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DYNAMIC ANALYSIS OF SOIL-PILE-STRUCTURE INTERACTION IN LATERALLY SPREADING GROUND

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ABSTRACT

In the simplified approach, a pseudo-static beam-spring method is used; this analysis can be performed using common site investigation data such as SPT blow count, yet it captures the basic mechanism of pile behaviour. However, the phenomenon of soil liquefaction is complex and predictions of the seismic response are subject to a high level of aleatoric uncertainty. Therefore in the simplified analysis the key input parameters are varied parametrically to identify key features of the response. The effects of varying key parameters are evaluated and summarised to provide guidance to designers on the choice of these parameters.

The advanced analysis was based on the effective stress principle and used an advanced constitutive model for soil based on a state concept interpretation of sand behaviour. The analysis results give detailed information on the free field ground response, soil-structure interaction and pile performance. The modelling technique is described in detail to provide guidance on the practical application of the effective stress methodology and to illustrate its advantages and disadvantages when compared to simplified analysis. The likely effects of liquefaction, lateral spreading and soil-structure interaction on the bridge during a predicted future earthquake are examined.In the simplified approach, a pseudo-static beam-spring method is used. ; this analysis can be performed using common site investigation data such as SPT blow test

1 INTRODUCTION

Pile foundations are primarily designed to transfer vertical loads from the superstructure to the bearing stratum. For this reason, piles are relatively vulnerable to lateral loads such as those imposed by ground shaking during strong earthquakes. In the case of soil liquefaction, this vulnerability is particularly pronounced since the loss of strength and stiffness in the liquefied soil results in a near complete loss of lateral support for the embedded piles. It is known from previous earthquakes that liquefaction can cause very large loads on pile foundations, both from inertial loads from the superstructure and from lateral displacements of liquefied soil. The extensive damage and failure of piles have affected numerous bridges, buildings and storage tanks in the past.

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During recent strong earthquakes, a large number of pile foundations of modern structures have been severely damaged or collapsed in liquefied soils. In the 1995 Kobe earthquake, for example, massive liquefaction of reclaimed fills caused damage to numerous pile foundations of multi-storey buildings, storage tanks and bridge piers. The unprecedented level of damage to foundations of modern structures instigated a great number of research studies in order to better understand soil-pile interaction in liquefied soils and to improve the seismic performance of pile foundations.

2 OBJECTIVES AND METHODOLOGY

The objective of this research is firstly to investigate and summarise the seismic performance of pile foundations in liquefiable soil, and then to contribute to the improvement both of simplified and advanced design methodologies. The behaviour of pile foundations in liquefiable soil observed in (a) case histories from previous earthquakes; (b) experimental tests using 1-g shake tables and centrifuge models and (c) analytical studies is summarised. This is to provide evidence of the performance of pile foundations and to identify key issues and damage characteristics. The capabilities and performance of existing analytical methods are also summarised.

2.1 **KEY PARAMETERS AND UNCERTAINTIES**

Cubrinovski and Ishihara (2004) identified the following key parameters affecting the pile response:

- The stiffness and strength of the liquefied soils, β and p2-max
- The ultimate pressure exerted by the crust layer, p1-max
- The magnitude of the lateral ground displacement, UG2
- The inertial load applied, F

The intrinsic uncertainties associated with piles in liquefiable ground are directly reflected on these key parameters. Therefore for the analysis of piles in liquefiable soil these parameters should not be uniquely determined; rather a range of values should be considered. For this reason a parametric study was performed on a case study to examine how variations in these four key parameters affect the pile response.

2.2 STUDY – FITZGERALD BRIDGE

To illustrate the effects of variation in key parameters on the pile performance, parametric studies were conducted on a case study of twin bridges crossing the Avon River in Christchurch, New Zealand. The Fitzgerald Avenue Twin Bridges, shown in Figure 1, cross the Avon River and carry three lanes of southbound traffic on the east bridge and two lanes of northbound traffic on the west bridge. Both bridges are supported by piled abutments on the banks with a central piled pier at the mid-span. According to the initial investigations, the existing piles were founded on potentially liquefiable soils.

