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THE KINEMATIC AND INERTIAL SOIL-PILE INTERACTIONS: CENTRIFUGE MODELLING

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ABSTRACT. Piles supporting superstructures undergo with the soil two interactions during an earthquake: the kinematic interaction and the inertial interaction. The kinematic soil-pile interaction is the pile loading by the soil displacement produced by the seismic waves propagating. Inertial superstructure-pile-soil interaction results from forces due to the superstructure actuation by the kinematic interaction. These two interactions are superimposed in seismic events and there independent study is therefore difficult, due to the nonlinearity of the soil behaviour.

This communication presents an initial set of seismic and impact modelling on soil-pile-superstructure performed in the LCPC's geotechnical centrifuge. It is showed that this modelling approach can contribute to analyse separately the kinematic and the inertial interaction that are non-separate in a simple seism experiment, through seismic tests and impact tests carried out on pile and pile-structure systems embedded in dry sand deposits.

1. Test equipments and procedures

Model tests were performed using geotechnical centrifuge at Laboratoire Central des Ponts et Chaussées (France). It is 5.50m beam centrifuge. The reduction scale was 1/40e hence the centrifugal gravity was 40g.

The soil bed for the pile foundation was homogeneous dry Fontainebleau sand with density of 86% (1600kg/m³). The sand was air pluviated using a raining technique with the LCPC's automatic hopper, reconstituted in a 1.20 x 0.8 x 0.36m³ strong box for impact tests and in a 0.9 x 0.45 x 0.456m³ strongbox for the seismic tests.

The model pile was an aluminum pipe representing a prototype tubular-steel pile 0.72m in diameter, 15m long and wall thickness of 0.035m with respect to the scaling laws. The bending stiffness EI of the prototype pile is equal to 476MN.m² characteristic of a flexible pile. The pile model was instrumented with 20 pairs of strain gauges for the bending profile at 15mm distances (0.6m prototype). Displacement laser sensor and accelerometer were also used to record the pile cap movement. A force sensor was fixed on the pile cap for lateral loading tests.

The pile was driven into the sand deposits at 1g (earth gravity) before rotating the centrifuge, using a hammer with constant height drop.

A rigid aluminium pile cap model has been used to simulate a 13360kg superstructure. The cap was rigidly fixed on the pile head with it centre of mass 1.6m above grade. The pile-cap end and the pile tip were then considered as in free rotation and translation conditions.

Lateral impact tests

Lateral dynamic loading of the cap was generated with an electromagnetic hammer accelerating a steel ball developed in LCPC (Halialilue-bonab et al, 2007). This device generates Dirac-like force impulses with typical shock duration of 0.25ms in model scale (10ms on prototype scale). The global setup in the rigid box for this test is given in figure 1(a).

Seismic tests

Seismic events have been generated by the 1-D LCPC's earthquake simulator. This electro-hydraulic device generates sine acceleration sequences as well as wide band realistic earthquakes sequences at the model basis (Derkx et al, 2006).

The same sand air pluviation and pile driving processes, as for impact tests, have been used. Density control process has been repeated for the same density index (ID = 86 %).

Figure 1(b) shows the seismic test setup. Sensors have been used to record the horizontal soil particle accelerations in different depths.

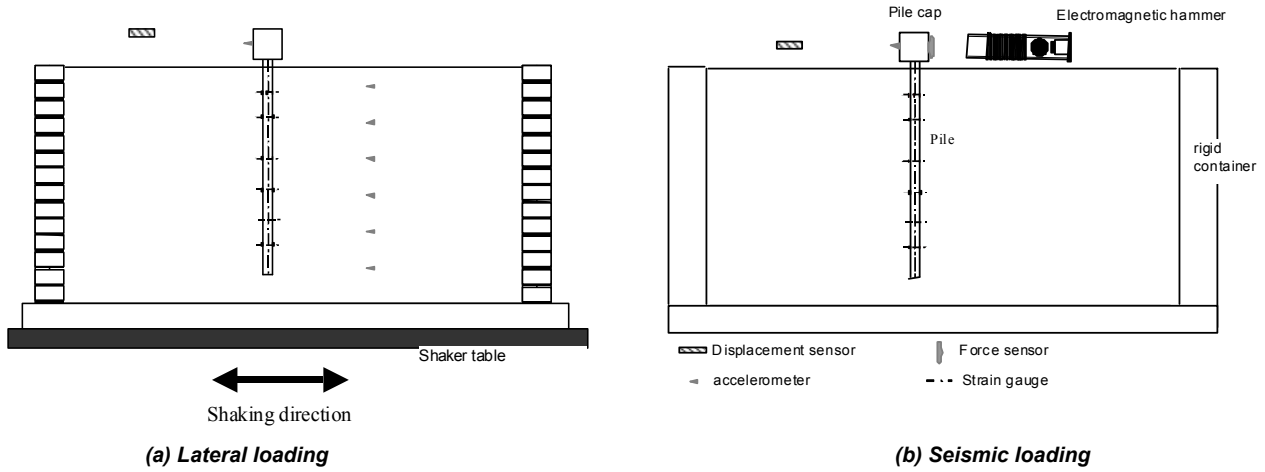


Figure 2. Lateral impact and seismic test setup and measuring instrumentation

A typical time recorded head pile loading is shown on figure 2(a), the frequency recording is given on figure 2(b). The maximum obtained force was 3600kN for approximately 10ms duration (prototype scale). The frequency content of the head dynamic loading is up to 180Hz.

