pile head, with maximum horizontal acceleration estimated as 0.06g and 0.08g at the upslope and downslope pile head respectively. This horizontal acceleration response is very close to case 1, where the maximum horizontal acceleration measured at the pile head is 0.09g. The acceleration response at the upslope and the downslope free field seems to be similar.

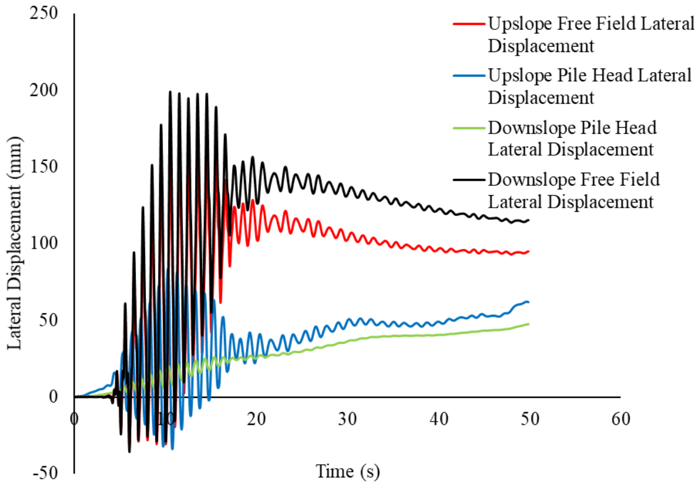


Fig. 9 – Lateral Displacement profile for case 2

The lateral displacement profile for case 2 is shown in Figure 9. The maximum lateral displacement at the upslope and the downslope pile head is estimated as 83.60 mm and 47.46 mm at 10.25 sec and 49.8 sec respectively. The maximum lateral displacement at the upslope pile head is estimated at the point of occurrence of liquefaction similar to case 1 and afterwards it decreases to a residual value of 61.79 mm at the end of shaking. However, the lateral displacement at the downslope pile head continue to increase even after the occurrence of soil liquefaction and records a maximum value at the end of shaking.

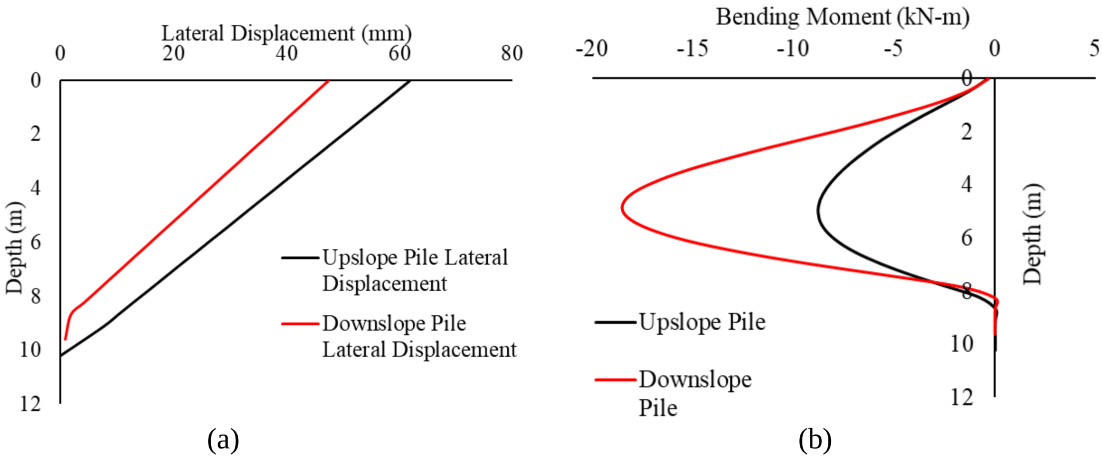


Fig. 10 – Residual Lateral Displacement and bending moment along the pile length (estimated at end of shaking)

Although the residual lateral displacement (at the end of shaking) at the upslope pile head is larger than the downslope pile head as shown in Figure 10, the maximum bending moment for the downslope pile is estimated to be much larger as compared to the upslope pile at the end of shaking. The continuous increase in the downslope pile head lateral displacement even after the occurrence of liquefaction may have led to significantly higher value of maximum bending moment estimated as 18.5 kN-m as compared to the upslope pile maximum bending moment evaluated as 8.81 kN-m.