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Figure 1 Fitzgerald Avenue Twin Bridges over the Avon River

The bridges have been identified as an important lifeline for post-disaster emergency services and recovery operations. To avoid structural failure of the foundations or significant damage causing loss of function of the bridge in an anticipated earthquake event, a structural retrofit has been proposed by the Christchurch City Council. In conjunction with bridge widening, thisretrofit involves strengthening of the foundation with new large diameter bored piles to be installed; the location of the new piles are shown schematically by the solid circles on the plan of the site shown in Figure 3.4. The new piles will be connected rigidly to the existing foundation and superstructure, and founded into deeper strata consisting of non-liquefiable soils.

2.3 SEISMIC HAZARD

Previous seismic hazard studies for Christchurch (Dowrick et al. 1998; Stirling et al. 2001) indicate that the most significant contribution to the ground shaking hazard arises from a magnitude 7.2-7.4 event on the strike-slip Porters Pass fault, which is located at a distance of about 40-60km from the site. With regard to the importance level of the bridge as a lifeline, the loadings standard NZS1170.5 requires an ultimate limit state (ULS) design seismic event with an annual probability of exceedance of 1/2500, i.e. a 2500 year event. This corresponds to a peak ground acceleration of 0.44g, as calculated in NZS1170.5 based on the soil conditions and period of the structure.This is roughly in agreement with the above mentioned peak ground acceleration from Stirling et al. (2001)

The seismic response of the proposed 1.2m diameter pile at the north-east corner is evaluated using the pseudo static approach described in Section 2. The key parameters in the procedure identified in Section 2.3 are varied to account for uncertainties in the analysis; this is to gain insight into how variations in

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these parameters affect the analysis results. In all analyses the properties of the pile, the crust and base soil layers were kept constant. The two phases in the response, the cyclic phase and lateral spreading, were treated separately. In cyclic phase analyses, an inertial load was applied at the pile head in addition to the ground displacement shown in Figure 1b. In contrast, the lateral spreading cases have no inertial load and the ground displacement has a cosine profile throughout the liquefied layers with a magnitude UG at the top of the liquefied layer.

3 2-D MODELLING OF 3-D EFFECTS

Effective stress analysis techniques such as the method described in Chapter 4 can be formulated in two or three dimensions. The response of pile foundations in liquefied soil is clearly a three dimensional (3-D) problem; three dimensional effects arise from:

(a) The geometry of the soil-pile-structure system,

(b) Multi-directionality of earthquake motion, and

(c) The 3-D stress strain behaviour of soil.

Whilst full 3-D analysis methods are desirable, the application of these methods in practice is constrained by large computation demands, the high level of user knowledge and time required to set up the model and process the results. 2-D finite element simulations can give sufficient accuracy and have been verified by many studies; however it is difficult in 2-D models with stiff pile groups to model the effects of large lateral ground displacements typical of lateral spreading. For example, consider the case of a pile group embedded next to a quay wall or riverbank. In a conventional 2-D model the seaward soil is separated from the landward soil by a stiff pile group, thus large lateral ground displacements are unable to develop. Also, each pile in the group experiences the same ground displacement.

3.1 Modelling concept

Figure shows three types of 2-D finite element models. Conventional 2-D plane models (Figure 5.1a) can be extended by adding an out-of-plane thickness(Figure 2b) to account for the width of the finite element mesh in the z- direction.

