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Numerical Modeling of Dynamic Centrifuge Experiments On A Saturated Dense Sand Stratum

T. Lai[1], A. Elgamal[2], Z. Yang[2], D. W. Wilson[3], and B. L. Kutter[3]
[1]AIR Worldwide Corporation, Boston, MA
[2]Department of Structural Engineering, University of California at San Diego
[3]Department of Civil and Environmental Engineering, University of California at Davis

Abstract— **A highly instrumented centrifuge experiment was conducted at the University of California at Davis (UCD) to investigate the dynamic response of a saturated dense sand stratum. In this experiment, a laminated container is employed in order to simulate one-dimensional (1D) site response. Peak accelerations near ground surface among a total of 27 earthquake-like shaking events ranged from 0.03*g* to 1.73*g* (in prototype scale) covering linear response as well as highly nonlinear response.**

The recorded input-output accelerations and pore pressures provide a unique opportunity for numerical model calibration. This paper presents the results of a computational study based on this comprehensive experimental set of data. Dynamic behavior of the saturated stiff site is modeled by a 1D finite element shear beam with a multi-yield-surface plasticity soil model. A set of soil properties that yields satisfactory results is defined, based on the entire seismic data set. The salient site response characteristics are discussed, along with a comparison of recorded and computed results.

Keywords—**dense sand, centrifuge testing, modulus reduction, damping ratio, dilatancy, site amplification, soil dynamics**

INTRODUCTION

A collaborative project between the University of California at Davis (UCD) and the University of California at San Diego (UCSD) has been conducted to investigate dynamic response of stiff soil sites. Such stiff site investigations are of significance to many urban areas worldwide and particularly to southern California. The UCD team focused on performing and documenting highly instrumented physical (centrifuge) model tests, to determine the behavior of stiff soil sites (dense sand) under low to high levels of seismic excitation. At UCSD, attention was directed towards analysis and numerical simulation of the UCD centrifuge testing results.

In this paper, the experimental data from one of the test series (DKS04 [10]) was studied. In this experiment, a laminated container was used to simulate one-dimensional (1D) site response of a saturated dense sand stratum. A solid-fluid fully coupled Finite Element (FE) program ([4], [5] and [12]) was used for the numerical simulation. The recorded downhole accelerations were utilized to identify the stiffness, damping, friction angle (defining shear strength of soil), and dilatancy characteristics of the saturated stiff soil deposit. Thereafter, numerical simulations were performed for representative weak to strong shaking events. In the following section, we start with a brief description of the experimental setup and recorded data.

CENTRIFUGE EXPERIMENTS

The centrifuge test series (DKS04) to be investigated in this study was conducted in a Flexible Shear Beam (FSB) container mounted on the 9*m*-radius geotechnical centrifuge at UCD [6]. The FSB container consists of a rigid base plate and five rigid rings, with overall dimensions of 1.651$m \times$ 0.787$m \times$ 0.553m in length, width and height respectively (Fig. 1). The container rings are sandwiched with soft rubber interfaces to provide lateral flexibility. Dynamic excitation was imparted primarily along the longitudinal direction. This configuration attempts to mimic the one-dimensional (1D) vertical shear wave propagation condition (shear beam response). The model was instrumented with extensive horizontal and vertical arrays of accelerometers, piezometers, and potentiometers (Fig. 1).

Nevada sand at about 100% relative density (*Dr*) was used to represent a stiff soil formation. This very dense stratum was prepared by air-pluviating sand to a *Dr* of approximately 90% in about 6*cm* lifts (model unit). Each lift was leveled and vibrated using a surface vibrator to reach the final *Dr* (see [10] for more details). Unit weight of the saturated sand and the pore fluid were measured as 20.3kN/m^3 and 9.8kN/m^3 respectively. A pore-fluid with viscosity equal to about 8 times that of water was employed, resulting in a prototype permeability coefficient within the range of medium to fine sands [8].

