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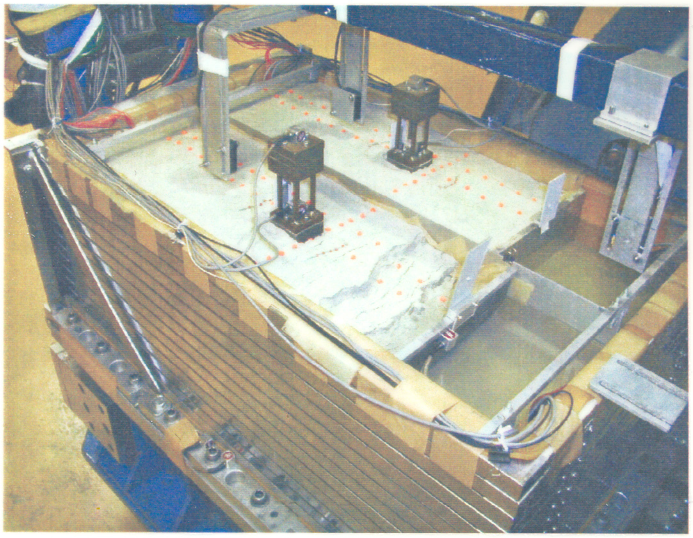

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Identifying interaction mechanisms for pile foundations in laterally spreading ground

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Abstract

Mechanisms of interaction between pile foundations and laterally spreading ground during earthquakes are identified based on the results of dynamic centrifuge model tests. Four aspects of interaction behavior are discussed: (1) the subgrade reaction behavior of liquefied sand, (2) the magnitude and phasing of lateral spreading loads and superstructure inertia loads, (3) the softer-than-expected lateral load transfer behavior between nonliquefied crust layers and pile groups/caps, and (4) the restraining effect of pile foundations on bridge abutment displacements.

INTRODUCTION

The development of reliable design and analysis procedures for pile foundations in areas of liquefaction and lateral spreading depends upon a solid understanding of the basic mechanisms of soil-pile-structure interaction. Mechanisms of interaction during lateral spreading were poorly understood only a few years ago. Dynamic centrifuge model and shaking table tests have since provided the means for identifying and quantifying basic interaction mechanisms.

This paper describes recent findings regarding mechanisms of interaction between pile foundations and laterally spreading ground, based on data from dynamic centrifuge model tests on the 9-m radius centrifuge at the University of California, Davis (Fig 1). Four aspects of behavior are described: (1) the subgrade reaction behavior of liquefied sand, (2) the magnitude and phasing of lateral spreading loads and superstructure inertia loads, (3) the softer-than-expected lateral load transfer behavior between nonliquefied crust layers and pile groups/caps, and (4) the restraining effect of pile foundations on bridge abutment displacements. The measurement of these different interaction mechanisms involved certain experimental features and data processing techniques that are briefly discussed first.

METHODOLOGY

Design of Centrifuge Experiments

Data from dynamic centrifuge model tests can be utilized to: (1) identify mechanisms, (2) calibrate advanced numerical analysis procedures, and (3) evaluate design-level analysis procedures. In all cases, the design of the centrifuge model and instrumentation plan depends on the physical mechanisms or behaviors that are the primary focus of the test. The model is often designed such that its dynamic response is expected to be sensitive, rather than insensitive, to the feature of interest, as this usually provides the greatest opportunity for insight and findings. The measurement of interaction mechanisms can require extensive data processing to extract quantities that are not directly measured by transducers, in which case the design of the model and instrumentation plan must also consider the data processing techniques that will be used.