3.3. Case 3: Single Pile with 10 Degree slope inclination

Figure 11 represents the horizontal acceleration response for case 3. The maximum horizontal acceleration during the lateral spreading event under a 10 degree inclined ground surface is found to be larger than that estimated for a 5 degree inclined ground surface. The acceleration response at the downslope free field surface contains some dilative spikes different from what is observed for the upslope free field ground surface.

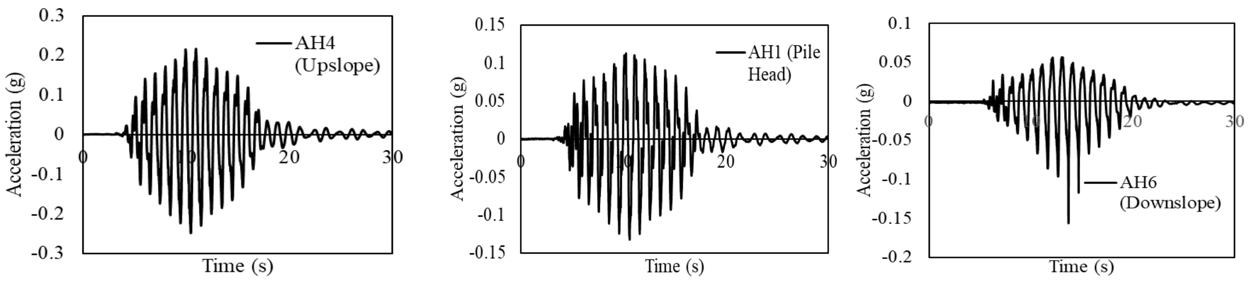


Fig. 11 – Horizontal acceleration response for case 3

The lateral displacement profile for case 3 is shown in Figure 12. The maximum lateral displacement at the upslope and the downslope free field ground surface is estimated as 228.96 mm and 184.26 mm at 14.5 sec and 49.8 sec respectively. The estimated maximum lateral displacement value at the upslope free field is much larger than that estimated for case 1 (under 5-degree slope condition). Although, the maximum lateral displacement is found to occur at the point of soil liquefaction similar to case 1 at the upslope. However, the lateral displacement at the downslope free field continuous to increase for the entire duration of shaking and a maximum residual lateral displacement is estimated at the end of shaking which is significantly higher than the residual lateral displacement estimated for case 1. The maximum lateral displacement at the pile head is estimated as 151.26 mm, which occurs at the point of liquefaction. The displacement is found to decrease beyond liquefaction with a residual value of 114.17 mm estimated at the end of shaking as shown in Figure 11.

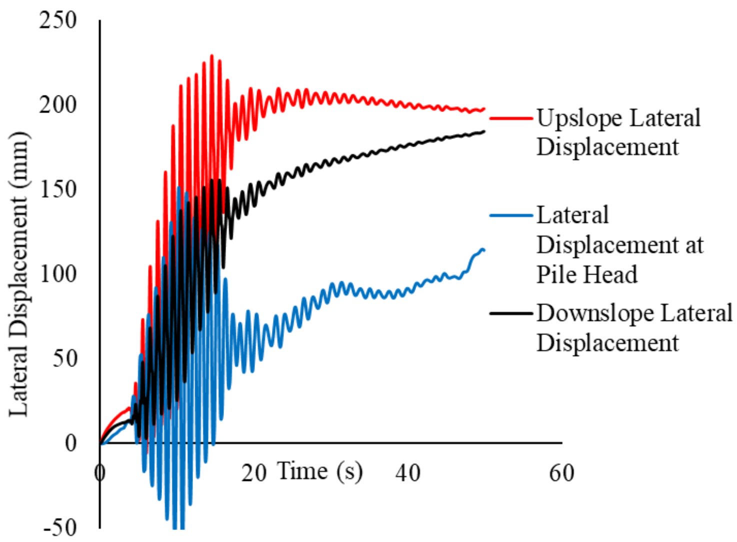


Fig. 12 – Lateral Displacement profile for case 3

Figure 13 represents the lateral displacement and bending moment profile along the pile depth at the end of shaking. The residual lateral displacement at the pile head and the maximum residual bending moment is found to be significantly larger than the soil pile system response estimated at 5 degree sloping ground surface.

