Soil structure interaction in laterally displacing ground

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ABSTRACT

Design or assessment of structures founded on ground with a potential for seismic induced ground displacements requires careful consideration of the associated soil structure interaction (SSI). These seismic ground displacements could be due to liquefaction and cyclic displacement or lateral spread, or due to slope instability. Potential ground movement and SSI includes considerable uncertainty. This paper outlines some SSI principles to be considered to allow for this uncertainty. Three case studies describe application of these principles. These principles include developing possible scenarios of ground movement, ground and structure shaking and SSI, and testing the design relative to these scenarios. Relative stiffness of ground and structural elements needs to be considered in developing these scenarios. Is the structure pushing the ground or is the ground pushing the structure? The impact of SSI on the magnitude of ground displacement needs to be considered. Will the SSI arrest the ground movement or will the ground movement potentially pull the structure apart? The presented principles and case studies focus on qualitative and simplified numerical assessments. Where considered appropriate and necessary, higher level analyses including dynamic finite element modelling could be undertaken. These higher level analyses should be to supplement rather than replace the simplified methods described in this paper. Higher level analyses could be particularly useful in understanding possible mechanisms of SSI. Assessment would require engineering judgement considering all available information.

1 INTRODUCTION

Design or assessment of structures founded on ground with a potential for seismic induced ground displacements requires careful consideration of the associated soil structure interaction (SSI). These seismic ground displacements could be due to liquefaction and cyclic displacement or lateral spread, or due to slope instability. In this paper we outline some SSI principles to be considered and then present a series of three case studies describing how these principles have been applied. These principles and case studies focus on qualitative and simplified numerical assessments. Where considered appropriate and necessary, higher level analyses including dynamic finite element modelling could be undertaken. These higher level analyses should be to supplement rather than replace the simplified methods described in this paper. Higher level analyses could be particularly useful in understanding possible mechanisms of SSI. Assessment would require engineering judgement considering all available information.

2 SOME SSI PRINCIPLES

2.1 Scenarios

The nature of the potential ground movement and of the SSI includes considerable uncertainty. It may not be possible to predict the ground movement and interaction, but we can develop possible scenarios of this to test our design or assessment against. As the first stage, the geotechnical and structural engineers should collaboratively develop the possible scenario(s) to be considered. The output should be a plan and cross section indicating assumed:

a) Ground movement (lateral extent, depth and direction; and ground inertia)

b) Soil structure interaction (restraint to the ground provided by the structure; and mobilising inertia forces imposed by the structure on the ground)

2.2 Magnitude of ground displacement

There will be considerable uncertainty in any prediction of the ground displacement magnitude. One of the following possibilities could be applied.

a) The structure provides sufficient lateral restraint to the ground such that any ground displacements are likely small and non-damaging (less than a few 10's mm). The analysis would need appropriate factors of safety and parameter selection to develop confidence that larger displacements are unlikely. The structural design will need to allow for the kinematic loading from the ground.
b) The assessed displacements can be tolerated by the structure. This assessed displacement to include consideration of the restraint provided by the structure. Because of the uncertainty in predicting the displacements this should only be applied with caution. In the case of lateral spread this option is unlikely to be appropriate because of the uncertainties. Option c) should then be considered.
c) Assume the ground moves past the structure. The structure would be designed to resist passive loads imposed on embedded elements and friction loads imposed on elements in contact with displacing ground.

2.3 Relative stiffness

Relative stiffness of the ground and structure need to be considered, i.e. If the structure is stiff relative to the ground, the ground can move past the structure imposing passive loads. If the structure is flexible it will move with the ground.

Relative stiffness of the various structural elements interacting with the ground need to be considered, i.e. where structural elements are tied together, the restraint each element provides to the ground, or the restraint the ground provides to the structure, is that at a consistent displacement.