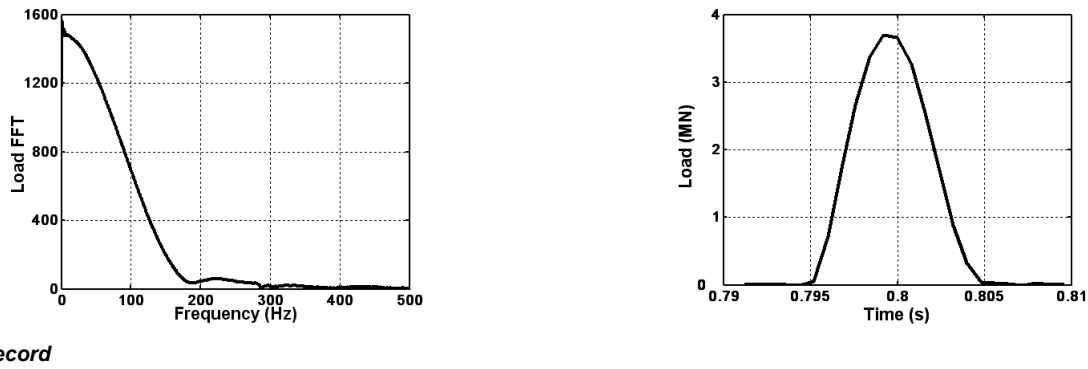


Figure 3. Lateral head pile loading : time and frequency recording

The seismic input was a 30 cycles sine sequence with 2 cycles ramps at 90Hz model -2.25Hz prototype with a total duration of 0.3s model- 12s prototype. The amplitude was 18g model -0.45g prototype. A typical recording of this event is given on figure 3.

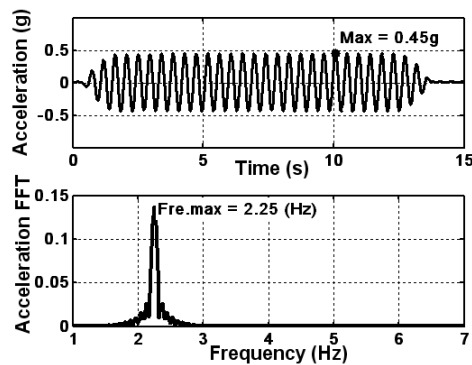


Figure 4. Seismic input signal characteristics

2. Typical set of recorded responses

The time histories of the pile cap displacement and acceleration for the impact loading applied to the cap are given figure 4. Pile head displacement and acceleration reach respectively 22mm and 1,40g.

Cap movements records are given in figure 5 for the seismic event applied to the pile with its cap. They illustrate the fundamental difference between these two series of experiments: the impact response in a free damped oscillation shed light the damped frequency of the cap-pile system in interaction with the soil while the seismic response is a forced response.