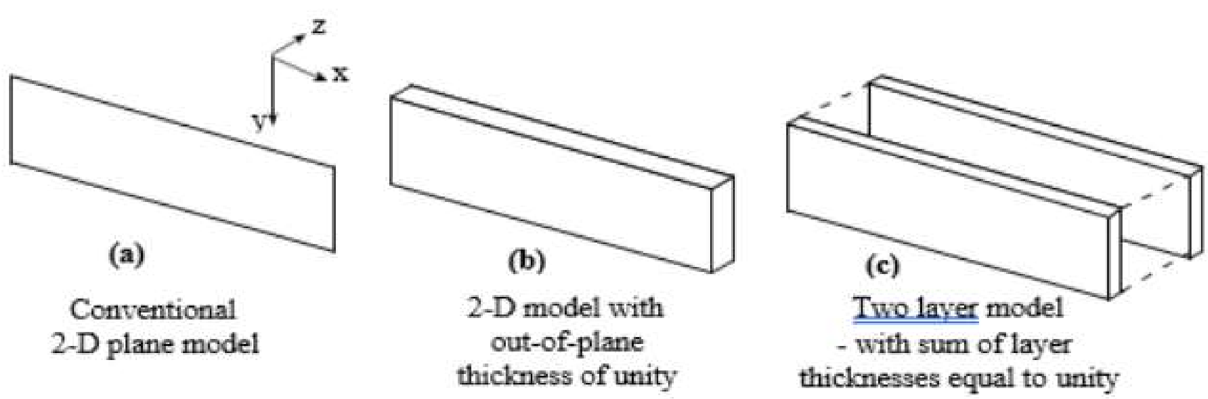

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Figure 2 Finite element modelling techniques: (a) conventional plane model with noout-of- plane thickness, (b) one layer model with out-of plane thickness, (c) two layer model with layers of different thicknesses

It is proposed that by overlapping two 2-D finite element meshes, linked by appropriate boundary conditions, certain characteristics of 3-D behaviour can modelled. For example to model the lateral spread of liquefied soil past a pile group, a 2-D finite element mesh representing the pile group is overlain by another mesh representing the free field soil. The relative contributions of these two meshes can be controlled by altering the out-of-plane thicknesses of the two meshes. It was found that the most effective modelling technique was to model the stiffer layer (i.e. the layer containing the piles) as a secondary layer attached to a primary layer of free field soil. The most appropriate way to connect the two layers was by constraining the nodal displacements of the edges of the secondary layer to those of the corresponding nodes on the primary layer.

This is shown schematically in Figure 3 for a deep-soil-mixing (DSM) wall. Here the primary layer represents a cross section through the centre of the DSM-wall cell and the

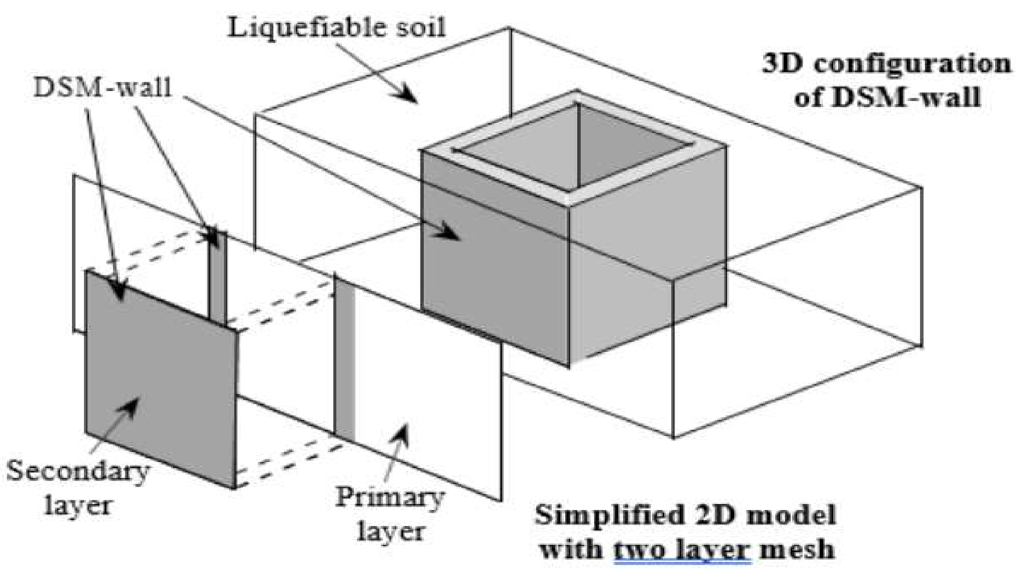

Figure 3. Simplified 2-D modelling of the 3-D configuration of a DSM-wall using a two layer mesh

3.2 Verification with simple model

To verify the modelling concept a simplified model was created of a point load on a cantilever beam. The model consisted of two layers of elastic solid elements, one layer has a stiffness of k= EI and the other layer has a stiffness of k = 2EI. The layers were connected at both the fixed and free ends of the beam. A point load was applied at the free end; the magnitude of the load was kept at a constant value.

