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EFFECT OF LATERAL STIFFNESS OF SUPERSTRUCTURE ON BENDING MOMENTS OF PILE FOUNDATION DUE TO LIQUEFACTION-INDUCED LATERAL SPREADING

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SUMMARY

Centrifuge modelling is used as main tool to study the effect of the superstructure's horizontal stiffness on the maximum pile bending moments caused by lateral spreading. Results of four centrifuge tests which model a single pile embedded in a two-layer soil profile are presented. The superstructure's horizontal stiffness was modelled as a horizontal spring connected to the top of the pile. The recorded maximum moments were predicted using a simple limit equilibrium approach recommended by Dobry and Abdoun (1998). A generally good agreement was observed between predicted and recorded maximum moment distributions, both in terms of their distributions and values.

INTRODUCTION

Lateral spreading of sloping ground or of soil near a waterfront is a common occurrence of liquefaction-induced ground failure in earthquakes. Particularly damaging is the effect of the permanent ground displacements on deep foundations of buildings and bridges, as shown in the last twenty years by a number of earthquakes. Examination of case histories indicate that this is essentially a pseudo-static, soil-structure interaction phenomenon caused by the pressure of the laterally moving liquefied and nonliquefied soil layers on the piles and pile cap constituting the deep foundation. Which ones and how much of these effects are present in any situation depend in a complicated way on a number of factors, including the free-field permanent displacement and the restraining stiffness of the superstructure. This last factor is especially important for pile-supported bridge piers, where the lateral (typically longitudinal) stiffness of the superstructure can play a significant role on the foundation response.

The effect of the superstructural stiffness on the lateral displacement of the foundation and on the induced maximum bending moments in the piles is studied by means of four centrifuge tests, labelled Models 3-Abdoun, 2free-24, 2free-49, and 2free-168. The bridge lateral stiffness is modelled as a horizontal spring k connected above ground to the top of the pile; in the four models, the stiffness of this spring is different, varying from $k = 0$ to very stiff. Model 3-Abdoun corresponding to $k = 0$, already reported in previous publications, indicated that the pressure exerted by the liquefied soil per unit area of the pile has an approximately inverted triangular shape with depth, with a maximum pressure of about 17.7 kN/m2 occurring at the top of the pile (Abdoun, 1997; Dobry and Abdoun, 1998).

MODEL DESCRIPTION

The four centrifuge experiments study the effect of the superstructure's stiffness on the response of the pile subjected to lateral spreading. The basic setup is presented in Fig. 1. The RPI flexible laminar box container is used. The model consists of an individual end-bearing pile going through a uniform liquefiable sand layer. The

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prototype single pile being simulated is 60 cm in diameter, 8 m in length, has a bending stiffness, EI = 8000 kN-m2, and is embedded in the two-layer soil system. The displacement at the top of the pile is restrained by a horizontal spring connected at z = - 0.85 m. The corresponding horizontal spring constant for Models 3-Abdoun, 2free-24, 2free-49, and 2free-168, are k = 0, 24, 49, and 168 kN/m, respectively. The bending moments are measured at six positions along the pile using strain gauges SG1 to SG6. The displacement at the restraint is measured using LVDT6. The soil deformations in the free field are measured by connecting LVDTs to the laminar box rings (LVDT1 to LVDT5). The prototype soil profile consists of 6 m layer of Nevada sand saturated with water, having a relative density of about 40%, and placed on top of a 2 m slightly cemented sand layer. The soil is instrumented with piezometers PPT1 and PPT2. Two accelerometers are connected to the rings (A5 and A6), while two accelerometers measure accelerations in the liquefied soil (A2 and A3). The acceleration of the cemented sand layer is also measured (A4). The whole model is slightly inclined to the horizontal to induce lateral spreading. Figure 2e presents the prototype input acceleration consisting of 40 cycles of amplitude 0.3 g and frequency of 2 Hz applied parallel to the base.