Data Processing

There are certain quantities that are difficult to measure directly by transducers, but can be computed based on transducer measurements

Fig 1: Centrifuge at the University of California at Davis

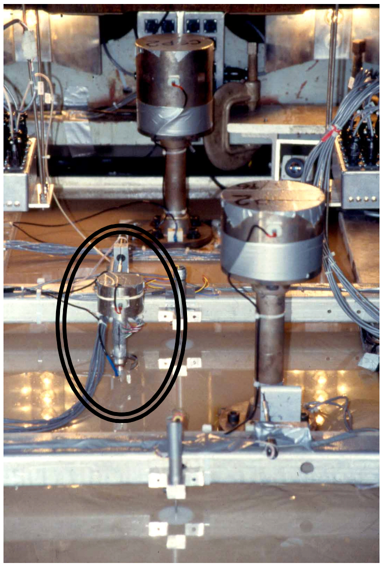

Fig 2: Model structures on piles in a level saturated sand

of other quantities. For example, the lateral load on a pile at a certain depth cannot be directly measured, but can be computed from the derivative of the recorded shear strain distribution in the pile or from the second derivative of the bending strain distribution in the pile. While conceptually simple, the numerical differentiation of discrete transducer measurements can be sensitive to the details of the transducer array, the electronics, and differentiation technique. The data processing techniques that might be used in any given study depend on the specific quantity being computed, the details of the centrifuge model, and the nature of the electronic systems (e.g., Wilson et al. 1998).

Discrete time series measurements can require digital filtering to remove noise, which requires knowledge of the transducer's response characteristics and the system electronics. Accelerations, for example, can be double-integrated to obtain transient displacements, but not permanent or very low-frequency displacements that are outside the frequency range of the accelerometers. Displacement transducers can generally record the permanent or low-frequency components of displacement, while the higher frequencies are out of the range of some instruments. Accurate displacement histories can be constructed by combining data from accelerometers and displacement transducers using appropriate combinations of low- and high-pass filters (Kutter and Balakrishnan 1998). It may also be necessary to add the dynamic displacements of the mounting brackets or frames to which the displacement transducers are attached.

Redundancy in certain measurements can be used to provide a check on consistency. For example, a few shear gages can be used to check results obtained from differentiating an array of bending moment gages on a pile.

Visualization software can be used to rapidly review the experimental data and identify potential problems with instrumentation (e.g., Weber et al. 2003). Models are initially shaken with very small motions (e.g., in the elastic range of model response) as a check on instrumentation, and many potential problems can be fixed prior to the main shaking events.

Numerical processing of the data often requires applying fitting functions or specifying boundary conditions, which require an understanding of the physical system. Finally, computed quantities are checked for their sensitivity to the various steps involved.

SUBGRADE REACTION OF LIQUEFIED SAND

The subgrade reaction or p-y behavior of liquefied sand was back-calculated from dynamic centrifuge experiments using single-pile-supported structures founded in loose ($D_R \approx$ 35%) and medium dense ($D_R \approx$ 55%) sand

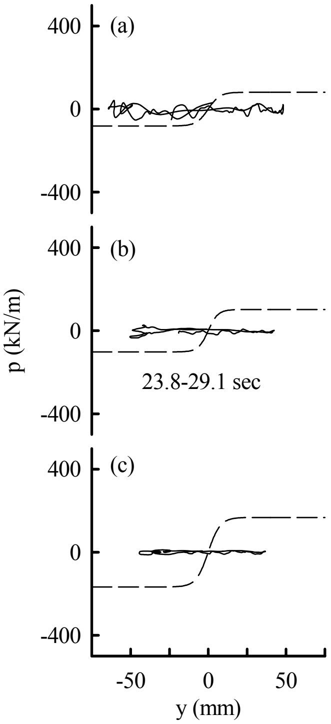

Fig 3: p-y behavior for loose sand late in shaking for a Santa Cruz motion with peak base acceleration of 0.45 g, and at depths of: (a) one pile diameter, (b) two pile diameters, and (c) three pile diameters. Static design relation shown as dashed line for comparison.

