Development of a Verified Non-Linear Winkler Model for the Seismic Analysis of Pile Foundations in Improved Soils

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Abstract and Background:

Earthquakes have caused significant damage to civil engineering structures worldwide due to inadequate lateral load capacity and excessive deformation of pile foundations supporting these structures. Several ground improvement techniques that are proven to be effective and economical solutions to increase the lateral stiffness and strength of weak soils around piles often result in unwarranted conservative volumes of soil improvement. There are also no rigorous techniques to analyze the seismic behavior of piles in improved soils that can be utilized in day-to-day engineering practice. In this study, a stand-alone finite element computer code called DYPAC (Dynamic Piles Analysis Code) using the Beams on Non-linear Winkler Foundation (BNWF) approach is developed to analyze the non-linear seismic response of the pile foundations in improved soils.

Method of Approach:

DYPAC analyzes the seismic response of a single pile in improved and unimproved soils. This computer code models the pile as a beam element and the non-linear soil behavior as springs and viscous dashpots using a non-linear *p-y* element, where *y* is the pile displacement and *p* is the soil reaction per unit length of the pile. This non-linear *p-y* element accounts for soil yielding, gapping, radiation damping, and soil cave-in and recompression during seismic loading simulations. A method to modify the *p-y* curves to account for limited lateral extent of ground improvement is proposed and validated. The input parameters for these curves can directly be obtained from in-situ or laboratory soil tests. These *p-y* curves were input into DYPAC to analyze a series of dynamic centrifuge tests of single piles in soils improved using Cement Deep Soil Mixing (CDSM). Free-field non-linear site response analyses were performed using the DEEPSOIL computer program, and the soil displacement-time histories were input to the free-field ends of the non-linear *p-y* elements. The predictions made by DYPAC are validated using the centrifuge test results.