TEST RESULTS

Figure 2 shows typical results obtained from a centrifuge test using the setup presented in Fig. 1. These particular results are from Model 3-Abdoun reported by Abdoun (1997). The pore pressure (Fig. 2d) first increased rapidly and then more slowly. After the shaking stopped, the excess pore pressure slowly dissipated. The lateral displacements in the free field increased monotonically or stayed constant during the shaking (Fig. 2a). The maximum permanent lateral displacement occurred at the ground surface. The maximum ground surface displacement for Models 3-Abdoun, 2free-24, 2free-49, and 2free-168 at the end of shaking was 80, 90, 72, and 68 cm, respectively. The pile head displacement (Fig. 2b) and bending moments (Fig. 2c) in all tests, first increased reaching a maximum and then decreased to a final permanent value. These maximum and permanent values of pile head displacement and bending moments decrease as the stiffness, k, increases presumably because of the additional force exerted by the spring to the head of the pile. Fig. 3 shows the free field displacement profile at the end of the test measured in Model 3-Abdoun.

Figure 4 presents the profile of maximum recorded pile bending moments for the four centrifuge experiments. As the magnitude of the spring constant, k, increases, the maximum recorded moment at z = 5.75 m decreases and the moments recorded in the pile at shallow depths increase in the negative direction. Also, the depth at which the moment diagram crosses the zero axes, increases as k increases.

LIMIT EQUILIBRIUM ANALYSES

Abdoun (1997) suggested a limit equilibrium analysis to evaluate maximum bending moments measured in lateral spreading centrifuge tests involving instrumented piles. Dobry and Abdoun (1998) concluded that the maximum bending moment could be obtained by applying an inverted triangular pressure distribution having a value of 17.7 kN/m2 at the ground surface.

Abdoun (1997) modelled the pile as a cantilever beam fixed at the bottom of the pile, Fig. 5a. This structural model assumes that the pile does not rotate at the interface between the bottom slightly cemented layer and the liquefiable layer. The predicted lateral displacement of the pile using this structural model and the inverted triangular pressure distribution is 15.7 cm, which is much less than 30 cm measured in Model 3-Abdoun. The discrepancy between the predicted and measured moment is attributed to rotation at the bottom of the pile.

To improve the structural model of Fig. 5a, a rotational spring, kr, was added at a depth of 6 m to incorporate the finite stiffness of the bottom nonliquefiable layer, Fig. 5b. The maximum pile head displacement obtained in Model 3-Abdoun was used to calculate the value of kr. This measured maximum pile head displacement is 30 cm, which is the sum of two displacements: one related to the deformation of the pile due to the pressure exerted by the liquefied soil on the pile, Δdef, and the other related to the rotation at the rotational spring, Δrot (occurring at the interface between liquefied soil and the bottom slightly cemented layer). That is, Δdef + Δrot = 30 cm. Using the triangular pressure distribution of 17.7 kN/m2, Fig. 6, suggested by Dobry and Abdoun (1998) and modelling the pile as a cantilever beam, the displacement at the pile head due to the pressure of the liquefied soil, gives Δdef = 15.7 cm. Then, the displacement at the pile head associated with the rotation of the rotational spring, kr, can be calculated as Δrot = 30 – 15.7 = 14.3 cm. Assuming small rotation, the rotation of spring kr can be calculated as θ = 14.3 cm/600 cm = 0.023833 radians, where 600 cm is the length of the pile. Finally, the rotational spring constant is calculated as the moment at the rotational spring assuming a triangular pressure distribution divided by the rotation of the rotational spring. That is, kr = M/θ = 127.44 kN-m/0.02833 rad = 5347 kN-m/rad. This value of kr will be used in this paper to model the rotational stiffness of the bottom slightly cemented sand layer, in the rest of the limit equilibrium analyses of the four centrifuge tests.

Figure 6 presents the analytical model used to evaluate the results of the four tests. It represents the pile as a beam 6.85 m in length, supported at the base by the rotational spring kr = 5347 kN-m/rad and at the top by a horizontal spring k. The values of this spring are k = 0, 24, 49 and 168 kN/m depending on the test. The beam is loaded with the inverted triangular load of maximum pressure 17.7 kN/m2 suggested by Dobry and Abdoun (1998) from Model 3-Abdoun. That is, for the 0.6 m diameter pile used in the centrifuge experiments, this corresponds to a triangular load per unit length of pile of (17.7)(0.6) = 10.62 kN/m at the ground surface and zero at a depth of 6 m. In Fig. 6, Fs is the force taken by the spring, which is calculated as part of the solution.