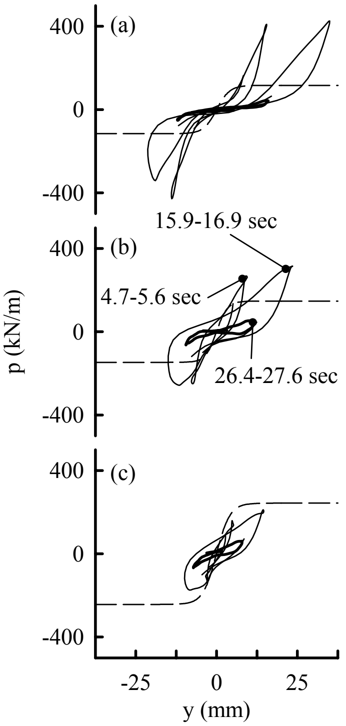

Fig 4: p-y behavior for medium-dense sand at different times in shaking for a Santa Cruz motion with peak base acceleration of 0.41 g, and at depths of: (a) one pile diameter, (b) two pile diameters, and (c) three pile diameters. Static design relation shown as dashed line for comparison.

profiles and subjected to a range of earthquake input motions (Wilson et al. 2000). The photograph in Fig 2 shows a single-pile-supported structure and two pile-group-supported structures in one of the tests. Typical p-y behavior at different depths is shown in Fig 3 for loose sand and Fig 4 for medium dense sand.

The p-y behavior showed characteristics that are consistent with the stress-strain response of liquefying sand. The lateral resistance p in loose sand was usually small when the soil liquefied, even when relative displacements y were fairly large. Lateral resistance in the loose sand was much smaller and softer than in the medium dense sand, which is consistent with effects of D_R on the undrained shear resistance (or cyclic mobility) of saturated sand. The lateral resistance in the medium dense sand progressively softened during shaking as excess pore pressures, strains, and number of load cycles increased (e.g., as shown by loops for early in shaking versus late in shaking). The p-y behavior stiffened with increasing displacement when relative displacements approached or exceeded past values, which was attributed to nearly undrained loading conditions and the tendency for the sand to dilate under these loading conditions (i.e., large enough strains to move the sand through a phase transformation). Similar p-y behaviors have been observed in shaking table tests (e.g., Tokimatsu et al. 2001) and in field studies with blast-induced liquefaction (e.g., Weaver et al. 2005).

LATERAL SPREADING & INERTIA LOADS

The combinations of lateral spreading loads and inertia loads during lateral spreading were evaluated using a series of centrifuge model tests with pile groups embedded in mildly sloping ground (Brandenberg et al. 2005, Chang et al. 2005). A cross-section of a typical

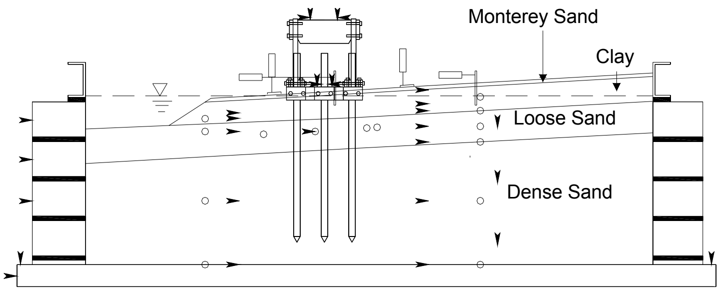

Fig 5: Cross-section of centrifuge model of pile group in laterally spreading ground

Fig 6: Photograph of pile cap after testing with the surficial layer of sand removed

model is shown in Fig 5, and a photograph of the model structure after testing with the surficial sand cover layer removed is shown in Fig 6. The lateral load from the nonliquefied clay crust was computed based on the free-body in Fig 7 and the measured pile forces, pile cap acceleration, and superstructure acceleration. The lateral load from the crust was the dominant driving force on the pile-structure system and was dominated by low-frequency components due to the effects of liquefaction in the underlying sand. Structures with fixed-based periods of 0.3 and 0.8 s were excited primarily in their first mode of vibration with the crust load, pile cap inertia, and superstructure inertia tending to be in phase at critical cycles (e.g., Fig 8). The critical combinations of crust and inertia loads depend on the dominant frequencies in the input base motion and non-liquefied crust motion relative to the effective fundamental periods of the pile-structure system. The relatively long-period nature of the crust loads after liquefaction should be considered in setting load combinations for design. The results were generally consistent with findings and recommendations based on large scale shaking table tests (Tokimatsu 2003).

