NUMERICAL SIMULATION OF SHAKING TABLE TESTS ON DYNAMIC RESPONSE OF DRY SAND

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ABSTRACT:
In this paper, experimental results obtained from dynamic tests with laminar shear box with dimensions of 1 by 1 by 1m^3, on Babolsar dry sand models are compared with numerical simulation results. Response of two types of dense and loose level ground models excited with harmonic loadings was observed. Different physical parameters like displacement of layers, accelerations at internal points and surface settlements were measured during tests.
For numerical analyses, first the analyses were done with one-dimensional softwares like EERA (Equivalent-linear Earthquake site Response Analysis) and NERA (Nonlinear Earthquake site Response Analysis). These codes are based on equivalent linear methodology. Then, more precise modeling of the laminar shear container and its inside sand is conducted using famous finite element software ABAQUS.
Due to very small frictional coefficient between box layers, in numerical modeling of laminar shear box this effect was neglected and proper boundary conditions were used for model. Also, in order to obtain more real results in 2D level ground analysis and avoiding reflect of waves from side boundaries into the model, infinite elements and quiet boundaries were used. The numerical analyses were performed for model scale. In all cases the computational results were compared with real and measured values for different physical parameters.

KEYWORDS: Shaking Table, Laminar Shear Box, Numerical Simulation, Dynamic Response, Dry Sand

1. INTRODUCTION

Measurement of dynamic soil properties is a critical task in the solution of geotechnical earthquake engineering problems. Wide varieties of field and laboratory techniques are available, each with different advantage and limitations with respect to the problem. Physical modeling tests as a method between element tests and field tests are applicable for determining soil dynamic properties. Physical model tests usually attempt to reproduce boundary conditions of a particular problem by subjecting a small scale physical model of a full-scale (prototype) structure to cyclic loading. This kind of test is performed under the earth gravitational field (*1g* model test) or higher gravitational fields (*ng* model tests). The *1g* tests are most commonly performed with the use of shaking tables and *ng* tests are usually performed in geotechnical centrifuge. Physical model tests using shaking table in geotechnical earthquake engineering provides valuable information about the behavior of granular sand (Kukosho & Iwatate 1979; Sunddaraj 1996), liquefaction (Jafarzadeh 1996), post earthquake settlements (Shamoto et al. 1996) and ground-structure interactions (Kagawa et al.1995; Tsukamoto et al.1995).
In this paper, experimental results obtained from dynamic tests carried out by laminar shear box on dry sand models are compared with numerical simulation results, in model scale. Response of two types of dense and loose level ground models excited with harmonic loadings was observed. Different physical parameters like displacement of layers and accelerations were measured during tests. The Numerical simulation is carried out using 1D and 2D different soft wares (NERA, EERA, and ABAQUS).

2. EXPERIMENTS

2.1. Laminar Shear Box

For performing the experiments in this research, a laminar shear box is used as a container. This box is a cube with dimensions of 1 by 1 by 1 m^3 and consists of 25 aluminum frames with 0.4 *m* height. In order to prevent reflecting waves from the boundary sides and creating complementary shear stress on vertical bounds, the friction between the frames was reduced ball bearings between frames. The average frictional coefficient between the frames is 0.022 (Jurabchian, 2003).

2.2. Soil and Instrumentation

The box was filled with Babolsar dry sand. In order to compare the results of experimental works with numerical analyses, dense and loose model responses were chosen.
Accelerometers and LVDTs were placed at *0.2 m*, *0.4 m* and *0.6 m* height of the model in order to capture the behavior of the soil during excitations. The box and configuration of the instruments is shown in Fig.1.