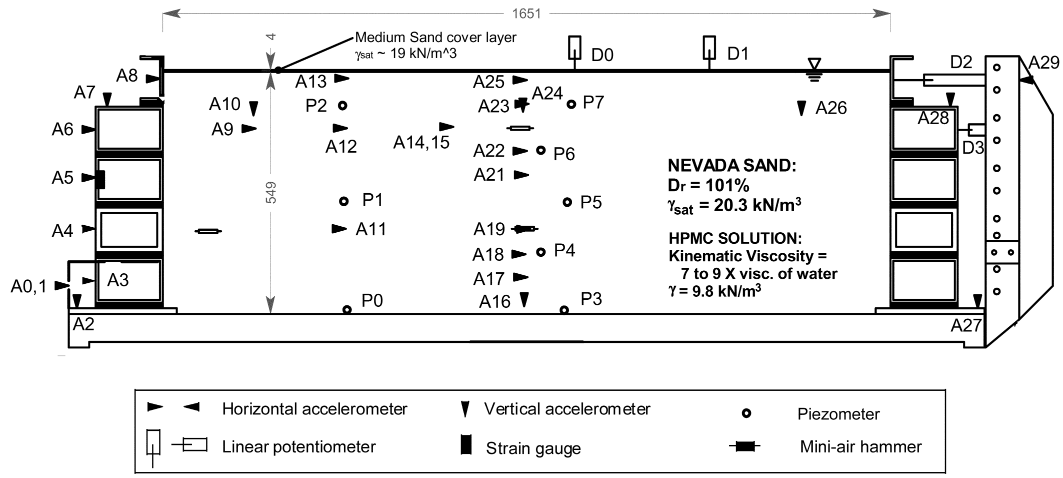

Figure 1. Model configuration of the DKS04 FSB container [10].

Table 1: UCD DKS04 shaking events and peak acceleration
(units in prototype scale [9])

No. (1)	Event ID	Peak acceleration (*g*)		Centrifuge g level (model depth)	Depth of central vertical array accelerometers (*m*)
		A25	A17		
1	DKS04_01	0.101	0.022	9.19*g* (5.08*m*)	0.22, 0.71, 1.69, 2.20, 3.32, 3.85, 4.32 (2)
2	DKS04_02	0.168	0.046		
3	DKS04_03	0.481	0.170		
4	DKS04_04	0.154	0.086		
5	DKS04_05	0.076	0.024		
10	DKS04_34	0.828	0.493		
11	DKS04_35	0.443	0.276		
12	DKS04_40	0.897	0.641	18.13*g* (10.03*m*)	0.43, 1.40, 3.34, 4.33, 6.55, 7.60, 8.53 (2)
13	DKS04_41	0.859	0.526		
14	DKS04_44	0.211	0.125		
15	DKS04_48	0.519	0.361		
16	DKS04_49	0.385	0.260		
17	DKS04_50	0.155	0.108		
18	DKS04_51	0.905	0.634		
19	DKS04_52	0.412	0.327		
26	DKS04_69	--- (3)	1.261		
27	DKS04_70	--- (3)	1.144		
6	DKS04_13	0.080	0.020	25.28*g* (13.98*m*)	0.59, 1.95, 4.65, 6.04, 9.14, 10.59, 11.89 (2)
7	DKS04_14	0.045	0.012		
8	DKS04_15	0.043	0.020		
9	DKS04_16	0.031	0.014		
20	DKS04_55	0.579	0.412	37.33*g* (20.64*m*)	0.88, 2.87, 6.87, 8.92, 13.49, 15.64, 17.56 (2)
21	DKS04_56	0.369	0.244		
22	DKS04_59	0.792	0.537		
23	DKS04_62	0.330	0.194		
24	DKS04_63	0.148	0.072		
25	DKS04_66	0.209	0.087		

(1) Sequence of imparted shaking events.
(2) Depth of accelerometers A25, A23, A22, A21, A19, A18 and A17 respectively.
(3) Out of range, and approximately around 1.73*g*