LOAD TRANSFER FROM NONLIQUEFIED CRUST LAYERS TO PILE GROUPS

The lateral load transfer behavior between pile groups and a nonliquefied crust layer spreading laterally over a liquefied layer was shown to be an order of magnitude softer than is commonly expected (Brandenberg et al. 2004). A typical model cross-section was shown in Fig 5, and a photograph of the pile group after testing was shown in Fig 6. The nonliquefied clay crust spread laterally over a liquefied sand layer and imposed large loads on the pile groups. Large relative displacements

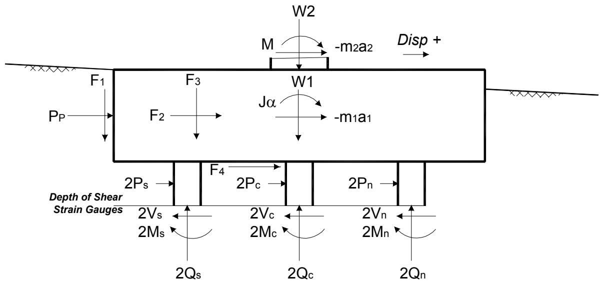

Fig 7: Free-body of pile cap in centrifuge model

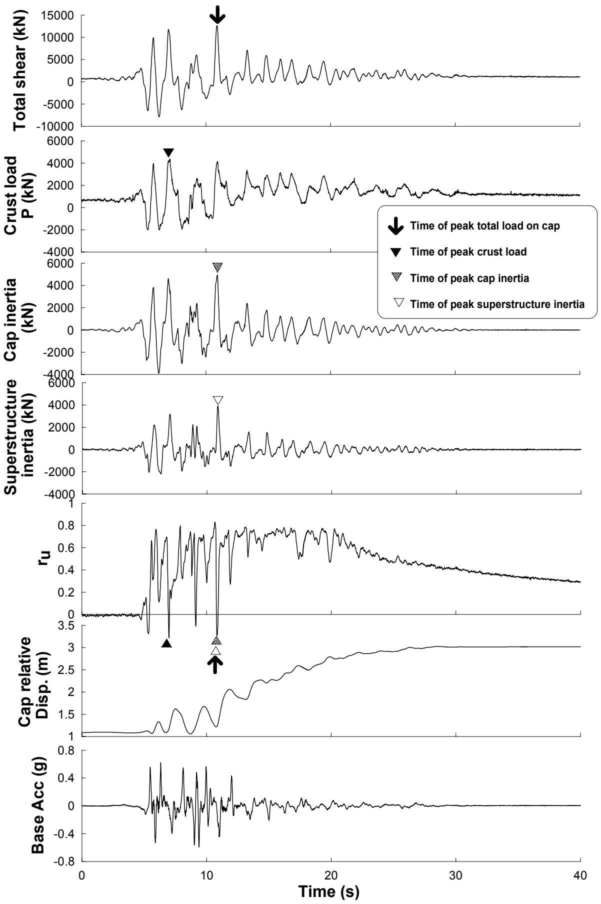

Fig 8: Time series of loads and responses during strong earthquake shaking of one model

between the pile caps and the free-field soil were required to mobilize the peak lateral crust loads (Fig 9). The relatively soft lateral load transfer behavior was attributed primarily to the effects of cyclic degradation and the influence of liquefaction on the stress distributions with the crust layer (Fig 10). The liquefied sand provided very low shear resistance along the base of the clay layer, such that the reaction forces from the pile group caused stresses to spread to much larger distances upslope in the clay crust. This larger zone of influence produced a softer load transfer behavior.