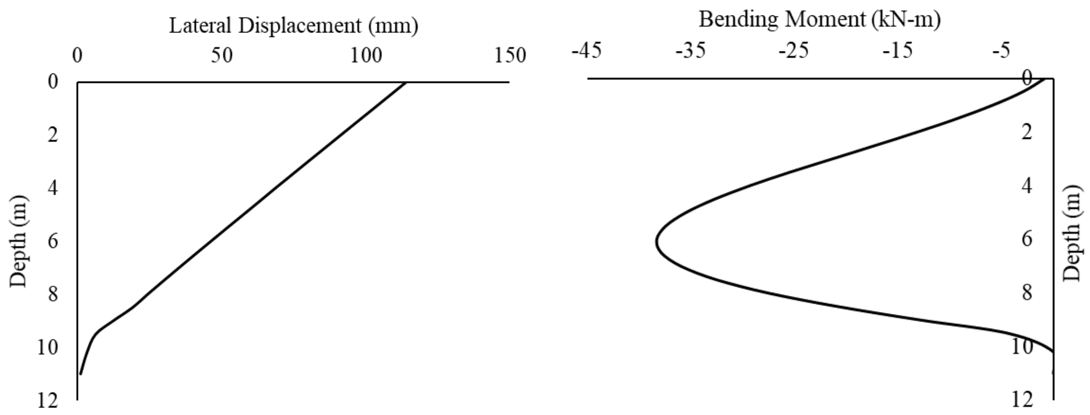


Fig. 13 – Lateral Displacement and bending moment along the pile length (estimated at end of shaking)

3.4. Case 4: 2X2 Group Pile with 10 Degree slope inclination

Figure 14 represents the horizontal acceleration response for case 4. The response at the upslope and the downslope free field ground surface is found to be similar to case 3. The maximum horizontal acceleration measured at the upslope pile head and the downslope pile head is 0.13g and 0.10g respectively.