The model in Fig. 1 was subjected to 27 earthquake-like shaking events. These events were imparted at centrifugal acceleration levels of 9.2*g*, 18.1*g*, 25.3*g* and 37.3*g*, representing a prototype stratum of 5.1*m*, 10.0*m*, 14.0*m* and 20.6*m* depth respectively. The sequence of imparted shaking events (Table 1) is completely documented in [9] and [10]. Preliminary back-analysis of the data showed minor change in the response characteristics of this dense sand stratum due to imparted shaking sequence.

Table 1 lists peak acceleration at A25 (near surface, Fig. 1) and A17 (near base) for all 27 shaking events. Near the model surface, recorded peak accelerations in the longitudinal direction ranged from 0.03*g* to 1.73*g* (in prototype scale). As will be shown below, this broad spectrum of acceleration magnitudes resulted in soil response covering linear to highly nonlinear scenarios.

Representative acceleration and excess pore-water pressure ratio time histories of a strong shaking event (Event 34) are depicted in Fig. 2. As shown, peak excess pore pressure ratio r_u (= u_e/σ'_v where u_e is excess pore pressure and σ'_v is initial effective vertical stress) remained relatively low at most monitored locations, ranging from 0.2 at depth to about 0.4 near ground surface. Close inspection of Fig. 2 indicates that most high acceleration peaks coincide with an instantaneous reduction in pore pressure. This phenomenon is a direct consequence of the shear-induced dilation tendency [8].

NUMERICAL MODELING PROCEDURE

The dynamic response of the central soil domain from the surface down to A17 (Fig. 1) was model by a 1D shear beam. In this modeling, a two-dimensional plane-strain FE program was employed ([4] and [12]), which implements the two-phase (solid-fluid) fully coupled *u-p* (where *u* is displacement of the soil skeleton and *p* is pore pressure) FE formulation of [2] and [13]. In this formulation, the saturated soil system is modeled as a two-phase material based on the Biot theory [1] for porous media, and damping is mostly generated from the soil nonlinear hysteretic response. Additional Rayleigh viscous damping can be added. Boundary conditions for all simulations were ([12] and [4]):

1). For the solid phase, lateral motion was specified along the base, as the acceleration recorded at A17 (Fig. 1). Use of the A17 record as input excitation avoids data inconsistency due to potential relative slip between the container base and the soil. To mimic a 1D shear beam effect, displacement degrees of freedom at any given depth were tied together both horizontally and vertically.

2). For the fluid phase, the base and two lateral boundaries were impervious (zero flow rate), with zero pore pressure prescribed at ground surface (i.e., water-table at ground surface).

3). Lateral inertia forces were increased by 24% to include the effect of container mass [10]. The relatively low shear stiffness of the container itself was neglected.

IDENTIFICATION OF DYNAMIC SOIL PROPERTIES

All the earthquake-like shaking events in Table 1, covering linear response as well as nonlinear response, were utilized in defining the dense sand model parameters. The general goal was to define a set of modeling parameters that achieve a satisfactory level of success in matching the recorded site response. To this end, the following steps were undertaken:

1). A Poisson's ratio of 0.24 was employed based on a pilot 3D investigation [7]. In this 3D study, Poisson's ratio was defined by matching the first lateral and vertical resonance of the same centrifuge container filled with dry dense sand of $Dr \approx 100\%$.

2). Permeability coefficients were defined in accordance with prototype fluid viscosity at the centrifugal acceleration levels.

3). The low amplitude shaking events (e.g., events 5, 13 – 16 in Table 1) were first employed to define the shear wave velocity profile and viscous damping of the sand stratum. The low-amplitude (linear) site stiffness profile was represented by the relationship: $V_s(z) = V z^b$ in which V is shear wave velocity at 1*m* depth, z is depth coordinate in meter, and b = 0.25 dictates a smooth variation of V_s with depth [3].