PILE PINNING EFFECT ON BRIDGE ABUTMENTS

Pile foundations in bridge abutments underlain by liquefiable soils can restrain the lateral movement of the abutment, which in turn reduces the loads imposed on the piles during an earthquake. This "pile pinning" effect is incorporated in recent NCHRP guidelines (Martin et al. 2002) and has been used in practice for several years. The common design methods for pile pinning effects are based on displacement compatibility between a pseudo-static pile pushover analysis and Newmark sliding block analyses of the abutment mass with various levels of pile restraining force. These analysis methods were evaluated against a dynamic centrifuge model test with two opposing abutments, as shown in Fig 11; one abutment with a row of six piles and one without any piles (Boulanger et al. 2005). The abutment without piles moved about 1.6 m while the abutment with piles moved about 1.2 m (e.g., a photograph of the dissected abutment after testing is shown in Fig 12). Analyses using current guidelines predicted much smaller abutment/pile displacements. Reasonable agreement between analyses and observations could be achieved by accounting for the following effects in the analyses (Fig 13).

- The critical slide mass increased with increasing pile pinning force.
- The restraining force from the piles progressively increases as abutment displacements increase, such that compatibility should be on the average pile restraining force and not on the final pile restraining force.
- The abutment's tributary mass should include a portion (e.g., ½) of the side slope masses, and not just the mass of the soil behind the crest width.
- Pile shear resistance across the liquefied layer reduces with decreasing pile fixity above or below the liquefied layer, which can result from shear deformations in the overlying abutment or underlying strata.

Further evaluations of pile pinning effects and analysis methods are in progress.

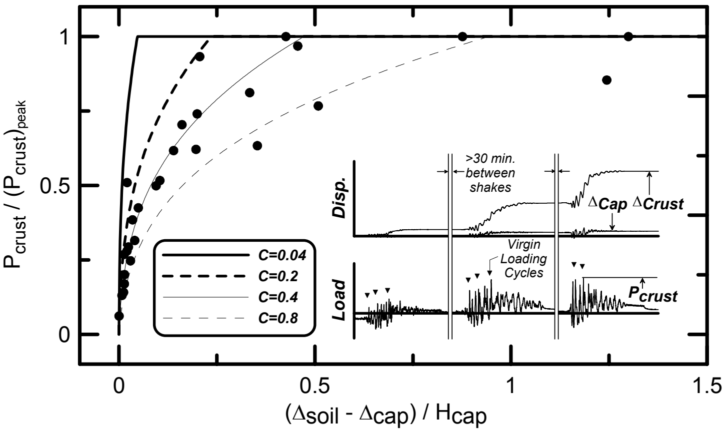

Fig 9: Normalized crust load versus relative cap-soil displacement (Brandenberg et al. 2004).

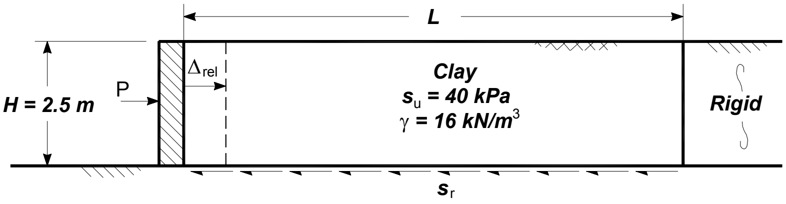

Fig 10: Two-dimensional schematic of the effect of liquefaction on load transfer between a pile cap and a nonliquefied crust overlying liquefied soil.