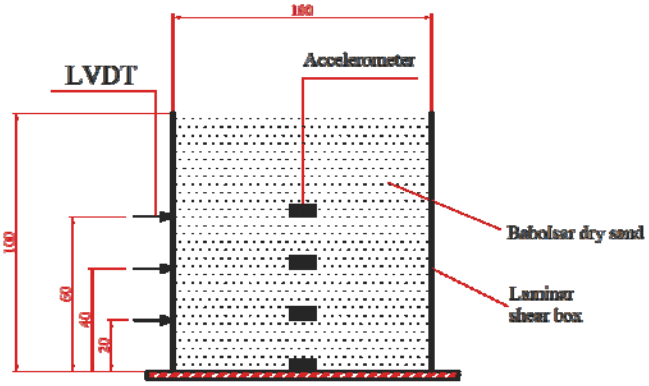
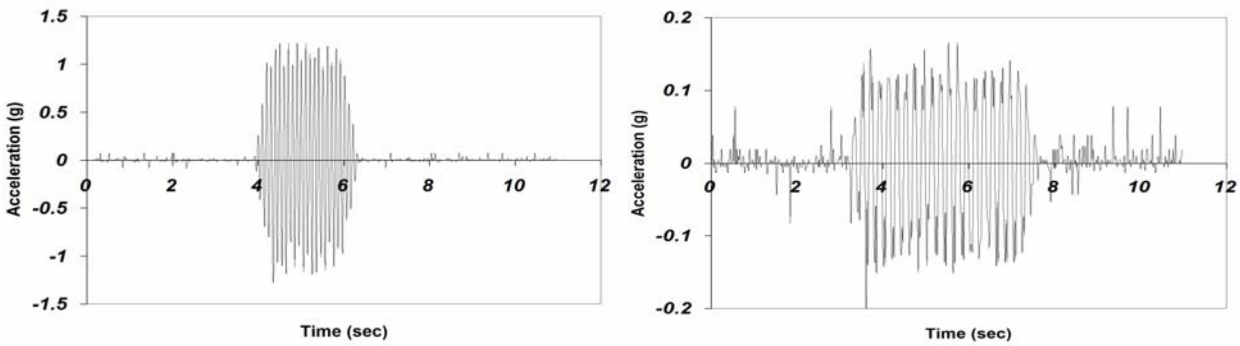


Figure 1 Configuration of instruments in laminar shear box (dimensions are in *cm*).

2.3. Excitations

A harmonic excitation of 20 cycles was applied to models. Relative density (*Dr*) of dense model changed from 87.7% to 90.7% and for loose model varied from %15.9 to %19.4 during excitation. The acceleration time histories induced at the bottom of each model through shaking table are shown in Fig. 2. The base acceleration of loose and dense models are about *0.1g* and *1.2g*; respectively. Detail information about the tests is available at Abazari (2004).



(a) (b)

Figure 2 Input excitation of (a) dense (b) loose sand.

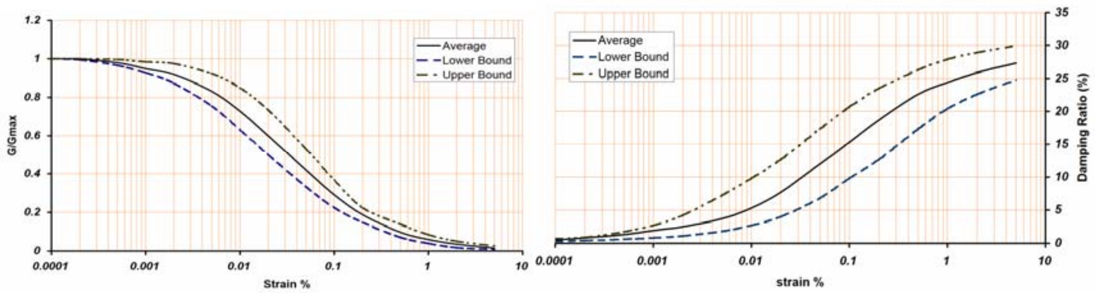
3. NUMERICAL SIMULATIONS

Numerical analyses were done in the box and level ground scales and the amount of displacements and accelerations were compared with test results in different elevations for dense and loose models.