Comparisons between the computed pile bending moments using the analytical model of Fig. 6, and those measured in Models 3-Abdoun, 2free-24, 2free-49, and 2free-168, are shown in Fig. 7. It can be observed that the calculated moment distributions agree well with the measurements from Models 3-Abdoun and 2free-24, while for Models 2free-49 and 2free-168, having a stiffer spring at the top, the measured moments are somewhat overestimated. One possible explanation is that these limit equilibrium analyses do not consider soil-pile interaction, and that the pressure exerted by the soil on the pile for the models with a stiffer spring at the top may have been different than the simple inverted triangular distribution of Fig. 6. However, the limit equilibrium results predict correctly the trends of decreasing bending moments at depth, and increase of negative moments at shallow elevations, as k increases.

CONCLUSIONS

The effect of the superstructure's horizontal stiffness on the pile bending moments induced on the pile by lateral spreading was studied using centrifuge models. Results of four centrifuge tests, Models 3-Abdoun, 2free-24, 2free-49, and 2free-168, with superstructural horizontal stiffness, k = 0, 24, 49, and 168 kN/m were presented and discussed.

In all tests, the recorded pile head displacement and the bending moments increased reaching a maximum, and then decreased to a final permanent value. The final permanent values of pile head displacement and of bending moments at depth decreased as the value of the horizontal stiffness increased.

The maximum measured bending moment always occurred at the interface between the liquefied soil and the cemented layer, and its value decreased as the horizontal stiffness increased. Similarly, the maximum pile head displacement decreased as k was increased. Negative bending moments appeared at shallow depths when the horizontal spring was introduced, and they increased with the value of k.

The recorded maximum bending moments along the pile were predicted using an inverted triangular lateral pressure distribution of 17.7 kN/m2 at the ground surface, as recommended by Dobry and Abdoun (1998). A good agreement between the predicted and recorded maximum bending moments is obtained when k = 0 and 24 kN/m. As k increases, a reasonable agreement is observed for the top part of the pile but the bending moments are overestimated for the bottom part of the pile. For all values of k, the limit equilibrium analysis predicts correctly the trends of decreasing positive bending moments at depth, decreasing pile head displacement, and increasing negative bending moments at shallow elevations as k increases.

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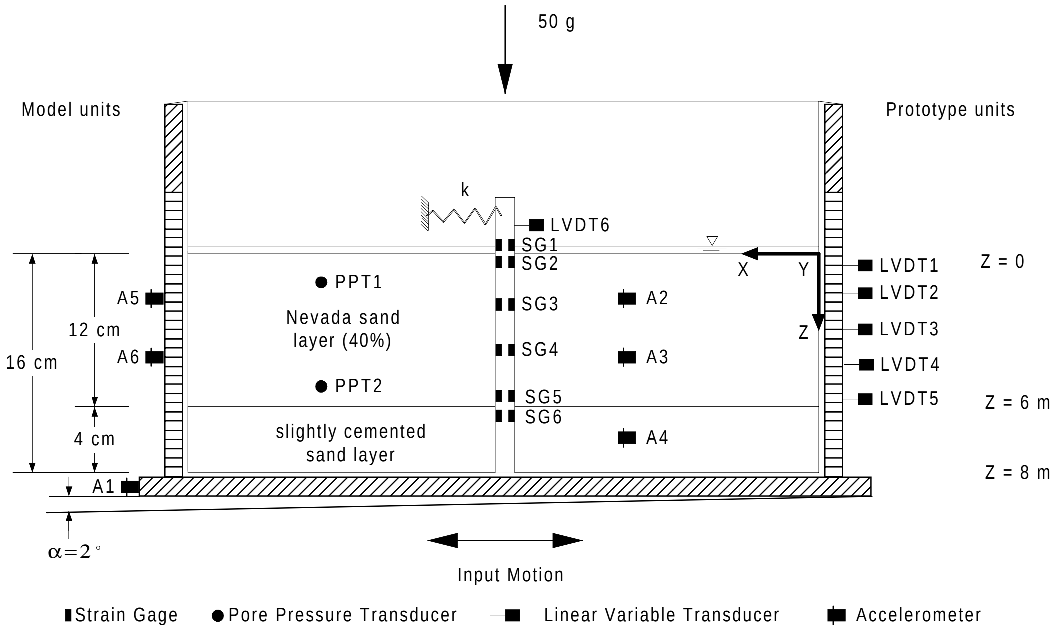