2.4 Tie capacity to resist tearing

A common consideration is the magnitude of tie force required across a structure to resist tearing where differential lateral displacement of the underlying ground is possible. Where the structural engineer identifies a line across the structure's footprint which could be prone to tearing, the geotechnical engineer can assess the magnitude of this stretch force by considering which side of this tear line would the structures footprint most easily slide relative to the ground. The stretch force is calculated as the sum of the passive and frictional forces to allow this sliding.

Where no particular weak line is identified the stretch force can be calculated as half of the total passive and frictional forces resisting sliding across the entire footprint of the structure. This is because the greatest stretch force would be when the two halves of the structure are just on the verge of sliding. It is noted that this may be a conservative estimate of the stretch force because a lesser stretch force may be sufficient to arrest differential displacement of the ground beneath all or part of the structure's footprint. Estimating this stretch force to arrest differential displacement has considerable uncertainty and therefore we have proposed half of the ultimate sliding resistance approach for initial assessment.

3 CASE STUDY 1 – BUILDING ON SHALLOW FOUNDATIONS IN LATERALLY SPREADING GROUND

This case study illustrates the SSI principles described under 2.4 (Tie capacity to resist tearing). This case is for design of a new building.

The building is on shallow foundations (strip footings) located near a reclamation edge in laterally spreading ground. The "free field" differential lateral spread across the building footprint is estimated to be in the order of 100 to 200mm. "Free field" being that if the building was not there. Ground moving more than the building would impose a stretch load on the structure (i.e. ground pulling the seaward side of structure away from landward side, see Figure 1). This stretch load would correspond to the lesser of:

a) The force to arrest differential displacement beneath all or part of the building's footprint.

b) Half of the lesser of:

   i. The frictional sliding resistance beneath the foundations and floor slab plus the passive resistance of the embedded elements (the strip footings).

   ii. The frictional sliding resistance beneath the foundations plus ground friction on a plane linking foundation bases (sliding at base of soil block between foundations).

Because of the high uncertainty in estimating a) it is likely to be appropriate to assume b), accepting that there is a possibility that this may be conservative (i.e. The possibility that a) is less remains).

This approach may be applied in design to calculate the required tie force, or in assessment to calculate if there is a risk of the structure tearing.