The out-of-plane thicknesses of the two layers were varied; this was done for three reasons:

• To verify that two layer meshes can be modelled successfully

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• To verify that the total stiffness of a two layer model can be controlled by varying the out-of plane thicknesses of the two layers

• To verify that the two layer model is consistent with an equivalent conventional one layer model

Figure 4 shows a plot of displacement calculated at the free end of the beam against the out of plane thickness of Layer No. 2, which has twice the stiffness of Layer No. 1. The y- axis is the displacement relative to the displacement of one layer model with a stiffness of k = EI. The thicknesses of the two layers were varied from zero to one; however the sum of the two thicknesses always summed to unity. For example when Layer No. 2 has thickness.

Layer No. 1 has a thickness of 0.4. The results of the two layer cases are plotted as points in Figure 5.3, these results are compared with a conventional one layer model (solid line) with an equivalent stiffness. When the thickness of Layer No. 2 is 1.0 and the thickness of Layer No. 1 is 0, the relative displacement is 0.5. This is expected as the stiffness of the model has doubled. Figure 5.3 shows that the total stiffness of a two layer model can be appropriately modelled by changing the layer thickness. Note that both the one and two layers cases do not quite match the straight line predicted by theory. It is assumed that this is due to the relatively coarse finite element mesh.

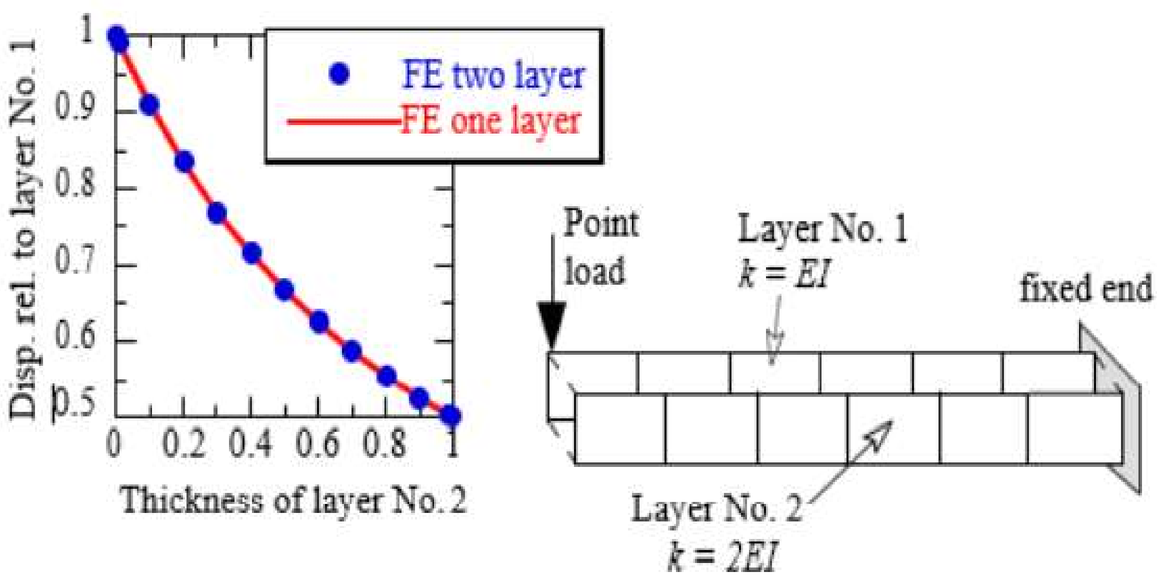

Figure 4 Comparison of theoretical and two layer cantilever beam results

4 EFFECT OF LAYER THICKNESS

The simplified method described above was extended to incorporate non-linear materials and more complicated loadings. A similar series of analyses were conducted on two layer models with varying thicknesses. The models consisted of a primary layer of liquefiable soil enclosed between two stiff elastic DSM-walls. A secondary layer consisting of a DSM wall was connected to each end of the model as shown in Figure 5.4b. Two different loading cases, shown in Figure 5.4c, were applied to the model. In