Figure 1: Test setup of centrifuge models

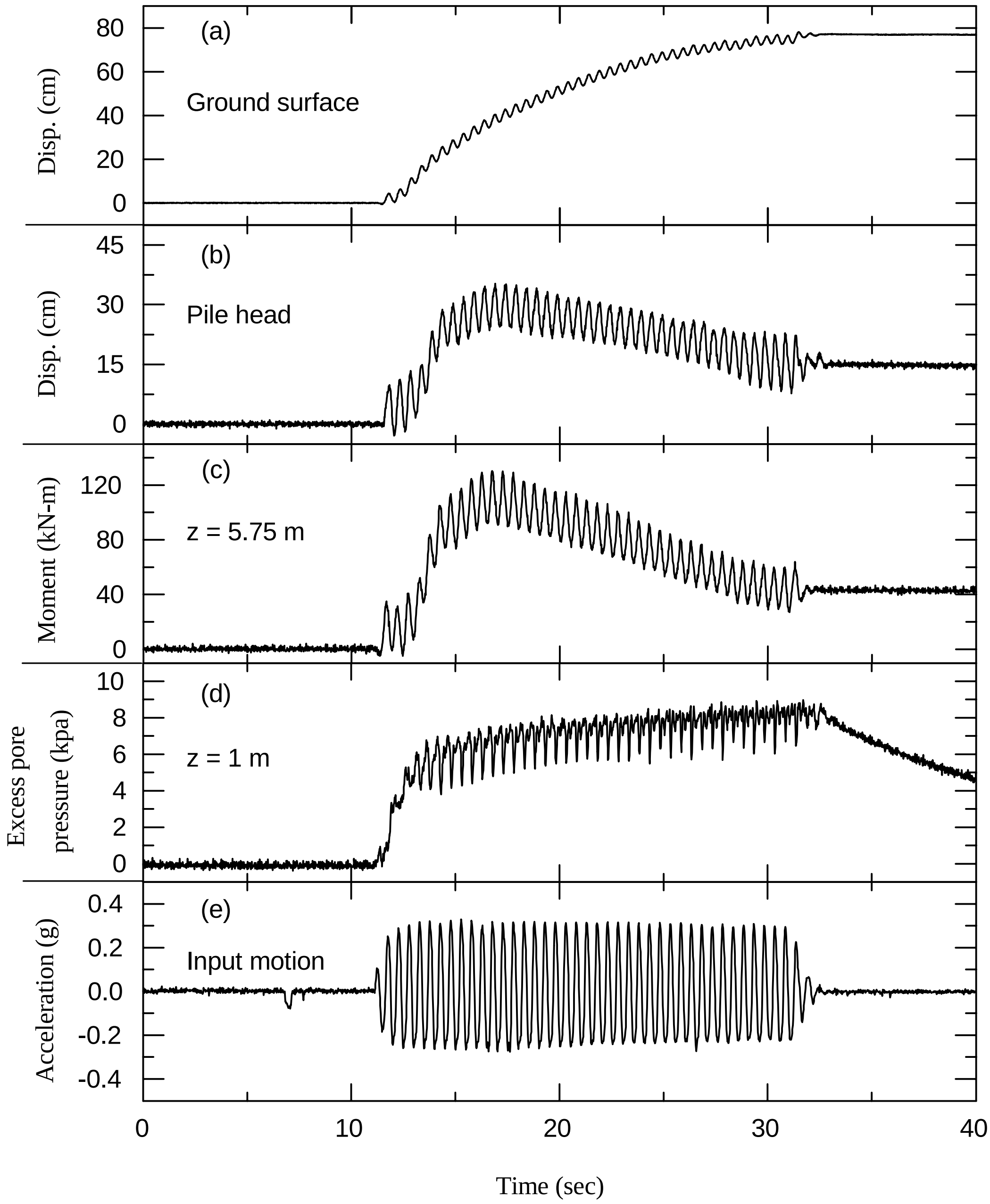

Figure 2: Typical results of Model 3 - Abdoun

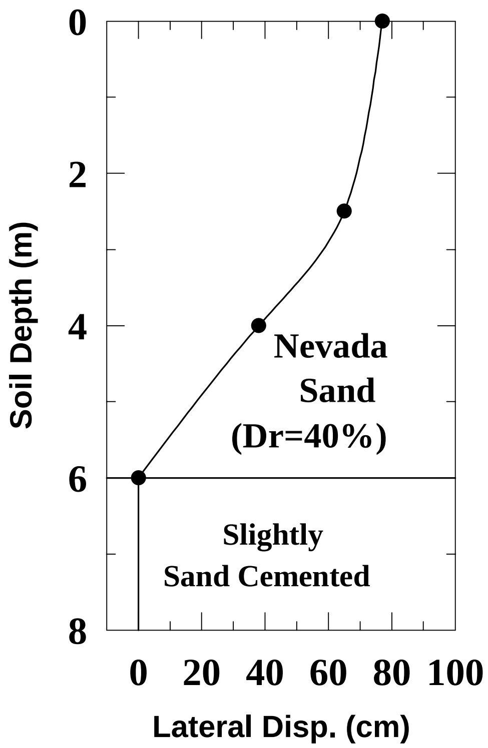

Figure 3: Free field displacement profile at the end of shaking, Model 3-Abdoun

