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Closure to "Centrifuge Model Tests of Liquefaction-Induced Downdrag on Piles in Uniform Liquefiable Deposits"

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This paper presents a closure to "Centrifuge Model Tests of Liquefaction-Induced Downdrag on Piles in Uniform Liquefiable Deposits" by Sumeet K. Sinha, Katerina Ziotopoulou, and Bruce L. Kutter. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002817.

The writers of this closure thank the discusser for his interest in this paper and for agreeing that the paper enhances understanding of seismic soil-pile interaction. Below is our response to each of the discusser's points.

Scope of Testing Program and Procedures

The writers agree with the discusser that the experiments should have included actual load tests on piles. In a subsequent test series, a static pile load test with a constant penetration rate was performed on the piles (Sinha et al. 2021b; Ziotopoulou et al. 2022). Furthermore, to enhance our ability to estimate the friction capacity, the surface of the pile was made rough enough that the interface friction could be assumed equal to the friction angle of the soil. The axial load distribution obtained from the pile load test was then used to obtain the limit load curve of the piles. Fig. 1 shows the load-deflection results from the pile load tests: PLT_1 and PLT_2 in Centrifuge test SKS03 and the interpreted limit load curve. The limit load curve of Fig. 1 was obtained from the axial load distribution during loading corresponding to the largest load (i.e., at about 5.5 MN, as shown by the red line in Fig. 1).

The discusser questioned our interpretation regarding the location of the 0D pile relative to the top of the dense sand. We are very confident that 0DPile's tip was directly located on the interface between the dense and loose sand. We know that a very distinct interface existed between the dense and loose sand because of the way the sand was placed during model construction (Sinha et al. 2021a). The apparent gradual transition of relative density (D_R) suggested by Figs. 5(a and c) in the original paper was a result of the zone of influence (extending above and below) around the cone's tip. The soil above and below influences cone tip resistance (q_c) measured at the interface. The writers should have pointed this out in the original paper. Interested readers are referred to Khosravi et al. (2022) for a discussion of thin layer effects on penetration resistance.

The writers agree that machining a pile's interface surface to maximize roughness is probably not practical. The modeling of the real roughness of piles [which is affected by installation type (drilled versus driven), corrosion after installation, and other factors] was not in the scope of our planned centrifuge tests. Our goal in roughening the surface was to minimize uncertainty in the