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the static case, a point load was applied at the top of the wall; the dynamic case was subjected to earthquake excitation. Figure shows how the calculated displacement of the model varies with the thickness of the secondary layer for both loading cases. The relative wall displacement is plotted on the y-axis. Here this represents the displacement at the top left node of the model divided by the corresponding displacement of a model with the secondary layer only. The thickness of the secondary DSM-wall layer is plotted on the x- axis. It can be seen that both loading cases show similar trends and that as the thickness of the wall increases the wall displacement decreases. This indicates that the modelling concept can be applied to complex materials such as liquefiable soil and complex loadings such as earthquake excitation.

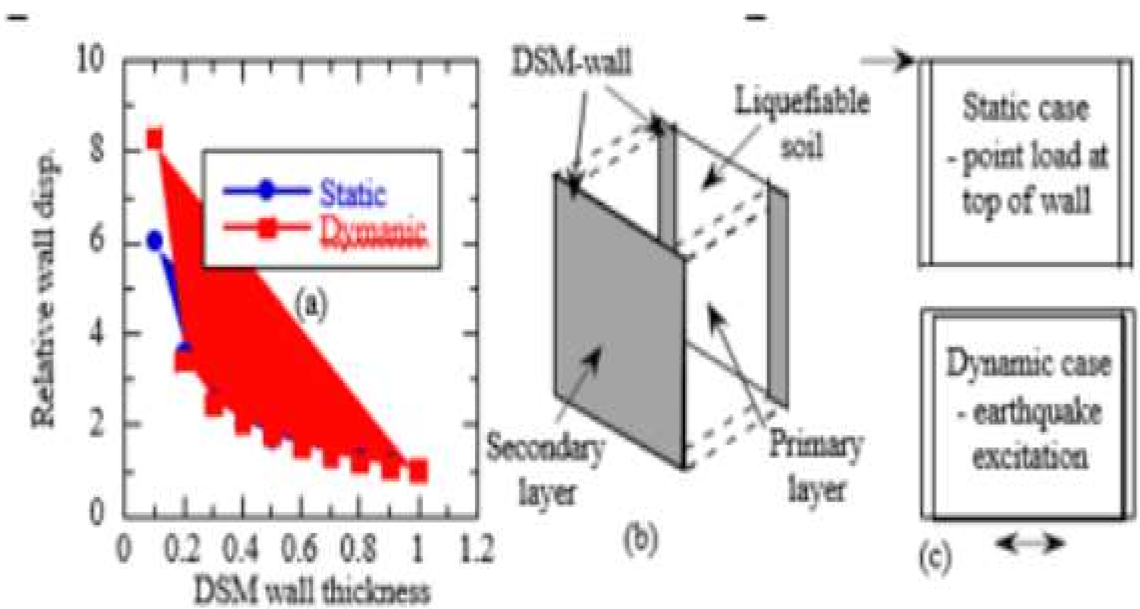

Figure 5 Relative displacement of wall as a function of DSM-wall thickness

5 CONCLUSIONS

The advanced analysis was based on the effective stress principle and used an advanced constitutive model for soil based on a state concept interpretation of sand behaviour. The analysis results give detailed information on the free field ground response, soil-structure interaction and pile performance. The modelling technique is described in detail to provide guidance on the practical application of the effective stress methodology and to illustrate its advantages and disadvantages when compared to simplified analysis.

Finally, a two-dimensional, two-layer finite element modeling technique was developed. This technique was successful in predicting three dimensional aspects of deep-soil-mixing walls and pile groups in liquefied soil. For cases where such aspects are important to the overall response of the foundation, this method is an alternative to the exhaustive demands of full 3- D analysis.

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