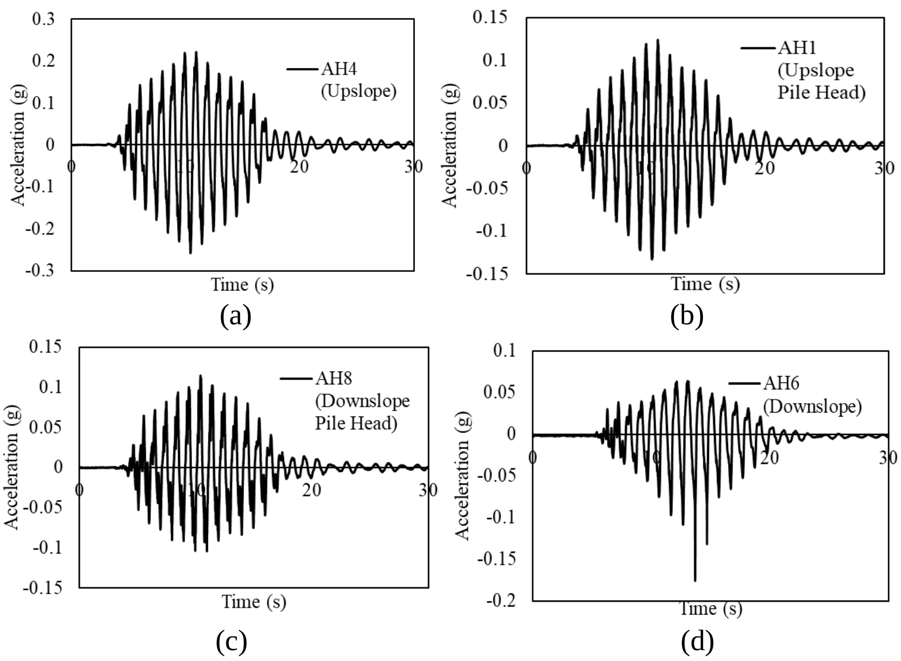


Fig. 14 – Horizontal acceleration response for case 4

Figure 15 represents the lateral displacement profile for case 4. The variation of the upslope and downslope free field lateral displacement is found to be similar as that of case 3. The maximum lateral displacement for the upslope pile head is estimated as 88.66 mm at the point of occurrence of liquefaction. The residual displacement is found out to be 51.84 mm for upslope pile head. However, the lateral displacement at the downslope pile head increases throughout the duration of shaking with maximum residual displacement estimated as 57.05 mm. The residual displacement is found be nearly similar for both the piles and is found to be much lesser than that obtained for case 3 (114.17 mm). Hence it can be said that residual lateral displacement for pile group foundation subjected to large lateral spreading events is much lesser than that of single pile. The lateral displacement and the bending moment profile along the depth of upslope and downslope pile at the end of shaking is shown in Figure 16. The residual lateral displacement is found to be nearly similar at both the pile heads. However, due to continuous increase of the lateral displacement till the entire duration of shaking, a significantly larger maximum bending moment is estimated for the downslope pile (24.15 kN-m) as compared to the upslope pile (12.9 kN-m).

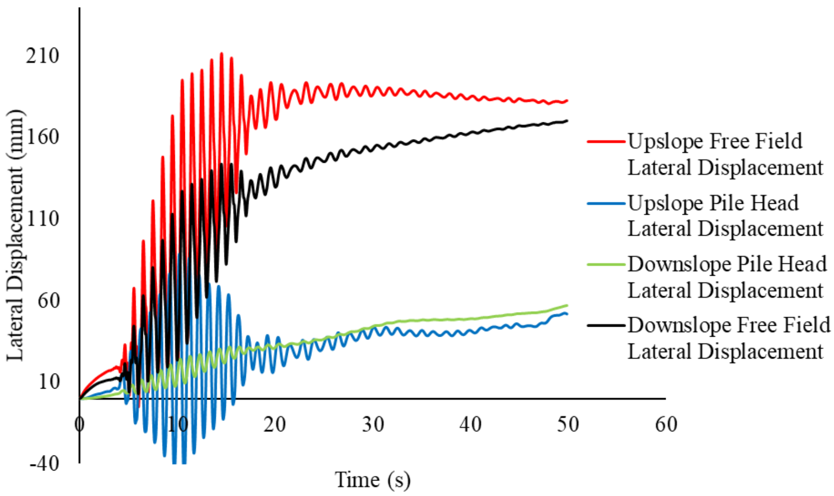


Fig. 15 – Lateral Displacement profile for case 4

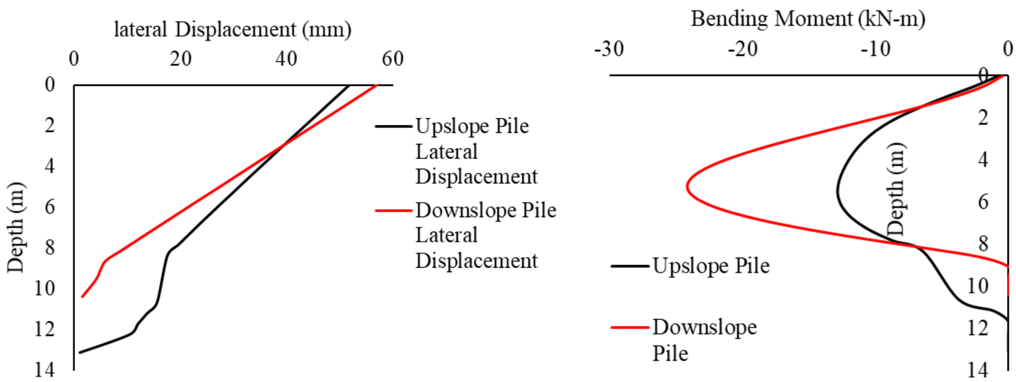


Fig. 16 – Lateral Displacement and bending moment along the pile length (estimated at end of shaking)

4. Comparison of the pile response for all the cases

The pile response for all the cases is compared in terms of residual bending moment and residual lateral displacement as shown in Figure 17. The maximum residual bending moment for all the cases is estimated to be at the center of the pile. The maximum residual bending moment among all the cases is obtained for a single pile subjected to a kinematic interaction under a 10 degree inclined ground surface. However, the maximum residual bending moment is found to significantly decrease for the case of 2X2 group pile under a similar 10 degree inclined ground surface. This value is also significantly lesser in the case of single pile subjected to lateral spreading under a slope inclination of 5 degrees. The residual lateral displacement is also found to be maximum for the case of single pile subjected to a lateral spreading under a higher inclined ground surface of 10 degrees, which is observed to drastically decrease in the case of group piles. The residual moment is estimated to be more for the downslope pile as compared to upslope pile in the case of group pile for a 10 degree inclined ground surface. Hence, it can be said single pile might be very susceptible to a large lateral spreading event with the possible formation of plastic hinges in the center of pile (for a uniform liquefiable strata) considering the inertial loading, if the applied plastic moments exceed the moment resisting capacity of the pile.