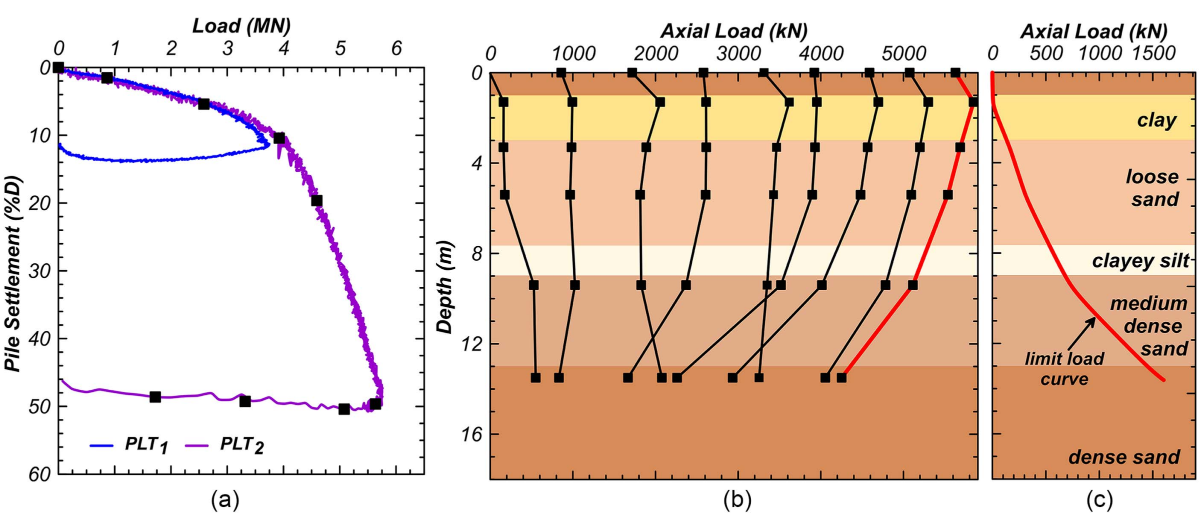

Fig. 1. Results for (a) load-deflection curve; (b) axial load distribution; and (c) interpreted limit load curve from pile load tests (PLT_1 and PLT_2) conducted on 3DPile during the SKS03 centrifuge test. (Adapted from Sinha 2022.)

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estimation of interface friction angle (δ), maximize drag load to emphasize the mechanism of liquefaction-induced downdrag, simplify the interpretation of results, and, by extension of the above, enable our follow-on numerical investigations (Sinha et al. 2022).

The discusser suggested that the state of soil and pile stresses does not adequately model what typically happens in a realistic scenario. The discusser argued that real piles are not likely to be subjected to multiple earthquakes or drag loads prior to a liquefaction event. The writers disagree with this argument since it is not unusual for a large earthquake to be preceded by several smaller earthquakes or for multiple earthquakes to affect a pile-supported structure over its life span. In essence, each shaking in the centrifuge test acted as an individual event occurring over the lifetime of the pile. Furthermore, piles near bridge abutments may be subject to drag loads caused by the postinstallation placement of fill, such as a bridge abutment. The centrifuge test results showed that liquefaction can erase the initial drag load. However, small soil settlements from the reconsolidation process can regenerate significant drag loads.

The writers agree with the discusser that the lateral stress coefficient, K, can change due to shaking and axial deformation. The writers agree that changes in K in successive shaking events might also explain the gradual increase in downdrag loads. The load curve in Fig. 10, assuming $K = 1$, is a reference line to help readers understand the magnitude of the measured loads. The writers did not mean to imply that $K = 1$ is a constant.

The discusser suggests including instrumentation for measuring soil and pile settlements along the pile's interface. The writers agree that this would have been useful, but such instrumentation was not feasible for the scope of this project. In lieu of this, a subsequent paper by Sinha et al. (2022) describes efforts to deduce soil settlement from pore pressure sensors, post-test excavations, and inverse numerical analyses. The pile settlement at any depth can be adequately determined from the pile head settlement minus the integration of axial strain measurements. The writers used the approach mentioned above for determining pile settlement profiles.

Interpretation of Shaking Test Results

The writers appreciate the discusser for analyzing the piles' response and offering valuable comments. Many of the comments pertain to the analysis of the axial load distribution of 0DPile. The writers would like to note that the instrumentation of the 0DPile measuring axial load was sensitive to bending and thus could cause errors resulting in some unusual and unexplainable axial load distribution. Laboratory tests (Sinha et al. 2021b) and the subsequent SKS03 centrifuge model test (Sinha 2022; Ziotopoulou et al. 2022) also confirmed this anomaly. Moreover, the inclination of 0DPile (vertically by about 1.4°) could have also resulted in bending moments affecting the axial load measurement. Thus, any analysis of the measured axial load distribution of 0DPile (for example, estimation of skin friction or lateral stress coefficient, K) should be treated with caution. It may result in unusual and unexplained behaviors, many of which the discusser has rightly pointed out. The writers realize that, due to instrumentation limitations, an experiment may not provide all data of interest; thus, for a more detailed investigation, follow-on validated numerical simulations are used to extract more insights. Sinha et al. (2022) developed a numerical approach (TzQzLiq analysis) for modeling the response of axially loaded piles in liquefiable soils and validated it against these centrifuge test results. Through the numerical work, Sinha et al. (2022) described the mechanism of the development of drag load, neutral plane, and axial load distribution in 0DPile and 5DPile. Fig. 2 shows the numerical results along with the centrifuge test results on the isochrones of effective stress, soil settlement, axial load distribution of 0DPile and 5DPile, and pile settlement at selected times during the EQM_3 shaking event and its subsequent postshaking reconsolidation phase. The figure also illustrates the time histories of drag load and neutral plane depth calculated from the numerical analysis. The results for axial load distribution and pile settlement from the numerical work matched reasonably well with the centrifuge test, thus validating the analysis. The comparison of 0DPile axial load distribution obtained from the numerical analysis with centrifuge test results [Fig. 2(c)] shows the magnitude of the error in axial load measurements of 0DPile. Enumerated below are the writers' responses to each of the points raised by the discusser on this issue.