4) The friction angle, which defines the shear strength of the soil, was estimated based on moderate excitation events (e.g., events 49, 56 and 62 where soil nonlinearity dominated the response).

5). Dilatancy related model parameters were adjusted such that a reasonable match was achieved for large-amplitude shaking events (e.g., events 40, 41, 51 and 59 in Table 1). Adequacy of the matching process was based on inspection of the recorded and computed acceleration response spectra (5% damping) at all accelerometer locations.

Table 2: Major modeling parameters of saturated dense Nevada Sand ($Dr \approx 100\%$)

Modeling parameter	Parameter value
V^l_s (*m/s*)	$108\ z^{0.25}$ (1)
Poisson's ratio	0.24
Rayleigh damping (2)	$a_m = 1.5$, $a_k = 1.1 \times 10^{-3}$ (5% over 1-10*Hz* range)
Friction angle	40º
Phase transformation angle	22º
Contraction parameter (3)	$c_1 = 0.004$, $c_2 = -0.05$
Dilation parameter (3)	$d_1 = 0.4$, $d_2 = 10$
Permeability, *m/s*	$8.25 \times 10^{-6} \times$ (*g* level)

(1). z is depth coordinate in meter.
(2). a_m and a_k are Rayleigh damping mass and stiffness multipliers respectively.
(3). See [5].

Table 2 lists the main model parameters for this saturated dense sand stratum. The identified shear wave velocity profile of $V^l_s(z) = 108\ z^{0.25}$ (*m/s*) closely matches the experimentally identified profile $V^M_s(z) = 115\ z^{0.25}$ (m/s) [11].

SIMULATION RESULTS

Representative simulation results of weak, moderate, and strong excitation (Events 63, 35, and 34 respectively) are shown in Figs. 3-5, in terms of acceleration time histories and the corresponding response spectra (5% damping) along the soil profile.

In the three cases, the numerical model gives an overall satisfactory match to the experimental counterpart at all accelerometer locations, both in the time and frequency domains. Moreover, the dilation-induced spiky acceleration response observed in Event 34 is reproduced by the numerical model (Fig. 5). In this case, the computed reduction in effective confinement (not shown) ranged from 0.1 near the model base to about 0.4 near ground surface, in agreement with the measured pore pressure increase at these locations (Fig. 2).

SUMMARY AND CONCLUSIONS

The UCD centrifuge site-response experiment with saturated dense Nevada Sand ($Dr \approx 100\%$) produced a comprehensive set of data covering linear to highly nonlinear response scenarios. Assuming a one-dimensional shear beam behavior, recorded accelerations of weak excitation events were first used to identify soil low-amplitude stiffness and damping, then the friction angle was estimated based on moderate excitation events. Finally, dilatancy related parameters were identified by utilizing large excitation events. Furthermore, numerical simulations were conducted for a representative set of weak to strong shaking events, using a fully coupled nonlinear Finite Element program calibrated by the identification results. The simulation results were in reasonable agreement with the experimental counterparts.

In the strong events, the influence of shear-induced dilation was strong. Under the practically undrained loading conditions of this study, the dilation resulted in: 1) instantaneous regain in effective confinement and shear strength, 2) regain in shear stiffness with the increase in shear strain, 3) reduced damping, and 4) instantaneous pore pressure reduction and strong acceleration spikes (approaching about 1.7g for some events in this data set). This type of response may be effectively reproduced by appropriate nonlinear hysteretic models.