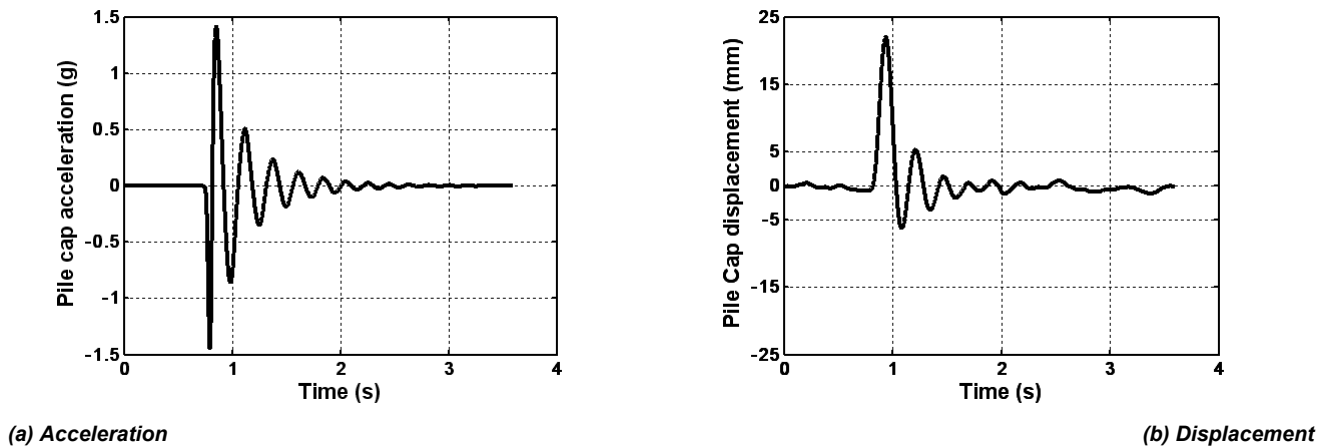


Figure 5. Pile cap movement record under horizontal impact loading

Seismic head pile displacement and acceleration recordings are representative of the artificial shaking generated by the earthquake simulator in figure 5. Pile head displacement and acceleration reach respectively 87mm and 0.56g for 0.45g shaking amplitude.

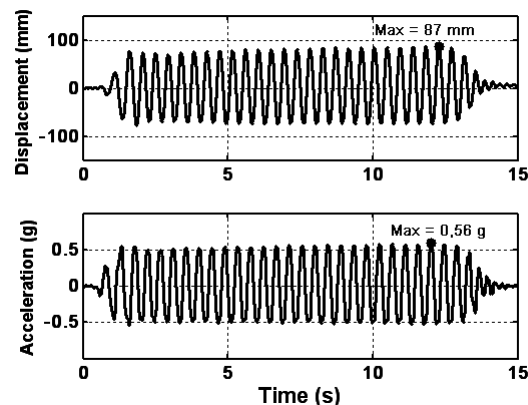


Figure 6. Cap pile acceleration and displacement for seismic experiments

3. Analysis of the experimental data of Inertial and kinematic interactions

The distribution of the maximum pile bending moments along pile is a first derived result than can more directly influence the design of piles. The moment induced by the inertia forces are called hereafter the ‘inertial component’, and the moments caused by the soil displacement are called the ‘kinematic component’.

The inertial component is evaluated from the lateral impact loading at the pile cap (Test A). The kinematic component is evaluated from the seismic test using a cap-less pile (Test B). The combined interaction is then from seismic test with pile equipped with a cap (Test C).

Figure 20 shows profiles of the maximum bending moment at each depth from tests A, B and C. The distribution of the bending moments indicate that the primary portion of large bending moments moves downward from the pile top to the pile tip from test A to C. Note that these three profiles should not be directly compared in quantitative terms as the tests could not be “normalized”. However, tests B and C can be compared as the seismic input is harmonic acceleration sequences of the same amplitude.

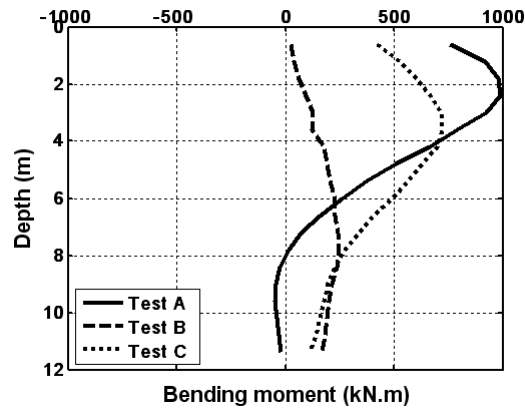


Figure 7. Comparison of maximum bending moments along the pile for Test A, Test B and Test C

In Test A, the maximum bending moments are large at the pile head. In test C, the moment is large from the pile tip to the pile head since the apparent soil stiffness decreases from depth to surface because of the soil displacement and the soil confinement stress. This also can explain why the inertial component extends deeper than in Test A. In the combine interaction, the inertial component can be considered to extend from the pile head to 6m deep. The kinematic component can be considered to extend from the pile tip to the pile head.

Test C: the instance of peak ground displacement may coincide with the instance of peak inertia force. In fact, they are most often in phase as demonstrated by Tokimatsu (2005).

At a depth of 6m, the maximum seismic bending moment with superstructure (Test c) is twice that in seismic test without superstructure test (Test B) indicating the important role of the inertia effects of the superstructure. It means, therefore, that the effects of the soil displacement and the inertial forces tend to be in phase.

The increase of the bending moments with depth between test A and C suggest that soil motion induced kinematic loads dominated the pile tip response.

4. Conclusion

Seismic and impact tests presented in this communication showed that this modeling approach can contribute to analyze separately the kinematic and the inertial interaction. Results of the model tests indicate that the pile bending moments near the pile head are greatly affected by the inertia effects of the structure. The influences of these inertia effects go deeper in the pile with the soil displacement in seismic events. It can be noticed that, for an input seismic frequency at 2.25Hz is below the estimated resonance frequency of the soil column (4Hz) the effect inertial is prevalent in the surface layers, the inertial and kinematic interaction are in phase and affect simultaneously the pile behaviour. The two effects act in the same direction thus amplifying the deformations in the soil at mid depth as well as in the deeper layers.

5. References

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