The discusser argued that the mobilized skin friction at some depths, as calculated from the measured axial load distribution, is higher than the one estimated from the limit load curve (with $K = 1$ and $\delta = 30°$) and can be explained with $K > 1$. The writers agree with the discusser that K could be higher than the assumed value of $K = 1$. Mobilization of peak stresses around the pile (especially near the pile's tip:11.7 m for 0DPile and 13 m for 5DPile) can result in the development of large lateral stresses with $K > 1$. However, the writers believe that the limit load curve with $K = 1$ provided a good reference for readers to understand the drag load's development and changes in its magnitude as the soil developed excess pore pressures during shaking and underwent settlement during reconsolidation. Comparing the numerical results of 5DPile's axial load distribution with the centrifuge test results [Fig. 2(d)] shows that the assumed limit load curve provides a reasonable representation of the skin friction distribution of the pile.

The discusser argued that the depth of the maximum axial load in 0DPile does not match the neutral plane depth determined from the final soil and pile settlement (i.e., after complete reconsolidation). The writers are not in agreement with the discusser's analysis. It is a common misconception to estimate the neutral plane as the depth at which the absolute soil and pile settlements are the same. However, in reality it is the depth at which soil velocity is equal to pile velocity (Wang and Brandenberg 2013). The neutral plane does not remain at a constant depth throughout a shaking event. Fig. 2(e) shows the changes in the neutral plane of 0DPile and 5DPile throughout the shaking event. During shaking, the settlement in a pile causes a decrease in the neutral plane depth. However, during the reconsolidation phase the soil settles significantly more than the pile, increasing the neutral plane depth. Results in terms of axial load distribution from the numerical analysis confirm the neutral plane depth as measured from the centrifuge test [Fig. 2(c)].

The discusser argued that the constant volume friction angle (ϕ'_{cv}) of the sand could be higher than the specified value of $\phi'_{cv} = 30°$ in the original paper. The writers are confident regarding the estimation of ϕ'_{cv}. The critical friction angle does not change with relative density and effective stress. Several laboratory tests on Ottawa F-65 sand (used in the centrifuge test) by Bastidas et al. (2017) with different relative densities and confining stresses confirmed a value of $\phi'_{cv} \approx 30°$.

As suggested by the discusser, Fig. 2 shows the profiles of excess pore pressure, soil settlement, pile settlement, axial load distribution, drag load, and neutral plane at selected times during shaking and reconsolidation of the EQM03 shaking event. Sinha et al. (2022) described liquefaction-induced downdrag mechanisms and the response of piles in detail while comparing the numerical results with the results of the centrifuge test. The axial load distribution of 0DPile obtained from the numerical analysis [Fig. 2(f)] shows mobilization of positive skin friction (hence zero drag loads) only between $t = 7$ s and $t = 30$ s. While measurements show that the surface did not settle much between $t = 30$ s and $t = 2.5$ min