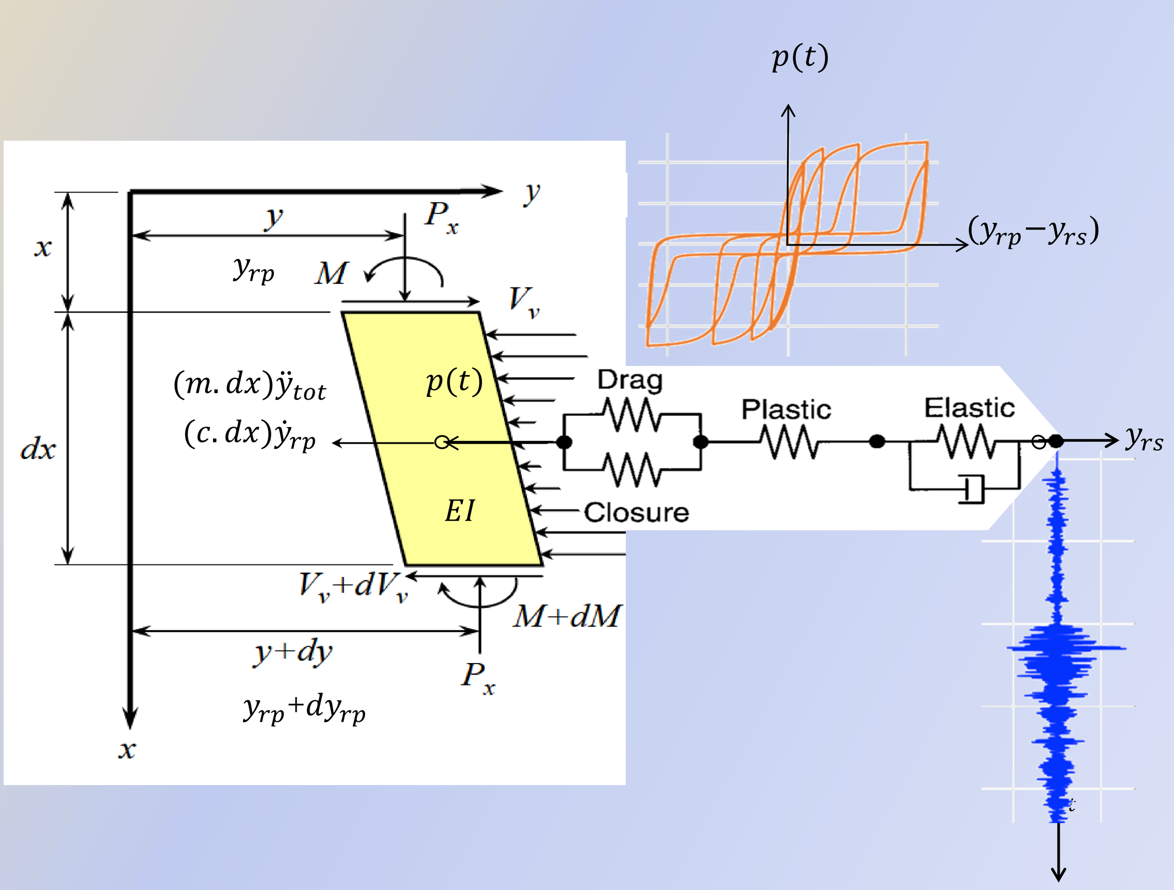

Fig. 1 An infinitely small element from a dynamic beam

Numerical and Centrifuge Modeling:

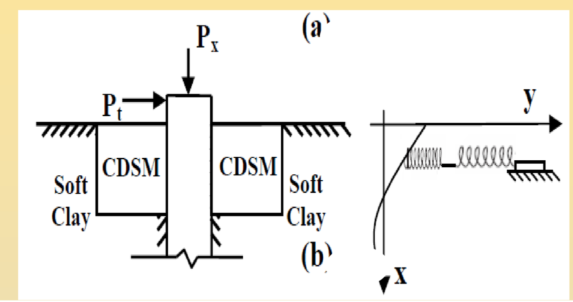

Fig. 2 Springs in series to account for soil improvement around a pile

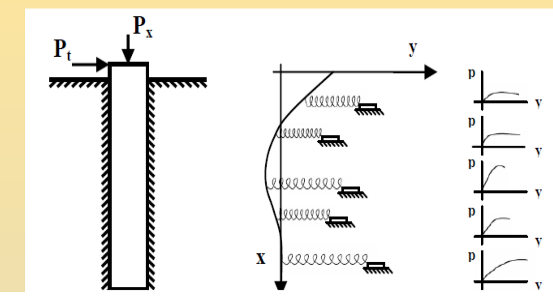

Fig. 3 Discrete nonlinear springs along the pile to simulate soil-pile interactions