3.1. One Dimensional

Numerical analyses first were done with one-dimensional softwares like *EERA* (Equivalent-linear Earthquake site Response Analysis) and *NERA* (Nonlinear Earthquake site Response Analysis). These codes are based on equivalent linear methodology (Bardet et al. 2000, Bardet et al. 2001). The input data for these softwares are soil profile, earthquake data, density of the soil, shear wave velocity, G/G_{max}-γ and damping ratio-γ graphs.

The profile of the soil is assumed to be 1*m* like the laminar box and the earthquake data considered as be shown in Figure 2. Shear wave velocity of dense and loose models were calculated from previous experimental tests 32.6 and 40.6 *m/s*; respectively. The softwares need the G/G_{max}-γ and Damping Ratio(%)-γ graphs in 0.0001% - 10% strain range. The tests were done in %0.5-%2 strain so these curves was not available in the experimental works, so the average graphs which are suggested by Seed and Idriss (1970) were used (Fig. 3).

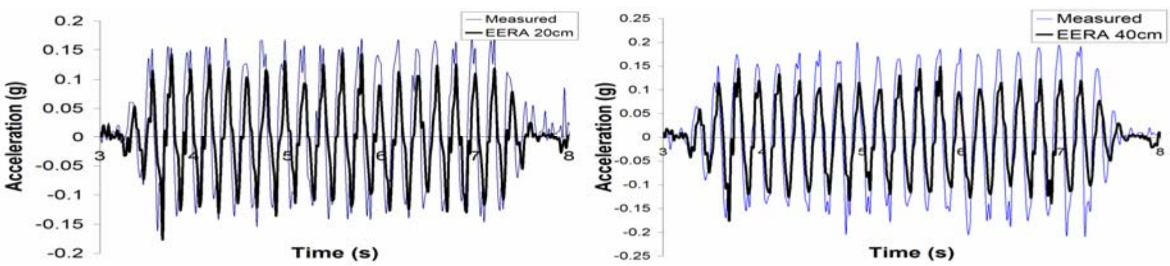


(a) (b)

Figure 3 Curves of (a) G/G_{max}-γ; (b) Damping Ratio(%)-γ at 0.0001% - 10% strain (Seed and Idriss, 1970)

The acceleration time histories obtained from tests, EERA or NERA are compared in Figs. 4 to 7. Also, the approximate differences of accelerations amplitudes are compared in Table 2. It clear that in loose model the amplitude of acceleration in measured data increase with height from bottom of the model which is in accordance with EERA and NERA results. EERA compared relatively well with measured data especially in lower depth but NERA shows lower acceleration in comparison with EERA and measured data.

In dense model (Figs. 6 and 7) the amplitude of acceleration is decreasing in higher levels experimental data. EERA has good agreement in higher levels with measured data; however NERA results show much lower acceleration.



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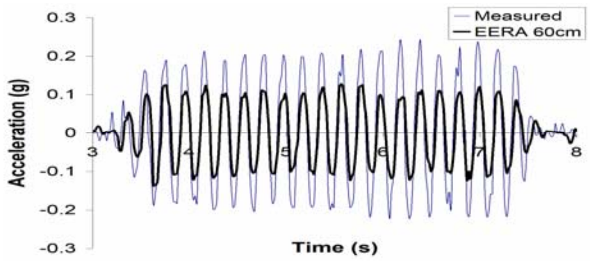


(c)

Figure 4 Comparison with EERA and Measured acceleration of loose model at (a) 20 *cm* (b) 40 *cm* and (c) 60 *cm*.