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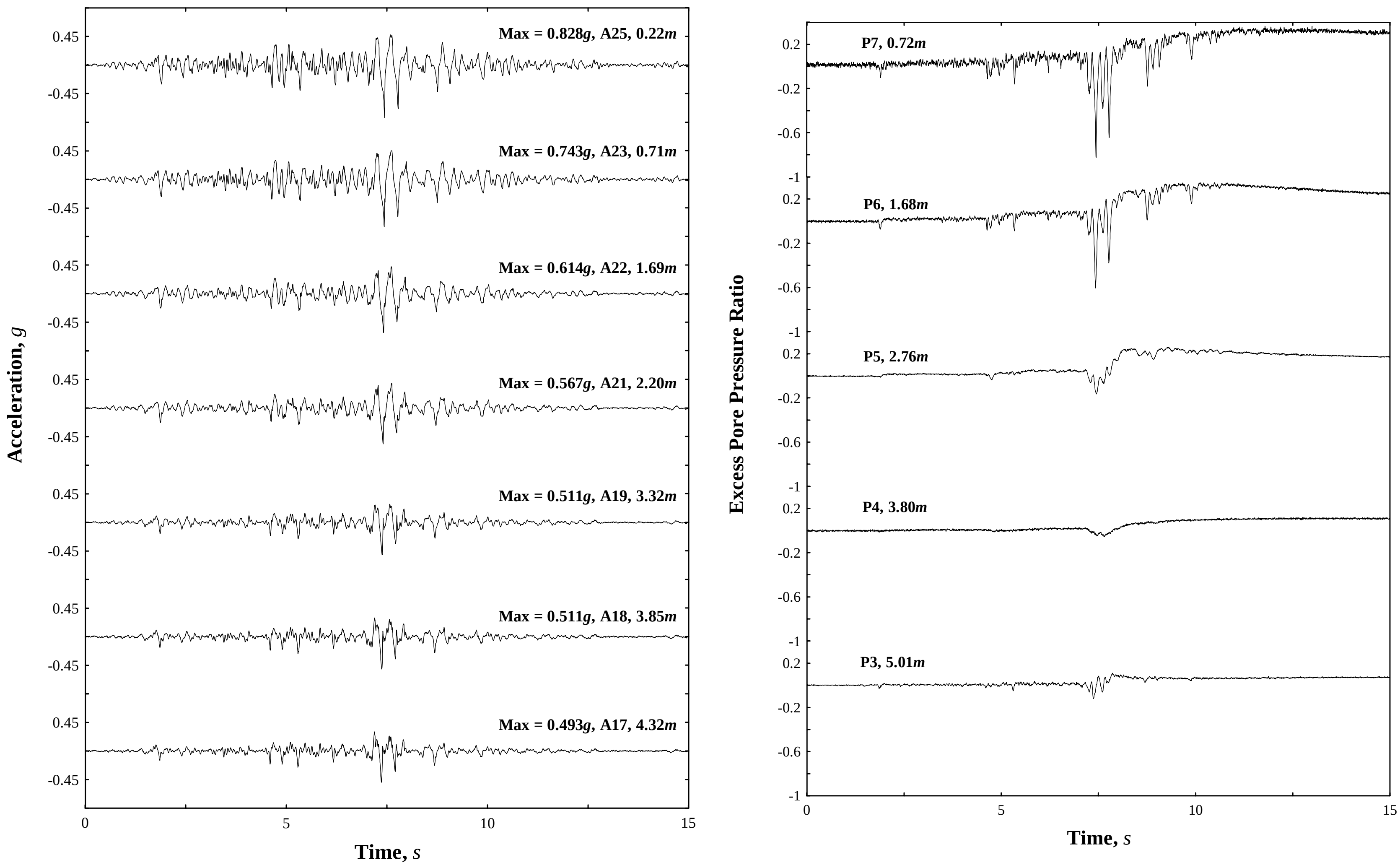

Figure 2: Sample acceleration and pore pressure time histories (Event 34)