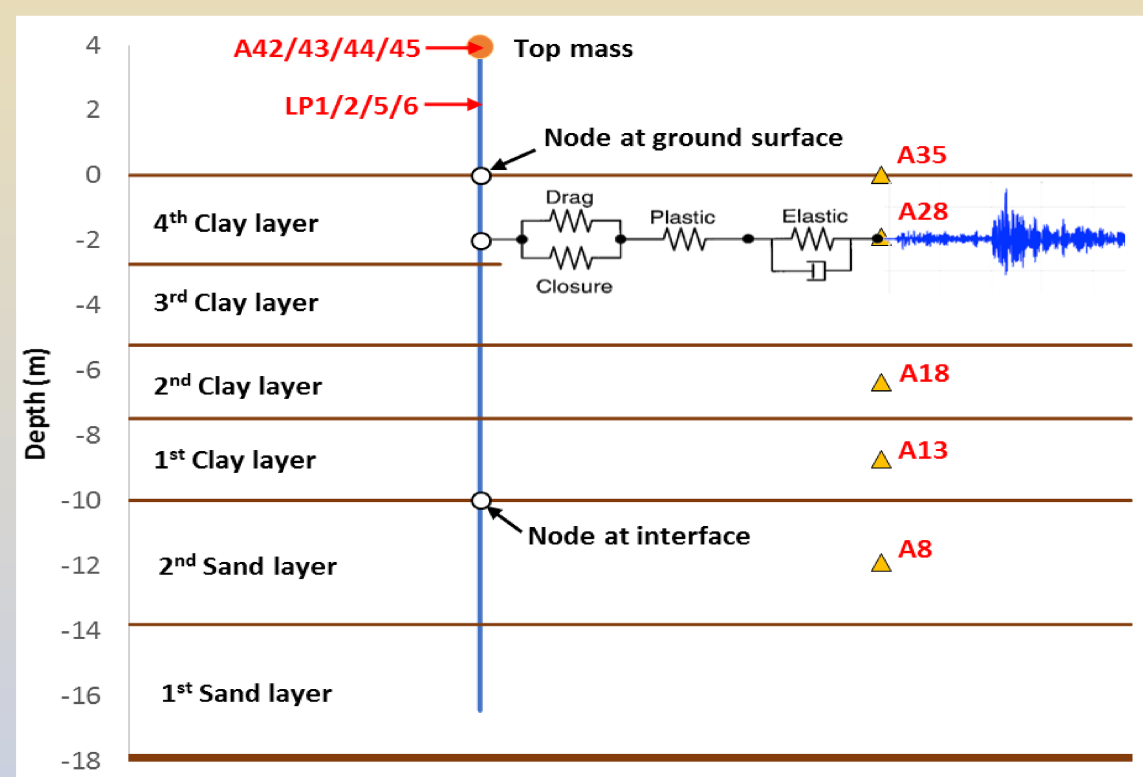

Fig. 4 Schematic illustration of DYPAC finite element model

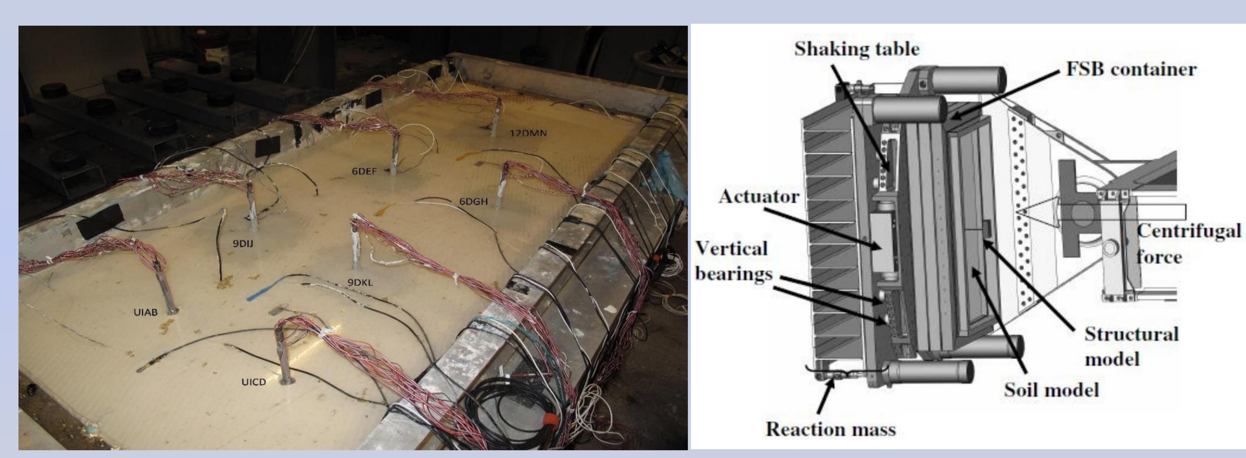

Fig. 5 Centrifuge model prior to testing

Table. 1 Soil properties used in the centrifuge and numerical modeling

Soil	Thickness (m)	Undrained shear strength (kPa)	Effective unit weight (kN/m³)	Strain factor, ε_{50}	K (kN/m³)
4th Clay layer	2.742	2.78-5.38	8.18	0.002	-
3rd Clay layer	2.490	8.61-9.86	8.68	0.002	-
2nd Clay layer	2.250	14.03-15.15	9.05	0.002	-
1st Clay layer	2.520	19.34-20.57	9.28	0.002	-
2nd Sand	3.810	-	10.88	-	33,900
1st Sand	4.230	-	10.44	-	33,900