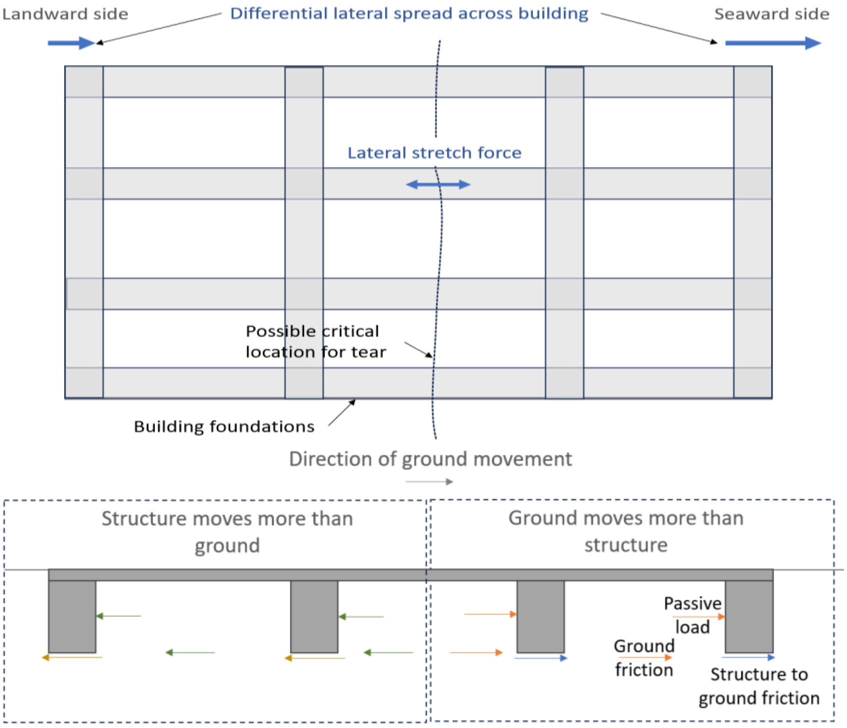

Figure 1: Loads on a structure in differentially laterally spreading ground

4 CASE STUDY 2 – BURIED PILED BOX STRUCTURE IN LATERALLY SPREADING GROUND

This case study illustrates the SSI principles described under 2.1 (Scenarios) and 2.3 (Relative stiffness). This case is for seismic assessment of an existing building. In the seismic assessment of existing buildings, a percentage of New Building Standard (%NBS) rating is assessed. %NBS is an index used to characterise the expected seismic life safety risk presented by an existing building relative to that of a new building. %NBS is calculated as the capacity of an existing building (or element of) divided by the demand imposed at 100%ULS earthquake shaking. In assessing geotechnical matters, capacity and demand are expressed in terms of %ULSshaking. Demand = 100%ULSshaking. Where there is potential for a sudden and large adverse change in geotechnical behaviour with increasing %ULSshaking, this is termed a “geotechnical step change”. To allow for this non-liner behaviour of soils, the %NBS may be factored down depending on the associated impact on the behaviour of the structure. This paper presents a SSI assessment to inform the calculation of %NBS. Assessment of geotechnical step change and the %NBS is beyond the scope of this paper.

A scenario of possible ground displacement, inertia and SSI has been postulated and the structure tested assuming this scenario. Assessment has considered relative stiffness and allowed for consistent displacement of ground and structure.

The structure is a buried basement box founded on piles. The box is ~20m x 55m (seaward wall) in plan and located in liquefiable reclamation fill. The piles extend into the underlying dense Alluvium. Refer Figure 2 for a sketch.

The structure is located near the reclamation edge and located within laterally spreading ground. Structural assessment has concluded that the probable capacity of the piles is a displacement of 90mm at the pile heads, and at this displacement the piles provide a lateral restraint to the structure of 6000kN. Exceeding this probable capacity leads to a significant life safety hazard. Soil structure interaction assessment was undertaken to evaluate the %ULS shaking at which this displacement could occur. That SSI assessment is outlined below. The SSI assessment may be conservative because it assumes:

- The structure and ground is in phase. I.e. the seismic earth pressure on walls, soil inertia and structure inertia all act in same direction and contribute to load at the same time.
- The inertia load is that of the non-liquefied case; however, the resistance the ground is providing is that of liquefied soil. Soil yielding may limit the acceleration transferred to the structure and soil above, and therefore limit the inertia. Piles yielding may change the period and therefore inertia of the structure.