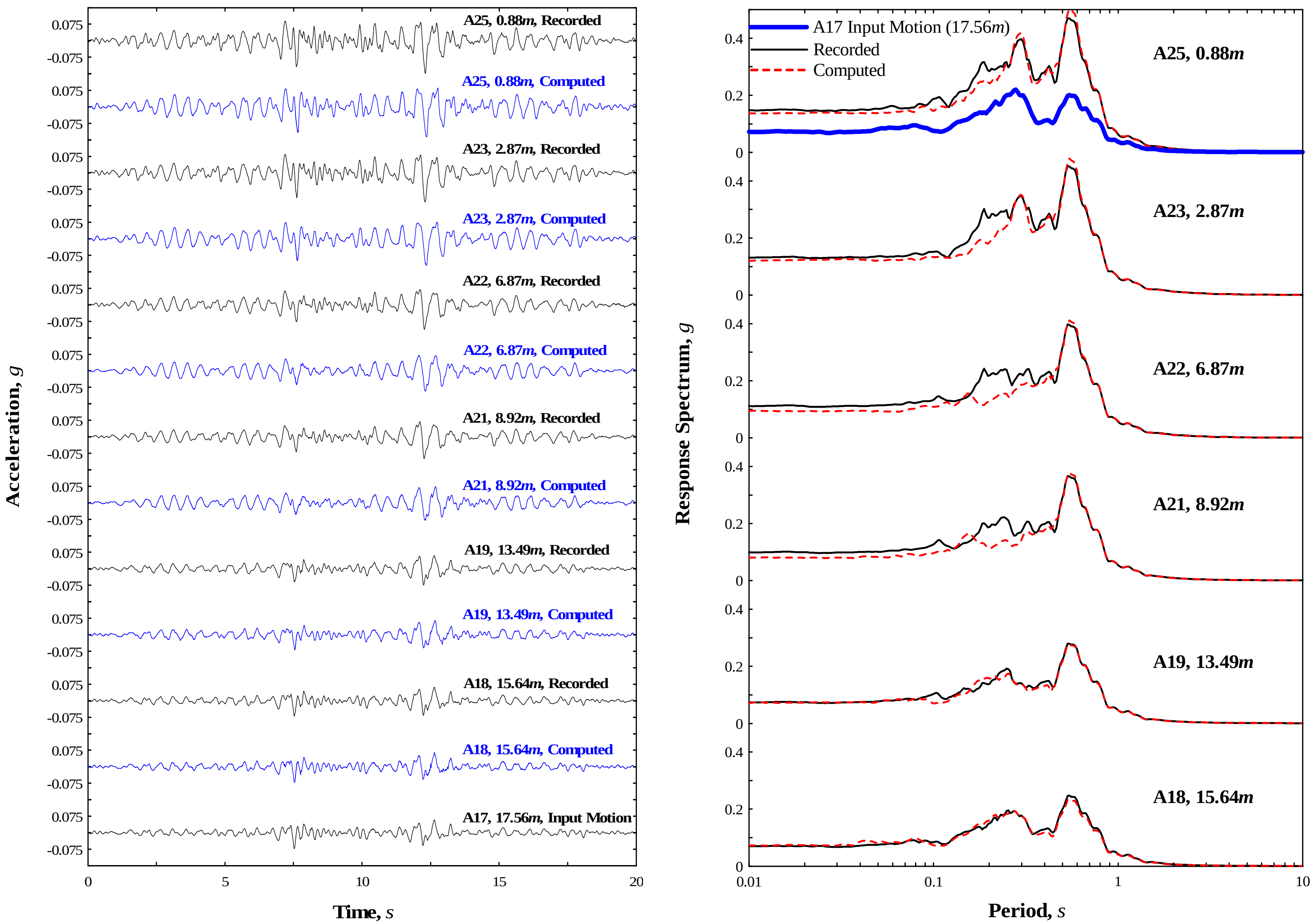

Figure 3: Event 63 recorded and computed acceleration histories and response spectra (5% damping and 37.33*g* Centrifugal Field).