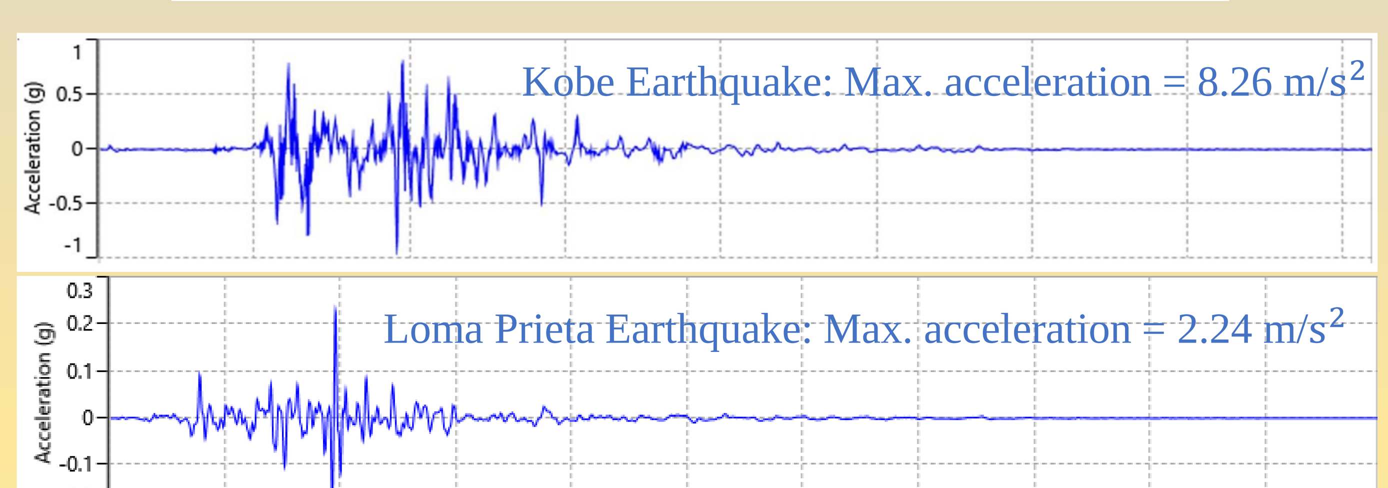

Fig. 6 Input motion time histories (Loma Prieta and Kobe earthquakes)

Results and Discussion:

The free-field soil displacements obtained using DEEPSOIL equivalent linear analyses were applied in DYPAC, and the pile deflections were predicted both in unimproved and improved soils. The CDSM improved soil was modeled in DYPAC using the proposed method explained before. The maximum displacements measured by displacement transducers were 4.5 cm and 60 cm for Loma Prieta and Kobe earthquakes, respectively. DYPAC predicted them as 8 cm and 80 cm, respectively. These predicted displacements are larger than the measured values. One possible reason for this discrepancy may be the neglected pile damping. Further, DYPAC-predicted displacement-time histories exhibited larger frequencies compared to the ones measured by the displacement transducers. The displacement transducers used in these tests are known to underestimate the frequency of the displacements during the seismic testing in the centrifuge and this is likely the reason for the above-mentioned discrepancy.