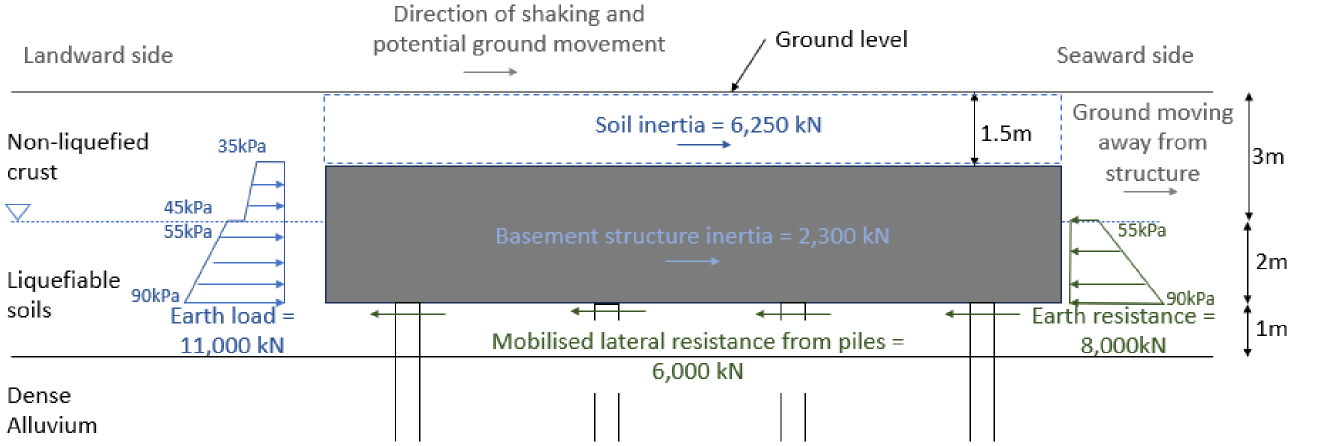

Figure 2: SSI model

Components contributing to lateral resistance:

- Assessed lateral spread potential is of the crust moving seaward away from the structure. The liquefied soil below GWL is assumed to slump back against the structure providing some lateral resistance. Earth pressure of liquefied soil below groundwater level = total stress on wall (The - 2.Su component of an active pressure is ignored because it is expected to be small) = 145 kN/m.55m = 8,000 kN.
- The maximum lateral restraint provided by the piles is at 90mm movement. Mobilised lateral resistance of 30No. piles (as assessed using lateral pile analysis software) = 200 kN/pile.30 piles = 6,000 kN.
- Total lateral resistance = 6,000 kN + 8,000 kN = 14,000 kN

Components mobilising lateral load on the structure (at 100% ULS shaking):

- The ground seaward of the structure is moving away, therefore the soil on the roof imposes an inertia load on the structure. Soil inertia = (weight of soil block).(yield acceleration) = 18kN/m^3.1.5m.20m.55m.0.21g = 6,250 kN.

  The yield acceleration has been calculated based on Newmark sliding block (NSB) assumptions as that which will allow 90mm of displacement during an earthquake with the 100%ULS shaking PGA of 0.59g. In line with NSB assumptions when accelerations higher than the yield are applied, displacements accumulate.
- Basement structure inertia = (Weight of structure).(yield acceleration) = 10kPa.20m.55m.0.21g = 2,300 kN. The structure and soil block above are assumed to be in phase, therefore the same acceleration is considered (rather than the spectral acceleration, or a percentage of it).
- Seismic earth pressure on landward side of structure = Earth pressure of soil above GWL + Earth pressure of liquefied soil below GWL = (60 kN/m + 145 kN/m).55m = 11,300 kN/m
- Lateral mobilising load on structure allowing 90mm displacement = 6,250kN + 2,300 kN + 11,300 kN = ~20,000 kN

In this example, at 100% ULS shaking, the lateral mobilising load (20,000 kN) is significantly greater than the lateral resistance (14,000 kN) at the maximum tolerable pile displacement of 90mm, i.e displacements greater than 90mm and a significant life safety hazard could be expected. At 34% ULS shaking, the lateral mobilising load and resistance are approximately ~14,000 kN (i.e. in equilibrium), when the structure has displaced 90mm.

5 CASE STUDY 3 – BUILDING ON A SLOPE

This case study illustrates the SSI principles described under 2.2 (Magnitude of ground displacement) and 2.3 (Relative stiffness). A design of the structure is developed to mitigate possible ground movements. Lateral design of piles considers their relative stiffness and a consistent displacement.

The proposed building is to be located on a slope and is to be founded on pile foundations. The structure includes an integral basement wall. Refer Figure 3 for a cross section. There are two key components for the soil-structure interaction assessment of this structure.

1) Slope stability / slope displacement potential, including allowing for the restraint from the structure to the ground.
2) Any kinematic loads plus structure inertia loads on foundations. Including relative stiffness of foundations.