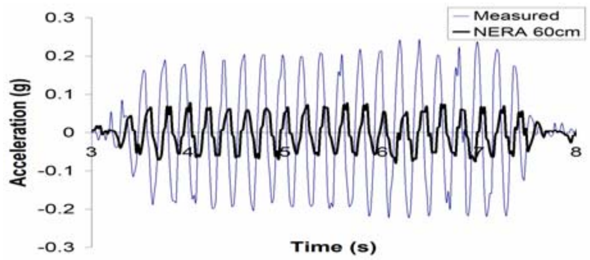
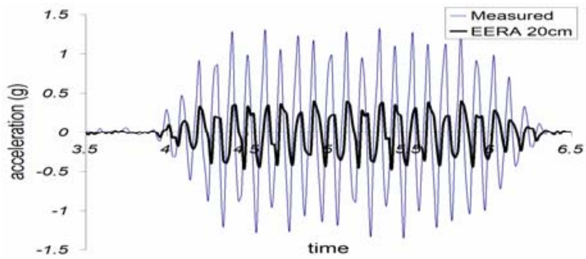
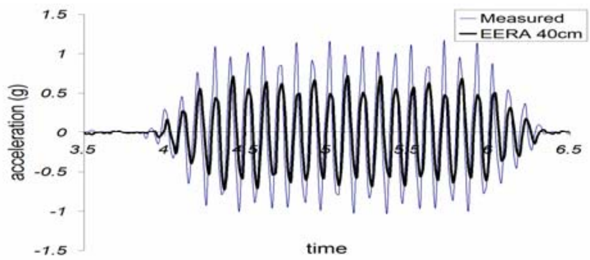


Figure 5 Comparison with NERA and Measured acceleration of loose model at 60 *cm*.



(a)



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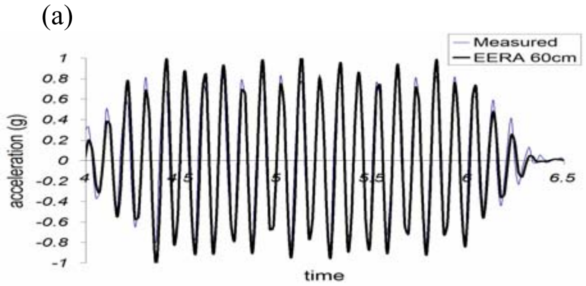


(c)

Figure 6 Comparison with EERA and Measured acceleration of dense model at (a) 20 *cm* (b) 40 *cm* and (c) 60 *cm*.

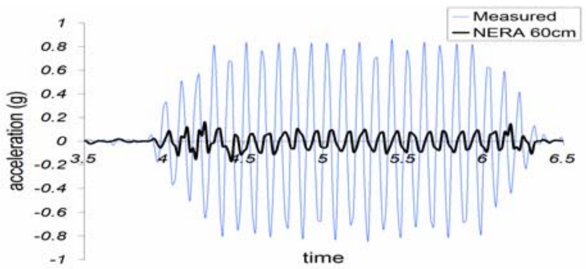
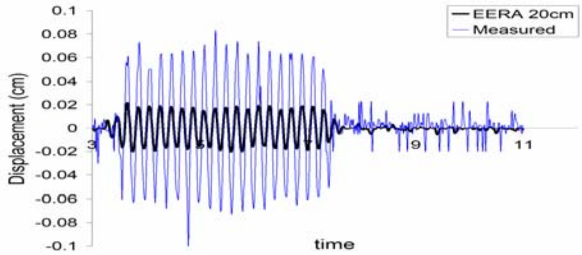
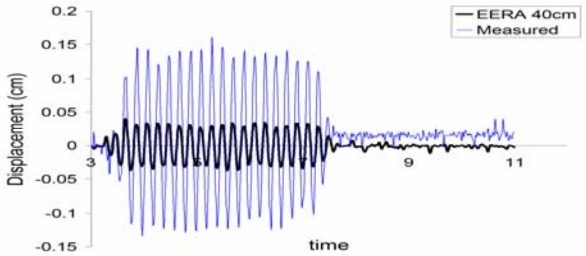


Figure 7 Comparison with NERA and Measured acceleration of dense model at 60 *cm*.

Comparison between measured displacements with NERA or EERA computed results of loose model are shown in Figs. 8 and 9 and Table 3. These figures indicate that the amplitude of displacement increase in higher level of the model in measured data and EERA. EERA shows lower displacement than experimental and the amount of differences increase in higher elevations. Although NERA shows unsymmetrical behavior of displacement, the amplitude of displacement is close to measured data. Also because of linear modeling of the material in EERA it failed to capture the plastic displacement which occurred at the end of loading, shown in Figure 9. The amount of plastic displacement remaining at the end of loading of each model is presented in Table 4. The situation is almost same in dense model (Fig.10.