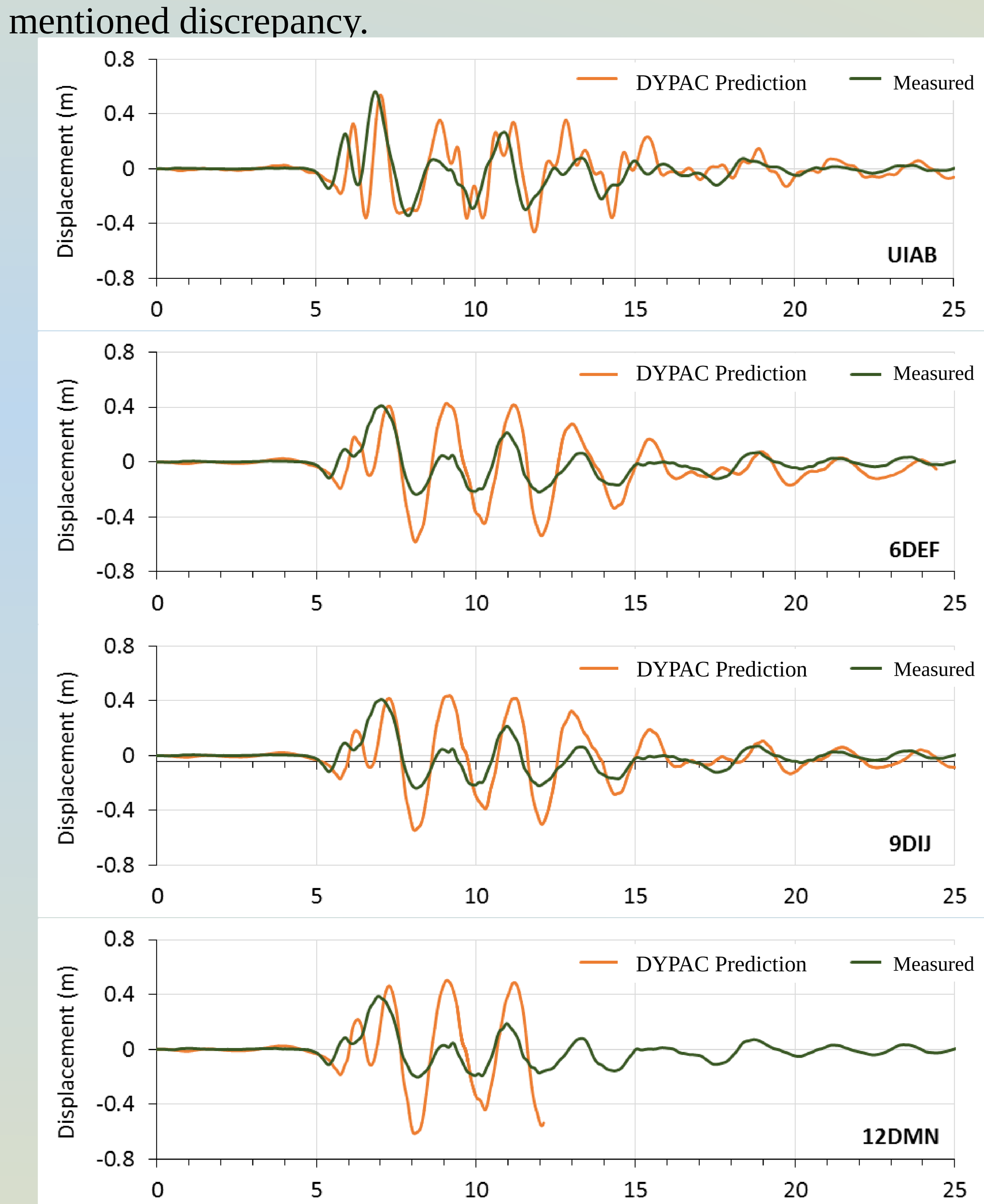

Fig. 7 Pile displacement-time histories predicted by DYPAC and measured by displacement transducers for Kobe Earthquake Scenario (UIAB: unimproved, 6DEF: 6D improvement depth, 9DIJ: 9D improvement depth, and 12DMN: 12D improvement depth)