Seismic slope stability

Free field (without the structure) slope stability analyses indicated lateral slope movement was possible in a ULS seismic event. Further assessment was carried out to determine the restraint to the ground required from the structure (basement wall and piles) to arrest slope movement.

Considerations for the slope assessment are outlined below. The results are presented in Table 1.

- A required slope stability factor of safety (FoS) in a ULS seismic event of 1.2 was adopted (NZGS/MBIE Module 6).
- Slope stability analysis carried out using a seismic coefficient of 70% of the ULS PGA. This coefficient (in combination with a target FoS of 1.2) was selected based on guidance provided in Kramer (1996).
- Three potential slip surfaces were considered. A global slip (Slip A), a slip behind the building (Slip B) and a slip below the building (Slip C). The three slips had varying elements providing slope restraint (number of piles and/or basement walls).
- The restraint provided to the ground by the basement wall assumes stiff wall earth pressures.
- The slope stability analysis was used to assess the minimum restraint required to be provided by the piles to achieve the target FoS. The pile and basement wall restraint is applied in the slope analysis at their respective locations.
- The ground restraint provided by the piles was applied in the lateral pile analysis at the depth of the slip surface. The modelled pile restraint force was dependent on the number of piles the slip extended through (down the slope), and the pile spacing (across the slope).

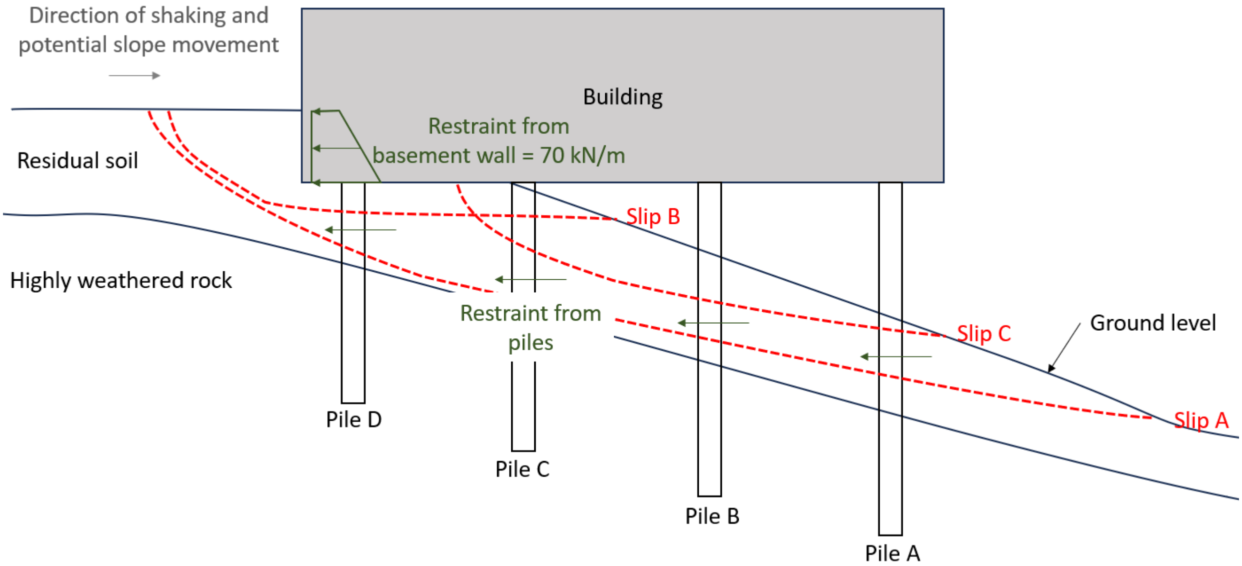

Figure 3: Conceptual slope model

Table 1: Seismic slope stability assessment

Slip ID	Seismic coefficient (g)	Restraint required from piles (kN/m)	Restraint provided by basement wall (kN/m)	Achieved FoS
A	0.48	75	70	1.2
B		-	70	1.5
C		100	-	1.2