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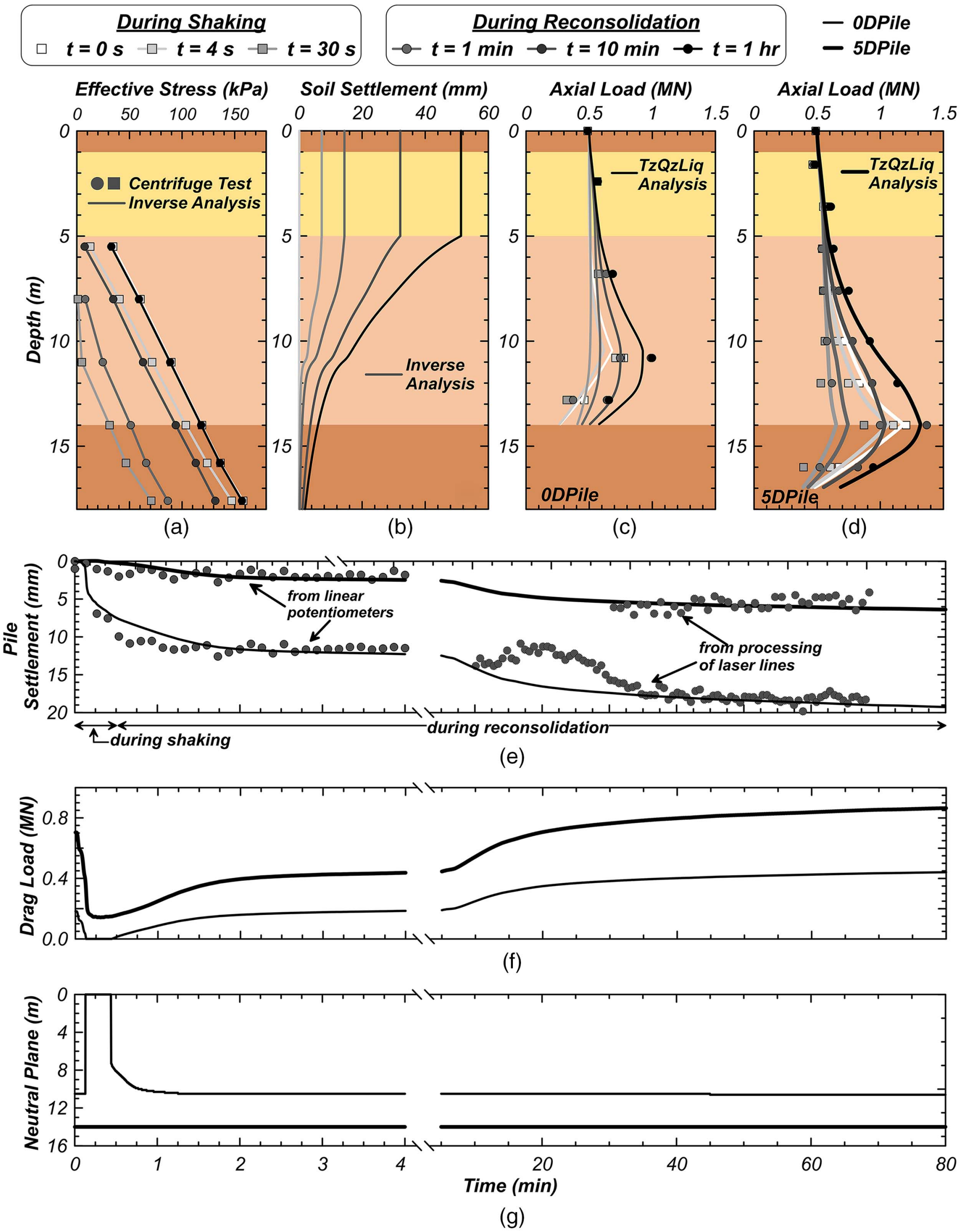

Fig. 2. Comparison of pile responses obtained from TzQzLiq analysis with centrifuge test results for the EQM_3 shaking event: profiles of (a) effective stress; and (b) soil settlement; and axial load distribution of (c) 0DPile; (d) 5DPile at selected times during shaking and reconsolidation; and (e) pile settlement time history. Predicted time histories of (f) drag load; and (g) neutral plane depth from TzQzliq analysis. (Reprinted from Sinha 2022, ©ASCE.)