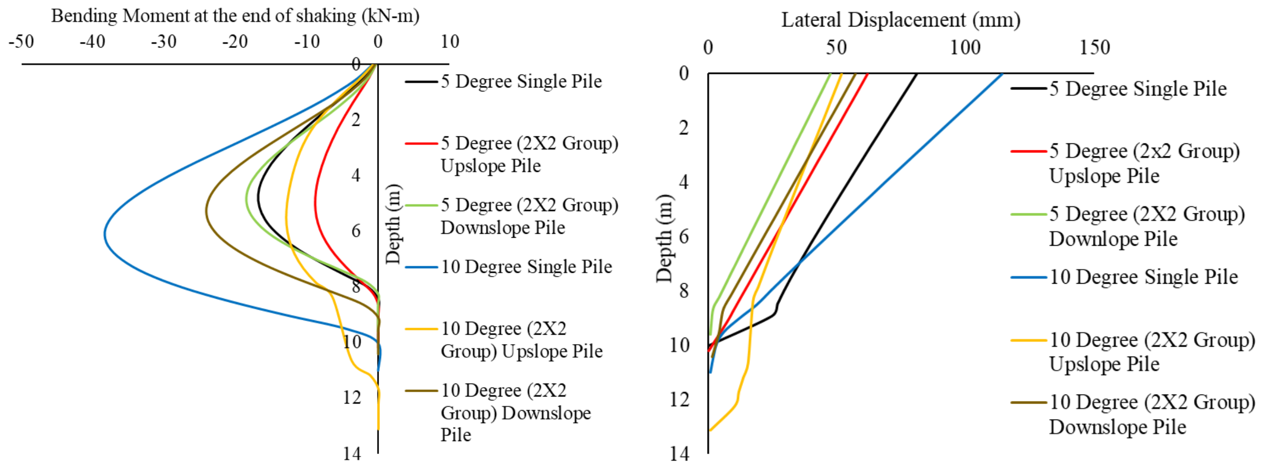


Fig. 17 – Residual Bending Moment and lateral displacement profile for all the cases studied

5. Conclusions

From the present study, some of the key findings are described below:

- The Kinematic interaction involved in soil-pile interface significantly depends on the amount of lateral spreading induced depending on the different sloping angles of the ground surface.
- The response of single pile seems to significantly differ based on the amount of lateral spreading induced. The residual maximum bending moment and the residual lateral displacement at the pile head are estimated as 38.3 kN-m and 114.2 mm under 10-degree ground slope, whereas the residual maximum bending moment and the residual lateral displacement at the pile head in case of 5 degree sloped surface is calculated as 16.9 kN-m and 81.13 mm. Hence the values are found to reduce by 55.87% and 28.95% respectively.
- The maximum lateral displacement estimated at the pile head under a 10 degree inclined ground surface is 151.26 mmm, whereas the pile head in case of a 5-degree slope suffers maximum lateral displacement of 107.92mm. However, in both the cases, the maximum value is estimated at the point of occurrence of liquefaction.
- The reduction in the residual bending moment and the residual lateral displacement at the pile head for the group pile as compared to single pile is found to be significant for a 10-degree slope.
- For a group pile, (under both the sloping conditions), the maximum lateral displacement at the upslope pile head is achieved at the point of liquefaction. However, for the downslope pile, the displacement increases beyond liquefaction till the end of shaking, achieving the maximum value as a permanent lateral displacement.
- The reduction in the maximum horizontal acceleration is found to be much larger at the pile head as compared to the upslope and downslope acceleration response.
- The downslope pile in the pile group under both sloping conditions (i.e. 5-degree and 10-degree) experienced larger residual bending moment as compared to the upslope pile, which is in close agreement with the observations of Motamed et al. (2013) and Ebeido et al. (2019).

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