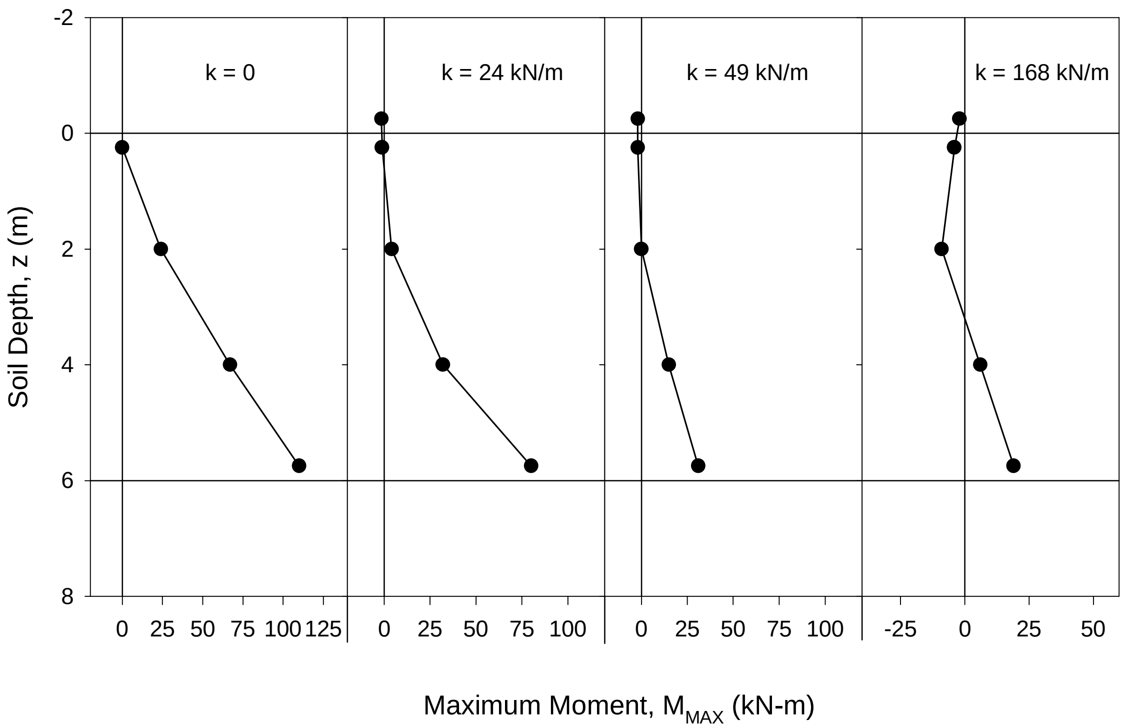

Figure 4: Recorded maximum bending moment profiles in four centrifuge tests

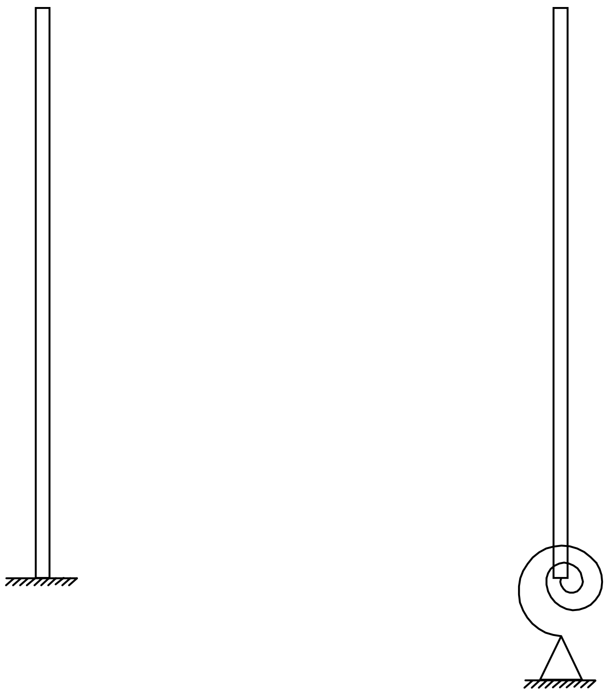

Figure 5: Structural models used to analyze the pile in Model 3-Abdoun