(a)



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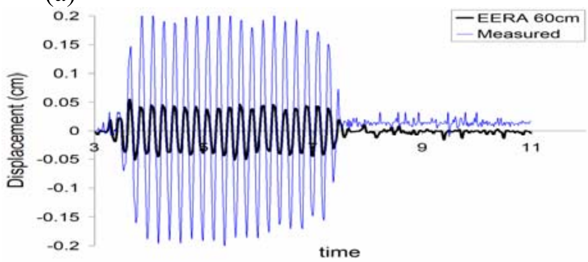


(c)

Figure 8 Comparison with EERA and Measured displacement of loose model at (a) 20 *cm* (b) 40 *cm* and (c) 60 *cm*.

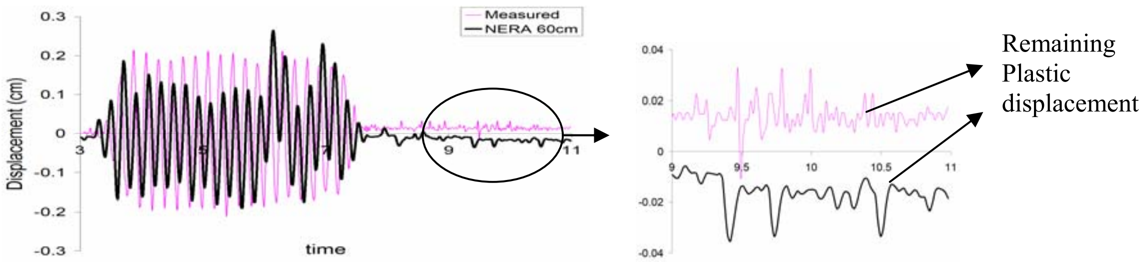
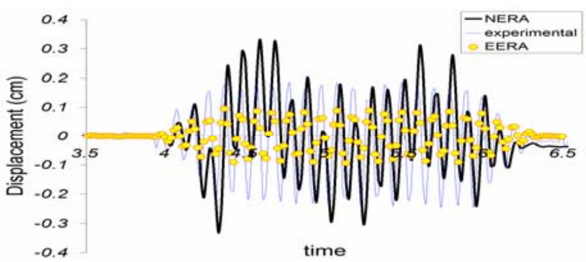
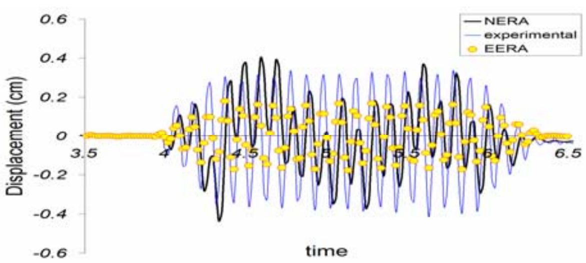


Figure.9. Comparison with NERA and Measured displacement of loose model.



(a)



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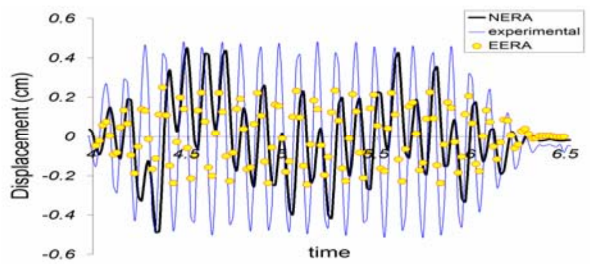


(c)

Figure 10 Comparison of EERA, NERA and Measured displacements in dense model at (a) 20 *cm* (b) 40 *cm* and (c) 60 *cm*.