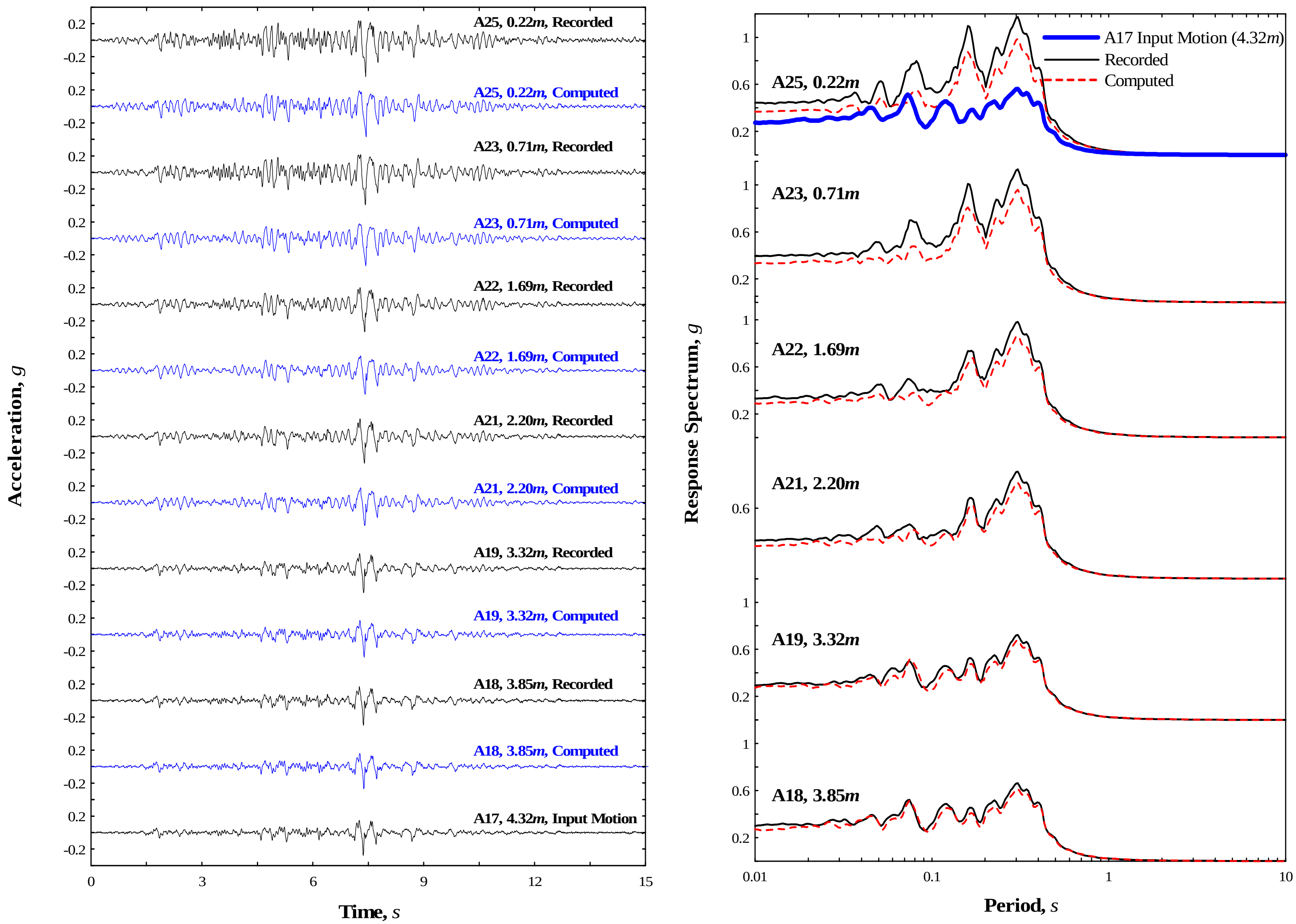

Figure 4: Event 35 recorded and computed acceleration histories and response spectra (5% damping and 9.19*g* Centrifugal Field).

