Experimental Analysis of the Dynamic Response of Saturated Clayey Soil Under Impact Loading

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Abstract-The impact of loads on machine foundations is a typical cause of vibrations in industrial applications. Typically, these foundations will transfer vertical dynamic loads to the surface, which will result in earth vibrations that may cause structural damage to nearby structures. Dynamic impacts can vary from significant failure of sensitive sensors or systems to evident structural damage. The current work investigates the behavior of saturated clay soil under a single impulsive load. Deflectometry via falling weights was conducted to produce single pulse energy by dropping different weights from various elevations. The reactions of soils at various places were investigated (vertical displacement at topsoil surface). Such reactions consist of displacements, velocities, and accelerations caused by the impact occurring at the surface depth. The maximum displacement reaction of stiff soil was reduced by 80% in comparison with soft soil under the same impact load. The average percentage of change for stiff soil was 49% larger than for soft soil, as a result of kinetic energy caused by an increased contact surface. Maximum displacements increased with increasing operational frequency and dynamic load.

Keywords-impact load; saturated clay; circular footings; displacement; surface level

I. INTRODUCTION

Foundations are regarded as the backbone of buildings. For their construction, we must have prior knowledge of the soil characteristics, such as shear strength and water absorption [1]. Saturated soils are subjected to a variety of dynamic/cyclic loading types, including high-strain (earthquake and blast) and low-strain loading (machine vibrations, traffic loading, and wave loading). Under these conditions, particle structure breakdown causes instability in the soil mass, which severely damages structures [2]. Dynamic soil properties determine the soil response to impact loads. The response of dynamic loading is evaluated in order to estimate the active soil properties. Dynamic studies consider stiffness, damping ratio, and unit weight [3]. Many studies have been conducted with regard to the surface depth and loading frequency effects upon shallow foundations in stiff and soft clay soil. Impact loads and excess pore water pressure are evaluated at the soil surface under the foundation. Maximum displacement increases with increasing operational frequency and the excess pore water pressure increases with increased dynamic load. The dynamic properties of the soil layers affect the site seismic response. This response impacts the performance of inserted or overlying structures. Identification and inverse problem-solving techniques are essential to value in situ soil factors and calibrating simulations of soil system dynamic forces. The increasing availability of high-quality laboratory and field data aided the rise in soil investigation system identification studies [4].

Hammers, presses, and turbines are supported by foundations that experience significant dynamic and vibratory effects [5]. The dynamical behavior of the soil-foundation systems is the most significant factor in ensuring the successful operation of a machine. The basic purpose of the design of a machine's foundation is to limit its motion to amplitudes that neither risk the machine's functioning, nor disturb nearby employees. Consequently, a vital element of a solid design of foundations, the plan is the engineering analysis of the footings' reaction to the anticipated dynamical force caused by the use of the machinery. Additionally, when significant movements of an existing footing restrict the operation of the supported machinery, an inquiry must be conducted to identify the fundamental causes of the problem. Therefore, in the investigation, Soil-Structure Interaction (SSI) phenomena that are exposed to impact load are studied [6]. Firstly, the dynamic SSI subject to impact forces is tested using vibrating tables. SSI impacts were then explored by contrasting the soil-structure system with a solid footing condition. After that, a mathematical analysis that passes the SSI tests is given. The nonlinear behavior of soil in the finite element simulation is modeled independently using a boundary surface deformation method and a related linear approach. The estimation results from the boundary surface plasticity model turn out to be more accurate than the experiments. Lastly, geometrical analysis is used to study the effects of different soils and structural features on SSI. The analysis shows that SSI greatly decreases the dynamical responsiveness of buildings, and this effect increases with the frequency of the superstructure relatively to the velocity of the soil. The impact of the contact between soil and structures is reduced by increased soil shear wave velocity.

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This is crucial of the way SSI affects the response of structures and also for uses in the design process [7]. The coupling of the reactions of their different elements makes the mechanics of saturated clay more complex than that of single-phase materials. For saturated clay, when the permeability is low and transient loading is rapid, because the soil pores are filled with water, the permeability is low and transient loading is rapid. This relationship should be considered for an appropriate assessment of the behavior of earth constructions and foundations [8]. When the applied loads to the structure increase and exceed the cracking load, the damaged supporter of individual groups exhibits a relatively high rate of stiffness drop [9, 10] as a result of a portion of the pre-stressing force, which increases the rate of cracking and displacements. Many researchers have looked into the way machinery moves. Authors in [11-15] looked into the way vertical vibrations affect surface footings.