3.2. Two Dimensional

For 2D simulation of the laminar shear box, ABAQUS finite element software was used. The finite element mesh used in the analyses, which consisted of four-node quadratic element namely *CPE4R* can be seen in Fig. 11. The height of the element and the laminar frames of the box are same. The dynamic implicit analysis used for simulating the shear box and sand during excitation. The nodes at the bottom of the model were fixed. Because of the low friction of the frames in shear box, they are not modeled and their effects were simulated at side bounds using two conditions. The nodes of side bound in same elevation constrained to each other in *x* direction to simulate the same movement of the frames in this direction. The laminar box can not move in *y* direction but the soil may slide toward to frames so in one analysis the relative displacement between two nodes in a same elevation in *y* direction released (*Ux*) and in another one these nodes constrained to each other in *y* direction (*Uxy*).

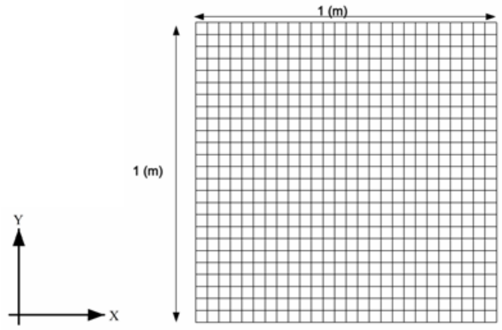


Figure 11 2D finite element mesh of laminar shear box.

Sand assumed to follow Modified Drucker-Prager/Cap constitutive model. Elastic parameter of the material was calculated from Eqns. 3.1 and 3.2.

$$v_s = \sqrt{G/\rho} \tag{3.1}$$

and

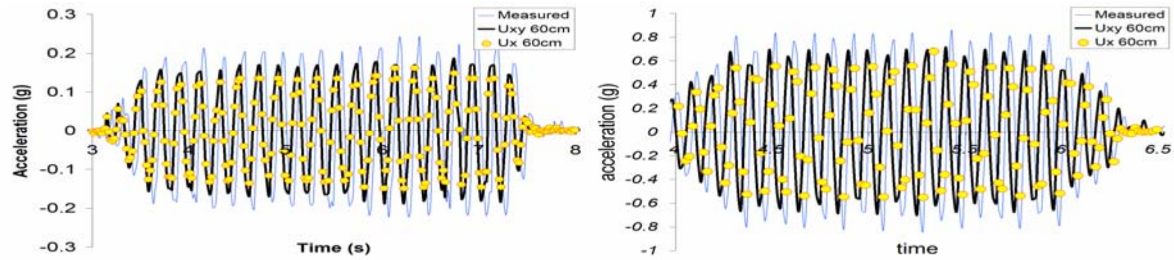
$$G = \frac{E}{2(1+\nu)} \tag{3.2}$$

The plastic parameters of the model are introduced in Table 1. In this table d and β are cohesive and angle of friction of the Drucker-Prager, λ and κ are the consolidation parameters of sand (slopes of consolidation and swelling line of the $e-\ln p$ curve), α and R are related to the shape of transition and cap surface and $K=0.8$ modified Drucker-Prager surface to simulate the real behavior of the soil.

Table 1 parameter of the plastic model for dense and loose Babolsar dry sand.

	d	β°	λ	κ	α	R	K
Dense Sand	0	48.8	0.03	0.005	0.05	0.8	0.8
Loose Sand	0	35.4	0.03	0.005	0.05	0.8	0.8