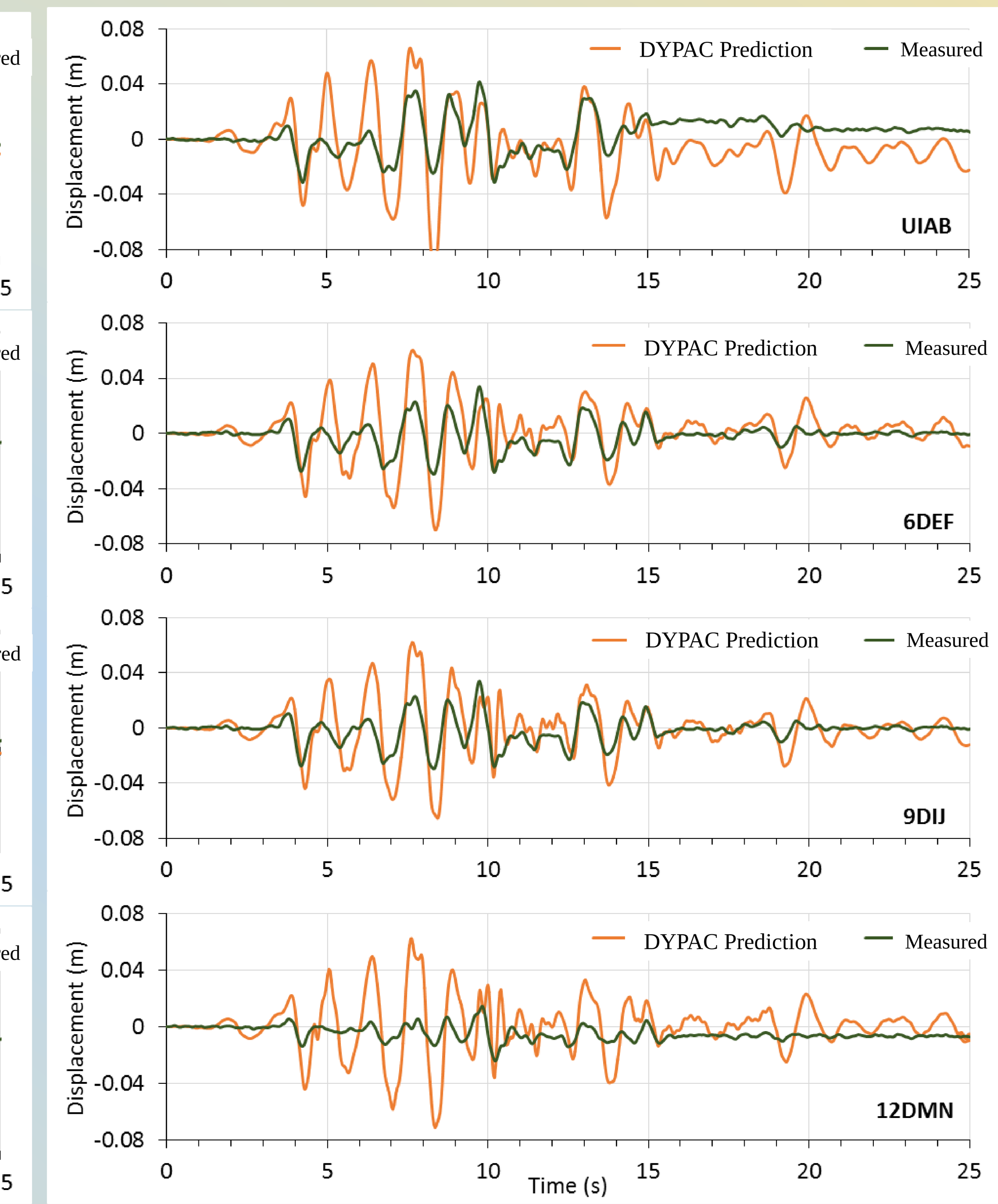

Fig. 8 Pile displacement-time histories predicted by DYPAC and measured by displacement transducers for Loma Prieta Earthquake Scenario (UIAB: unimproved, 6DEF: 6D improvement depth, 9DIJ: 9D improvement depth, and 12DMN: 12D improvement depth)

In summary, The DYPAC-predicted displacements are in the same order as the measured values, and overall, the predicted displacement follows a similar trend as the measured values. However, the predicted displacement magnitudes were slightly higher than the measured values. The quality of free-field soil displacements obtained from DEEPSOIL impacts the pile responses predicted by DYPAC. The quality of the DYPAC analysis was improved using the non-linear site response analysis conducted by DEEPSOIL. As seen in Fig. 9, the non-linear DYPAC predictions are significantly similar to the sensors' data. Hence, non-linear DYPAC predictions can estimate the seismic behavior of pile foundations in improved soils better.

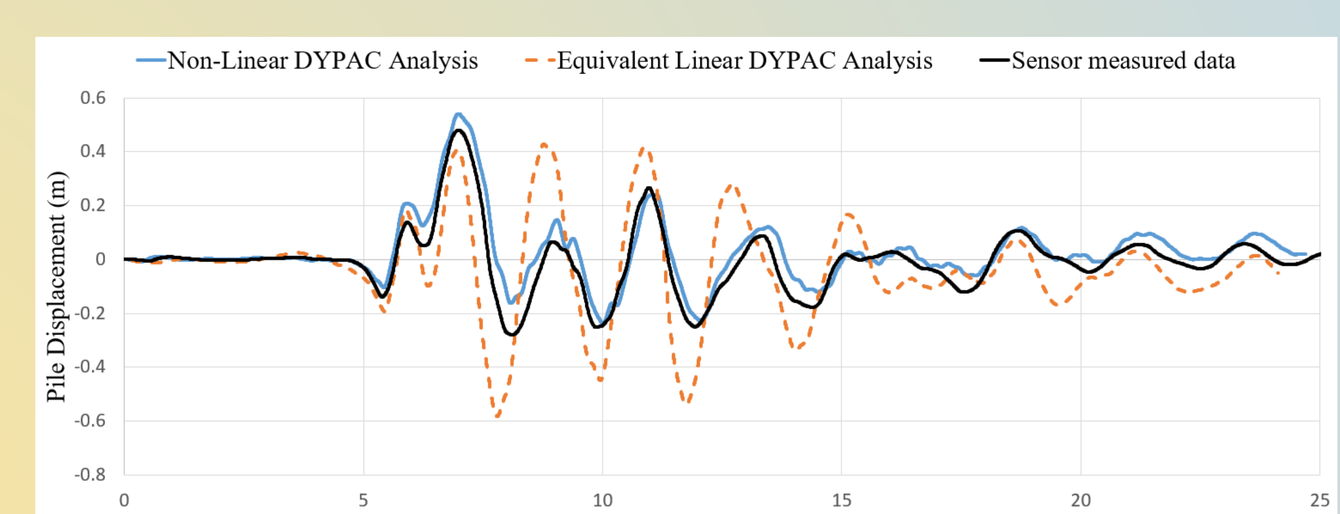

Fig. 9 Pile displacement-time history comparison between Non- and Equivalent-linear DYPAC analysis and measured data