Lateral pile analysis

As the structure is located on a slope, the length of pile extending above ground level (cantilever length) varies, resulting in the piles upslope being significantly laterally stiffer than the piles downslope. This variation in stiffness needs to be assessed to determine the base shear resistance provided by each pile at a consistent displacement. Pushover analyses (considering the kinematic / slope restraint load) was carried out for piles with varying cantilever lengths to:

- Assess the allowable lateral displacement of piles. I.e. the displacement at which the stiffest piles reach their moment capacity.
- Evaluate the base shear resistance provided by each pile (depending on cantilever length) at this allowable displacement.

An example of the bending moment and pile head shear force (base shear resistance) vs lateral displacement curves are provided in Figures 4 and 5. In this case, we can see that Pile D (upslope pile) reaches its bending capacity at ~15mm displacement. At this displacement, the base shear resistance provided by Pile A is negligible. Pile B, C and D provide 40 kN, 75 kN, and 205 kN respectively. I.e. the majority of base shear resistance is provided by the upslope piles.

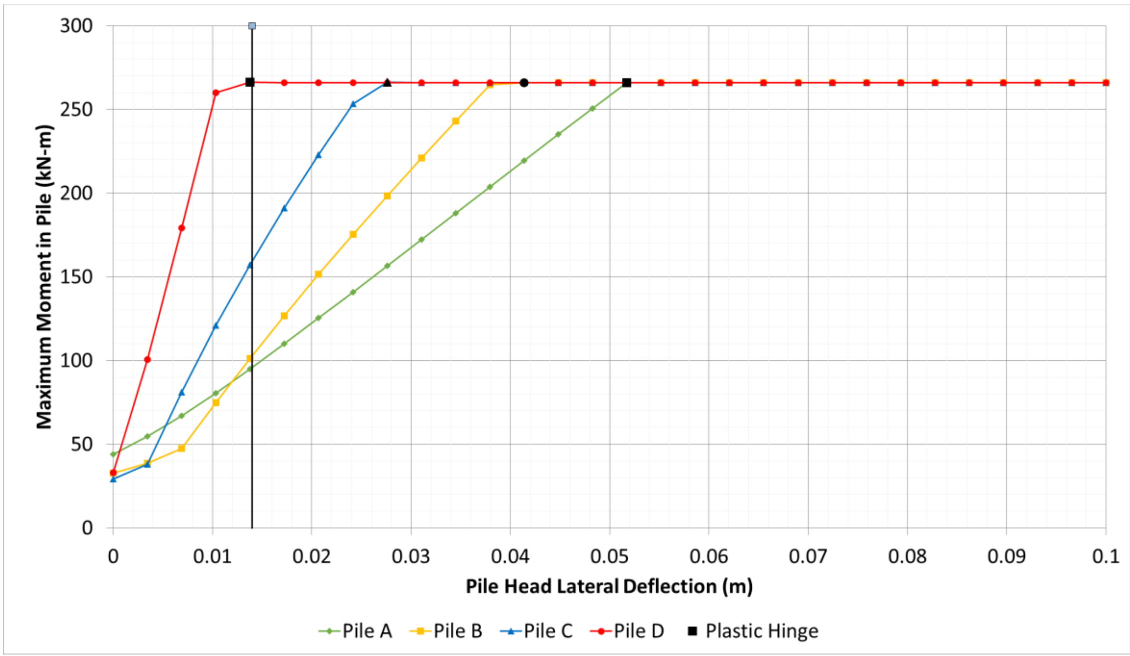

Figure 4: Pushover analysis of piles (maximum moment vs pile head lateral deflection) with varying cantilever lengths (Pile D upslope and Pile A downslope)