II. EXPERIMENTAL MODELS AND WITH MATERIALS

A. Soil Used and Material Properties

Brown clayey soil was taken from a depth of 1.0m from the soil subsurface of a brick factories site in the Al-Nahrawan city, 54km east of Baghdad. The tests were conducted following the standards for identifying the physical and chemical properties of the soil. The specifics of these requirements are detailed in Table I. A consolidation test was conducted for both stiff and soft clay according to [16]. The consolidation test results for both types of clay are shown in Table II. The experimental program consists of a series of 16 tests done on stiff and soft clay soil with dynamic loading of varied sources of energy, evaluated at the soil's surface (0B), with 2 different foundation sizes, where B is the diameter of the foundation. Systematic tests were carried out to test the dynamic reaction of foundations when subjected to an impactor. Figure 1 displays the equipment adopted for testing. It consisted of a steel container having a wall made of 2.0mm -thick plating and a basis as a soil container, as well as a falling weight deflectometer to apply impact loads to a modeling technique with a ground baseplate that remains measured as a surface footing on the topsoil under impactor. The dimensions of the steel container were 1200.0mm length, 1200.0mm width, and 800.0mm height. Trial tests were carried out to assess the efficiency of the preparation method, before the preparation of the soil. A relation between the water content and the soil's undrained shear strength can be seen found in Figure 3. The soil layers in the steel container were prepared as follows:

- The soil was left to dry in the air. Then, it was crashed into small pieces with a hammer and crushed with a machine.
- The dry soil was separated into two groups, 25kg each.
- Every grouping for each soil model was combined in mixing with enough water to provide an undrained shear strength (Cu) of 20-25kPa for the soft clay state and 73kPa for the stiff clay state. The value of moisture content was selected from Figure 4.
- Clay was mixed with water and added to steel containers in stages. Every level was then pressed down using special wooden compacting hammers that were 150mm×150mm in size. Every layer's outcome was around 50mm. The process was carried out until the clay bed's full depth.
- After the end of the clay layers' preparations, it was blanketed using nylon sheeting and then left for a curing time of 4 days.
- Using a portable vane shear apparatus, the undrained shear strength was determined every day to reach the nearest value of shear strength as seen in Figure 2.

TABLE I. SOIL PHYSICAL AND CHEMICAL PROPERTIES

Property	Value	Standard of the test
Specific gravity Gs	2.71	ASTM D854
Gravel (> 4.75mm) %	0	ASTM D422
Sand (4.75 - 0.075mm) %	3	
Silt (0.075- 0.005mm) %	40	
Clay (< 0.005mm) %	57	
Liquid Limit (LL)	39	ASTM D4318
Plastic Limit (PL)	22	
Plasticity index	17	
Gypsum content ($CaSO_4$ $2H_2O$) %	0.23	BS 1377-3
Total Dissolved Salts (TDS) %	0.39	ASTM D5907
SO_3 content %	0.19	BS 1377-3
Organic Matter (OM) %	0.2	ASTM D2974
Ph value	9.18	ASTM D4972
Classification according to USCS	CL	ASTM D2487

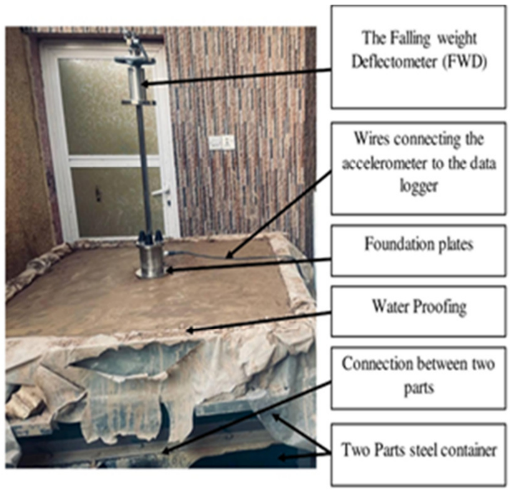

Fig. 1. The experimental soil model's setup.