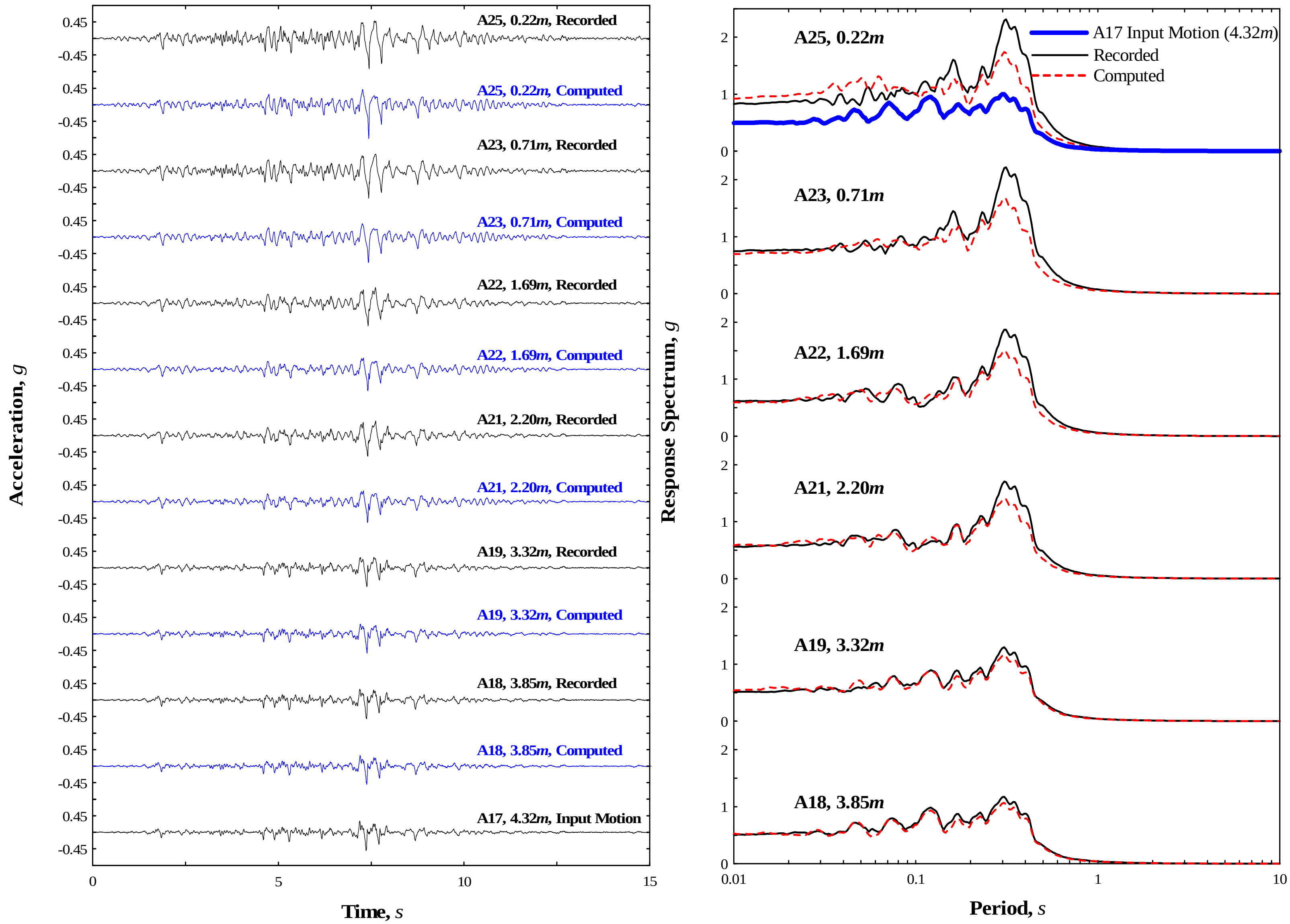

Figure 5: Event 34 recorded and computed acceleration histories and response spectra (5% damping and 9.19*g* Centrifugal Field).