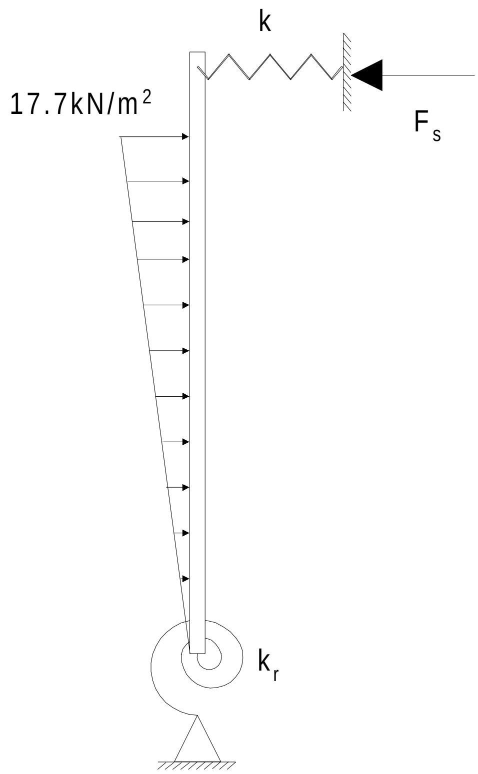

Figure 6: Structural model used in limit equilibrium analyses

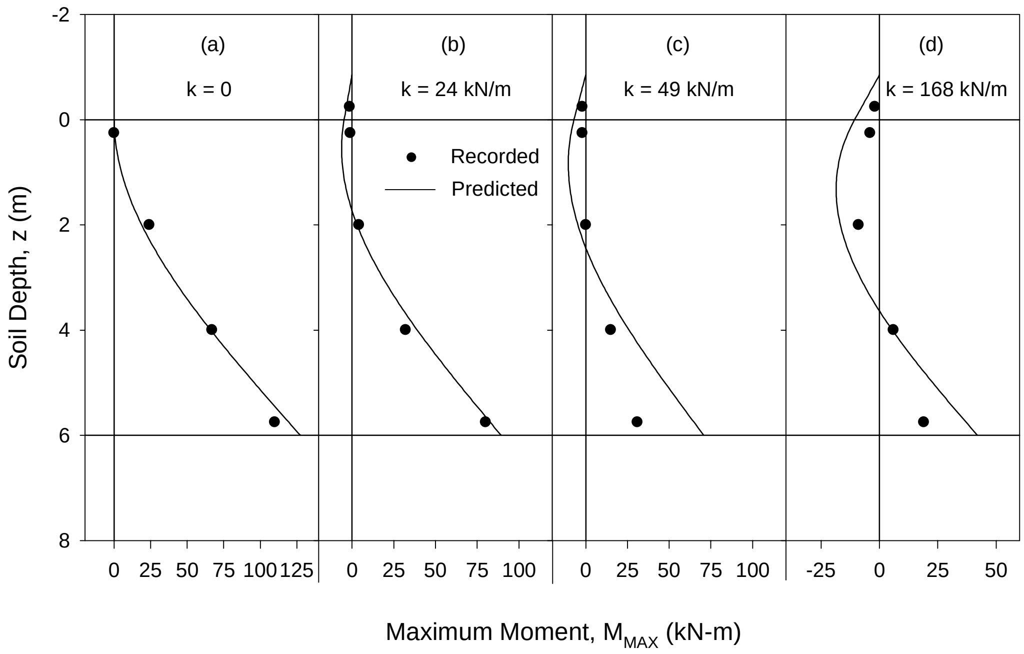

Figure 7: Comparison between recorded and predicted maximum moments using limit equilibrium analyses