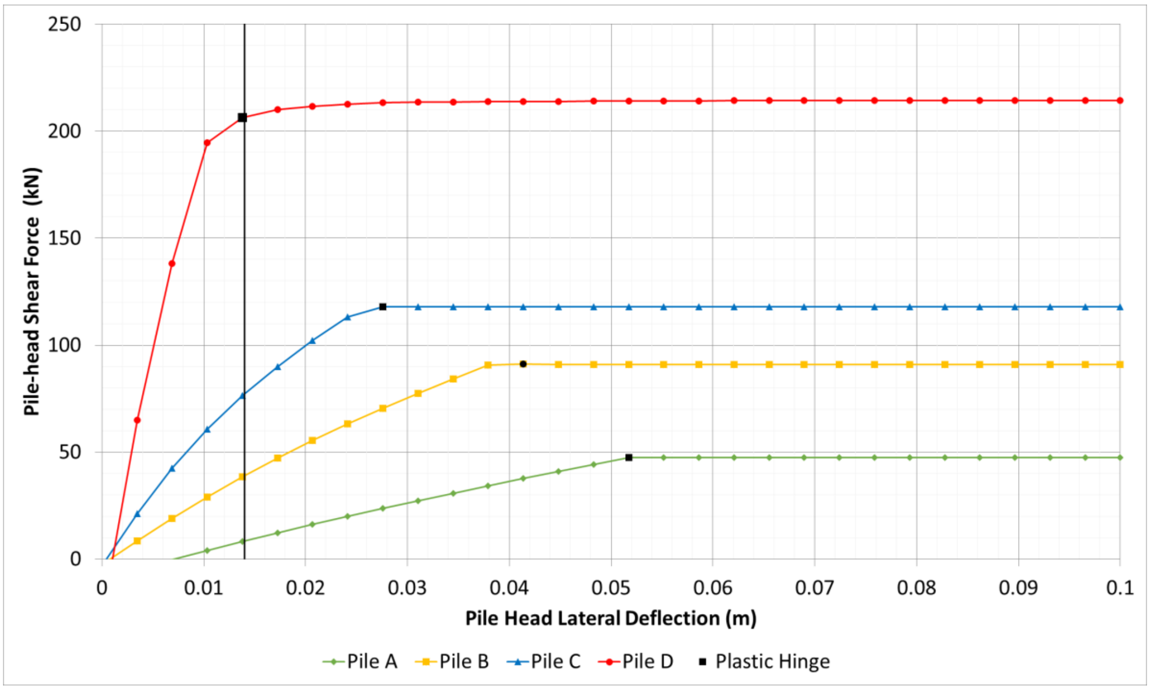

Figure 5: Pushover analysis of piles (pile head shear vs pile head lateral deflection) with varying cantilever lengths (Pile D upslope and Pile A downslope)

6 CONCLUSIONS

- Design or assessment of structures founded on ground with a potential for seismic induced ground displacements requires careful consideration of the associated soil structure interaction (SSI).
- Seismic ground displacements could be due to liquefaction and cyclic displacement or lateral spread, or due to slope instability.
- Potential ground movement and SSI includes considerable uncertainty, however SSI principles can be applied to test our design or assessment against. Geotechnical and structural engineers should collaboratively develop possible scenario(s) to consider.
- The restraint provided by the structure may arrest ground movement, the structure may (or may not) be able to tolerate the ground movement or the ground may move past the structure imposing passive and frictional loads on the structure.
- Stiffness of the structure relative to that of the ground will determine if the ground is loading the structure or providing resistance. Relative stiffness of structural elements interacting with the ground should be considered to determine the magnitude of restraint provided by each element at a consistent displacement.
- Qualitative and simplified numerical assessments can be used to assess the possible behaviour of the structure. However, the simplified assessments typically include a number of conservative assumptions, and engineering judgement should be exercised. Where appropriate and necessary, higher level analyses (e.g. dynamic finite element modelling) should be to supplement rather than replace the simplified methods.

7 REFERENCES

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