Fig. 2. Portable vane shear device used to control the undrained shear strength.

TABLE II. CONSOLIDATION TEST RESULTS FOR STIFF AND SOFT CLAY

Parameter	Stiff state	Soft state
Cu (kN/m^2)	73	20-25
e o	0.58	0.73
γ dry	19.12	16.45
γ sat	21.4	19.4

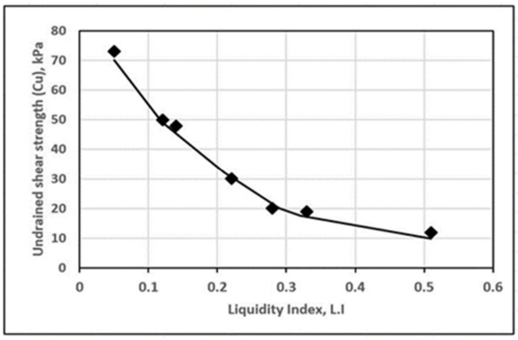

Fig. 3. Relations between shear strength and liquidity index.

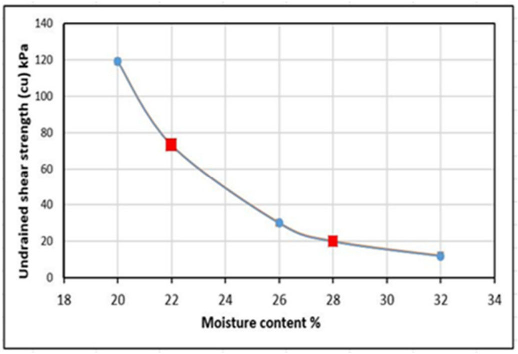

Fig. 4. Undrained shear strength versus moisture content.

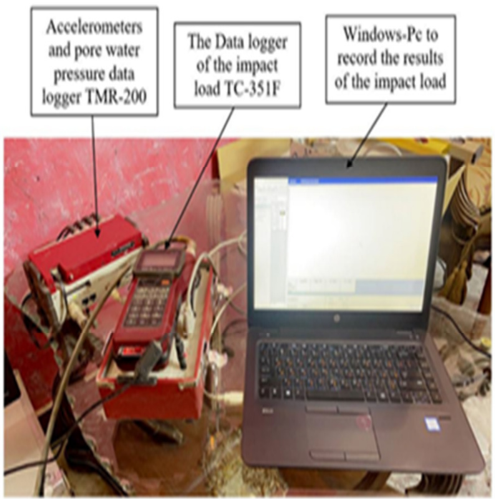

Fig. 5. Data acquisition system.

B. Measuring Instruments

The bearing plates were positioned directly at the soil surface and dropping masses used to apply the soil model in the vertical impact dynamic loading had different weights (5.0 or 10.0kg) and heights to simulate different impact values (500.0 or 250.0mm). Foundation contact plates were used in 2 sizes: 100.0 and 150.0mm, to determine the topsoil response to an impactor. Then, two pore water pressure gauges were inserted in the middle of the clay level in the vertical position beneath the centroid of the bearing plates at a depth of B or 2B, depending on the size of the bearing plates. Data collection was organized in such a way that all information could be analyzed and captured continuously. The transmitted impulse response record, displacement-time history, and soil surface depths could all be measured with this technique. The acceleration-time history was computed using an accelerometer transducer and surface levels for each test. The basic design of the FWD mechanism consisted of a base structure with an integrated accelerometer and an indicator unit. The card reader could collect and retain a variety of different calculations. The indicator shows the peak load value and the displacement value. Its storage card's data can be directly transmitted to a computer or through the indicator. The program includes a load cell and an accelerometer to assess the impact load and displacement after dropping the small FWD major body's weight in free fall. By integrating the measurements twice in the accelerometer, the displacement is calculated. For a measuring system that employs a laptop, measurement/processing software is necessary. In this system, the data transmitted to the indicators were sent, directly from the indicators, to the laptop, to recognize the acceleration in the clay.