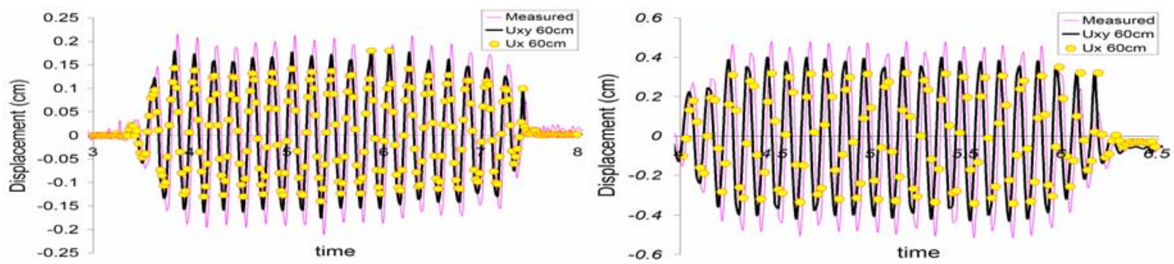
Fig. 12 shows the results of acceleration in loose and dense models in comparison with measured data. It can be inferred from this figure that 2D analyses show a better agreement with measured data in comparison with results of NERA and EERA. Also the curve of *Uxy* compared well with the results of experimental data especially in higher levels (Table 2).



(a) (b)

Figure 12 Comparison with *Ux*, *Uxy* and Measured acceleration of (a) loose (b) dense models at 60 *cm*.

Comparison of displacement in different elevations of loose sand shows very good agreement (Fig. 13) between computed and measured results. *Uxy* model has minimum differences and shows higher plastic strain at the end of excitation (Table 3 and 4). The result of displacement of numerical analysis with *Uxy* compared well with experimental work in dense sand at higher levels. The displacement in *Ux* is lower than *Uxy* and measured data which is presented in Table 4.



(a) (b)

Figure 13 Comparison with *Ux*, *Uxy* and Measured displacement of (a) loose (b) dense models at 60 *cm*.

The comparisons show that *Uxy* model can capture the behavior of both loose and dense dry sand in laminar shear box. Comparison of the results of 1D and 2D analyses with measured data indicates that 2D analyses shows better agreement with experimental tests.

Table 2 Comparison of measured and estimated acceleration amplitudes with different methods at three points

Acceleration %	20 cm				40 cm				60cm			
	EERA	NERA	Ux	Uxy	EERA	NERA	Ux	Uxy	EERA	NERA	Ux	Uxy
Dense Sand	64	60	52	32	38	60	40	20	0	90	31	19
Loose Sand	20	73	47	27	35	59	38	18	50	65	33	15

Table 3 Comparison of measured and estimated displacement amplitudes with different methods at three points

Displacement %	20 cm				40 cm				60cm			
	EERA	NERA	Ux	Uxy	EERA	NERA	Ux	Uxy	EERA	NERA	Ux	Uxy
Dense Sand	47	-	47	-7	47	-	38	19	43	-	20	5
Loose Sand	54	4	46	32	82	14	43	18	82	40	33	15

Table 4 Approximate plastic displacement at the end of excitation at three points

Plastic displacement (cm)	20 cm				40 cm				60 cm			
	measured	NERA	Ux	Uxy	measured	NERA	Ux	Uxy	measured	NERA	Ux	Uxy
Dense Sand	-0.03	-	-0.032	-0.03	-0.035	-	-0.02	-0.036	-0.03	-	-0.03	-0.06
Loose Sand	0	0	0	0	0.006	-0.002	0.001	0.002	0.003	-0.014	0.0017	0.0017

4. CONCLUTION

Experimental results obtained from dynamic tests with laminar shear box on Babolsar dry sand models are compared with numerical simulation results for accelerations and displacements. The numerical analyses performed by 1D and 2D softwares for model scales. Responses of two types of dense and loose models indicate that acceleration of the soil were amplified by laminar shear box and the amount of acceleration at higher elevation is more than base acceleration, which is the same in all numerical analyses.
1D numerical analyses show lower acceleration and displacement in comparing with measured data in model scale. One of the main reasons for differences could be using average curve of Seed and Idriss (1970) curves as material parameters instead of real parameter of the sand at very low confining pressure.
2D analyses show better agreement than 1D in model scale. Using different boundary conditions at side bounds indicates that constraining the side boundary nodes at same elevation in *x* and *y* direction can capture the behavior of dry sand in shaking table better. Generally it can be concluded that it is possible to simulate the laminar shear box correctly when the friction between the layers is neglected.

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