CONCLUSIONS

Mechanisms of interaction between pile foundations and laterally spreading ground were identified based on data from dynamic centrifuge model tests. Four aspects of behavior were described: (1) the subgrade reaction behavior of liquefied sand, (2) the magnitude and phasing of lateral spreading loads and superstructure inertia loads, (3) the softer-than-expected lateral load transfer behavior between nonliquefied crust layers and pile groups/caps, and (4) the restraining effect of pile foundations on bridge abutment displacements. Certain features of the experimental and data processing approaches were described. The improved understanding of interaction mechanisms, as obtained by centrifuge, shaking table, and field studies, provide an improved basis for developing reliable design and analysis procedures.

ACKNOWLEDGEMENTS

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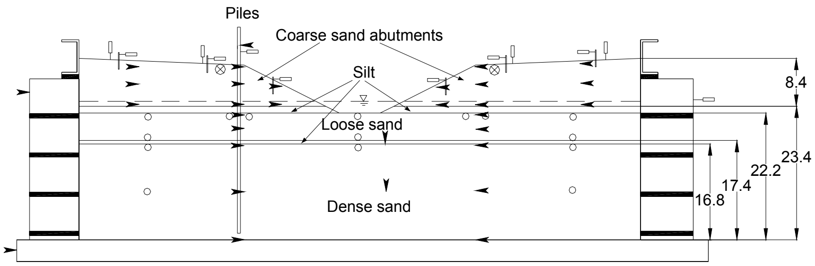

Fig 11: Cross-section of centrifuge model with dry sand abutments over loose saturated sand (prototype dimensions in m)

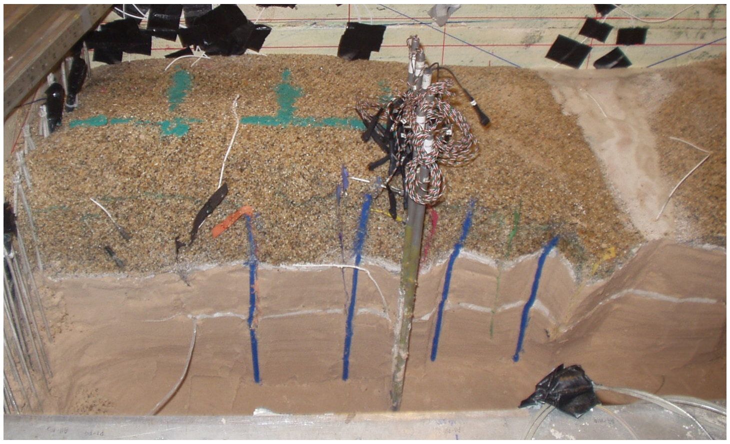

Fig 12: Photograph of model abutment with piles during dissection after testing

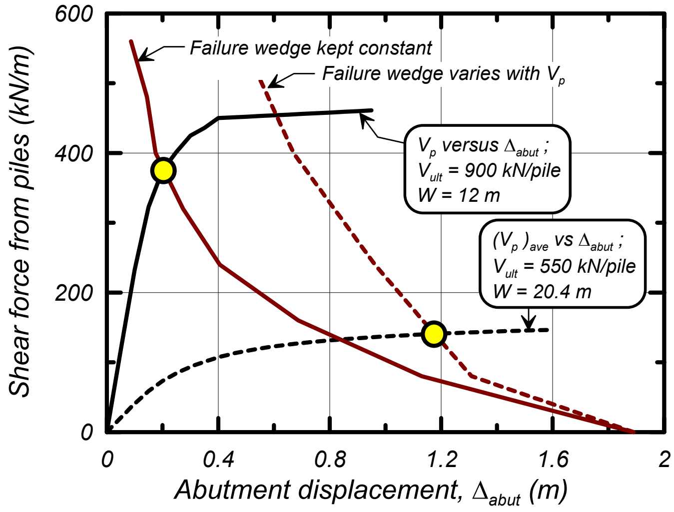

Fig 13: Compatibility solutions between pile pushover resistance and Newmark sliding block analyses of the abutment failure wedges

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