C. Testing Procedure

The following stages outline the testing process:

- Prepare the clay layers for stiff and soft states with a total depth of 800.0mm (100.0mm per level).
- Embed the accelerometer sensor in the middle of the clay layer in the vertical position underneath the bearings plate's center at depths of B or 2B depending on the bearing size.
- Place the sensors horizontally at a depth of 10.0mm, close to the surface.
- Mount the FWD in the middle of the model's ground and confirm its perpendicularity to the model's area after laying the ground.
- The reaction to delivering the impacting mass will be monitored and displayed on a laptop by the data acquisition system shown in Figure 5.

III. RESULTS AND DISCUSSION

Regarding the behavior of saturated clayey soils, it is important to specify that trials were conducted on stiff and soft clay states. A variety of load factors were used in impact testing on the plates ranging between 100.0mm and 150.0mm, depending on the bearing plate's size. They were positioned on the topsoil surface level (0B). A weight of 5.0 or 10.0kg was dropped out of a height of 500.0 or 250.0mm to generate the impact force. Figures 6 to 13 display the dynamic testing results. The data are represented in the (a), (b), (c), and (d) subfigures from every Figure with each reaction, accordingly, including load history, displacement, acceleration, and velocity functions of time. All these reactions were immediately measured beneath the plates. The variations in vertical displacement (below the plates) are shown in the subfigure (c) of every Figure.

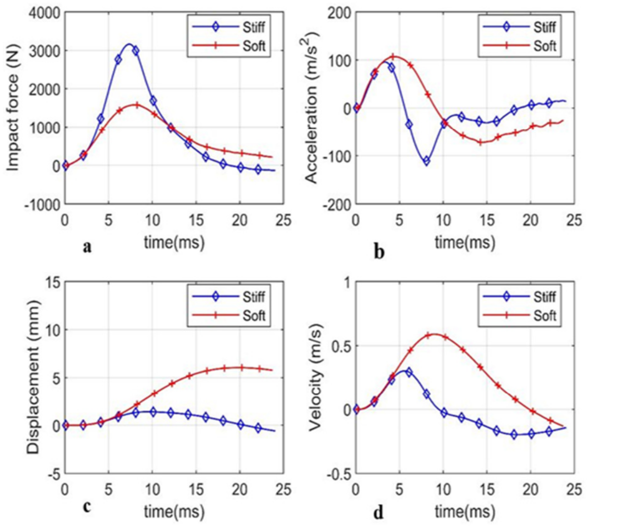

Fig. 6. Dynamic test results for the SOsP10M5H25 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

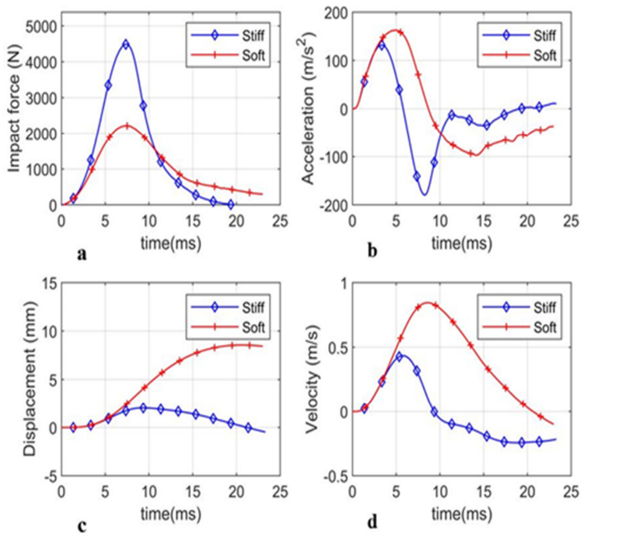

Fig. 7. Dynamic test results for the SOsP10M5H50 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

A. *Impact and Displacement Responses*

The reaction relates to the displacements of the soil surface layer beneath vertically impact energy (measured under the center of the impact plate at 0B depth only). Such reactions were represented in the lower segment of the portion (c) of Figures 6 to 13. There are typical characteristics related to impacts, and they include:

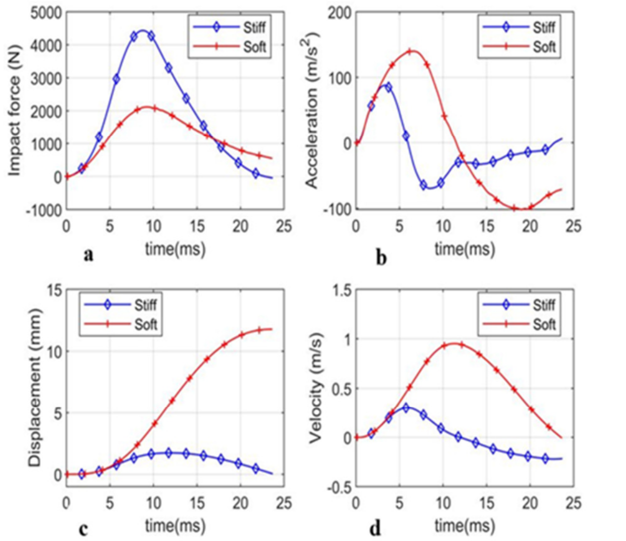

Fig. 8. Dynamic test results for the SOsP10M10H25 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

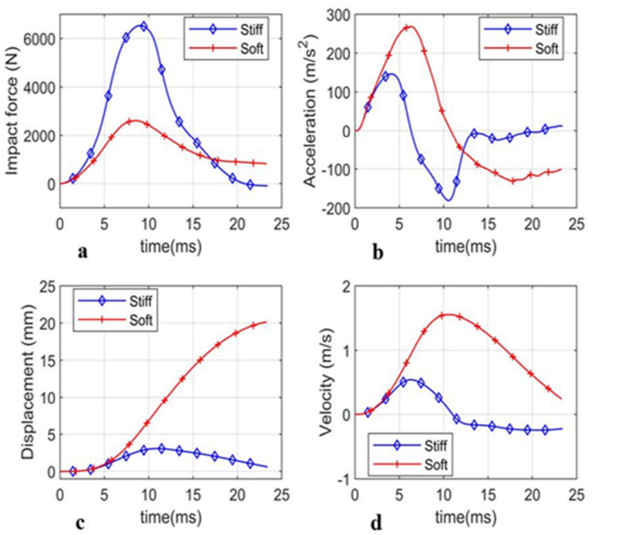

Fig. 9. Dynamic test results for the SOsP10M10H50 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

- Maximum impact loads and maximum displacement for stiff clay state occur when the impact plate is located at the topsoil surface of the foundation area (100.0mm) and 10.0kg impactor plate for an elevation of 500.0mm, as is clearly shown in Figure 9.
- Maximum impact loads and maximum displacement for the soft clay state do not occur as for the stiff state to the same soil model.
- The acceleration-time history with velocity-time history are represented in subfigures (a) and (c) of each Figure respectively. The impulsive waves (force-time histories) were discovered to consist of a single half-sine wave pulse. Sometimes in instances, there was no pulse's negative

phase, whereas in a minority of cases, a minor negative phase was observed. This tendency indicates that a stiff clayey stratum acts as a perfect continuous solid, regardless of its density. Because there is a significantly reduced void ratio, impulsive waves are more probable to reflect and refract, which produces the perfect solid-impact behavior.

- The vertical displacements of the foundation block caused by the first hammer blows were computed using the fatigue damage model proposed in this research, and were compared with the analytical results [17]. It can be shown that the simulation findings for vertical displacement are in good agreement with the analytical results.

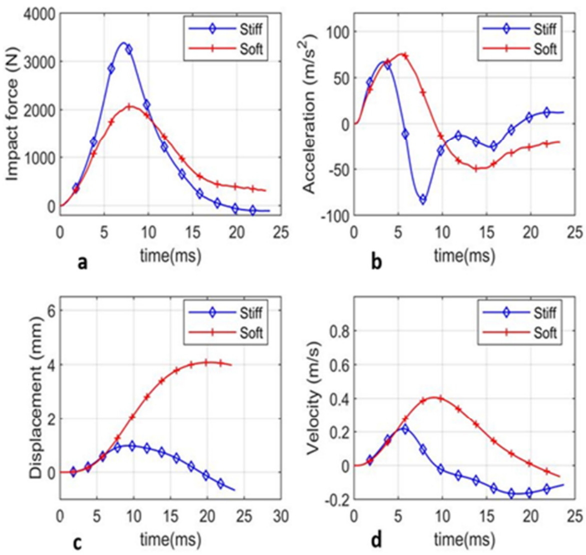

Fig. 10. Dynamic test results for the SOsP15M5H25 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