[because of the formation of a water film layer, explained in detail by Sinha et al. (2022)], the sand beneath the clay layer continued to reconsolidate and settle, resulting in the development of drag loads [Fig. 2(f)].

The discusser questioned the accuracy of the measured axial load of 0DPile in the clay layer, which always showed positive skin friction even during downdrag. The writers agree with the discusser that the measured axial load in 0DPile may not be accurate due to the aforementioned sensitivity of strain gauges to bending. The inclination of 0DPile and the large mass on its head could have developed significant bending moments in the surficial layer affecting the axial load measurement. As expected by the discusser, the numerical analysis results [Fig. 2(c)] show the mobilization of positive skin friction during shaking and negative skin friction during reconsolidation in the clay layer.

The discusser argued that the mobilized tip stress determined from the measured axial load at approximately 1.2 m above the pile's tip [i.e., at about two times the pile's diameter (D)] may not be accurate, and suggested that placing a load cell at the pile's tip could have provided a more accurate result. The writers agree with the discusser's comment. However, placing a load cell at the tip was not feasible due to the pile's small diameter and the test's complexity. The writers believe that, considering the zone of influence at the pile tip (which extended $2D$ and $3D$ above and below the tip), the strain gauge located at about $2D$ from the tip still provided a good representation of the tip load.

The discusser suggested that, during complete liquefaction (i.e., $\sigma_v' = 0$ at $t = 30$ s) between depths of 5 and 12 m, 0DPile should also show a constant axial load distribution similar to that of 5DPile. The writers agree with the discusser's comment. Due to cross-sensitivity, as mentioned earlier, in the axial gauges, the measured axial loads of 0DPile in the centrifuge test did not show such distribution; the numerical analysis results clearly show and confirm the expected constant axial load distribution [Fig. 2(c)].

Some Practical Considerations

The writers agree with the discusser that the results from this study apply only to single piles. The mechanism of liquefaction-induced downdrag on pile groups is more complex and involves interactions between the individual piles. The writers agree that future research should investigate liquefaction-induced downdrag on pile groups. However, the scope of the presented research was to start from the simpler problem before scaling up to more complex scenarios.

The writers agree with the discusser regarding future research on lateral spreading effects on single axially and laterally loaded piles.

The discusser noted differential settlement of pile-supported superstructures from the surrounding soil as one of the most urgent concerns in many cities such as San Francisco. The settlement of piles relative to the surrounding soil often damages utilities and disturbs access to buildings. The writers agree with the discusser that future research should consider studying this mechanism. Perhaps centrifuge model tests followed by numerical studies may help investigate this issue.

The discusser suggested that loading the pile at the end of the reconsolidation would aid understanding of the required load and pile settlement for relieving drag loads. The writers agree with this argument. In the SKS03 centrifuge test (Sinha 2022), load tests conducted on the pile with initial drag load (Fig. 1) provide that information. Fig. 1(b) shows that the load and the pile settlement required to erase the initial drag load were about 1,000 kN and 1% D, respectively.

Conclusions

The discusser provided valuable feedback regarding the accuracy and utility of the presented centrifuge model test. We agree with the discusser on the recommendation for future tests in investigating the response of piles most commonly used in practice, such as pile groups and driven piles for liquefaction-induced downdrag, differential settlement, and lateral spreading under more realistic boundary and loading conditions. At the same time, we would point out that this centrifuge model test was designed to emphasize the fundamentals of the problem under consideration and prove the feasibility of capturing these mechanisms on a reduced scale before adding more realistic complexities. The writers also agree that developing techniques for directly measuring lateral stresses at the soil-pile interface would be extremely useful. Unfortunately, such techniques do not exist and may not be feasible at the centrifuge model scale. Finally, no experiment is perfect; we maintain, however, that the results of this test program do enable a significant advancement in the understanding of liquefaction-induced downdrag on piles.

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