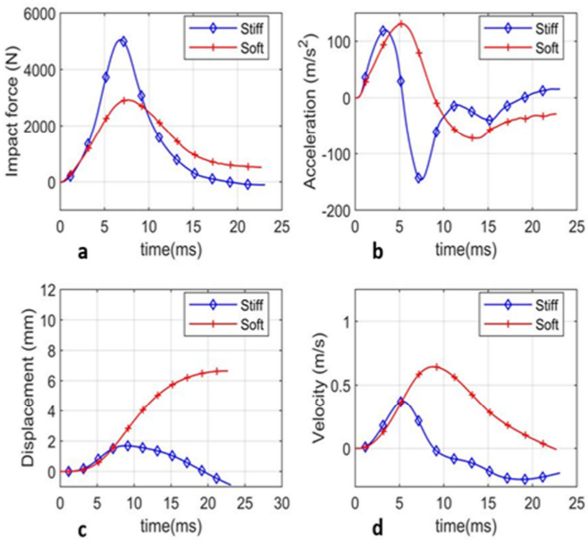

Fig. 11. Dynamic test results for the SOsP15M5H50 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

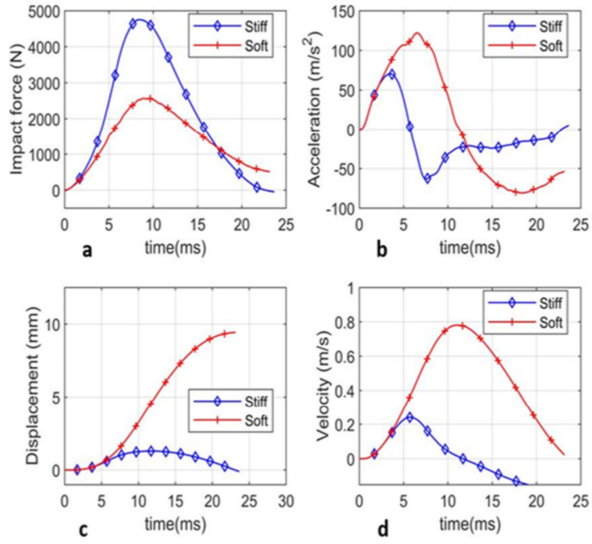

Fig. 12. Dynamic test results for the SOsP15M10H25 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

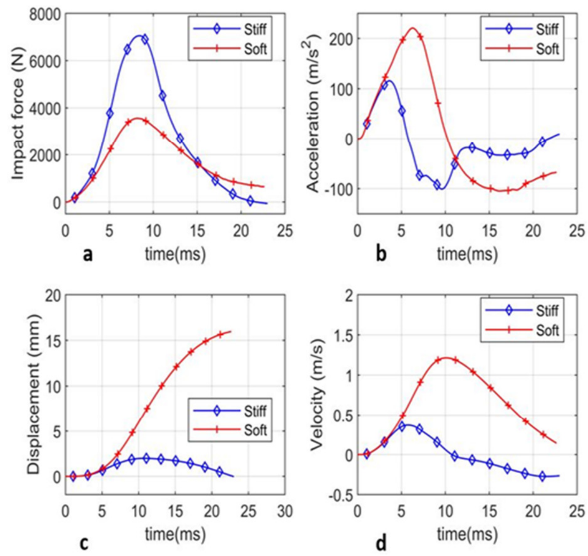

Fig. 13. Dynamic test results for the SOsP15M10H50 model. (a), (c) impact force-time history with displacements, (b) acceleration time-history, and (d) velocity time-history.

Two piezometers were put under experimental bearing plates to monitor the pore water pressure during the impacts. Figures 14 - 21 represent the excess pore water pressure-time histories recorded by pore water pressure sensors positioned at levels B and 2B underneath the bearing plate's center. The soil-foundations system displays the following behavior:

- For the stiff clay state, based on decreasing the water content, it was determined that the resultant impulse waves have a higher peak than the related soft clay in all observed instances.
- The peak displacement reactions inside the soft clay soil were always higher than those in the stiff clay soil. The rise

in reactions was seen to be higher when the falling hammer's kinetic energy increased (mass and level of fall), when either the mass of the hammer or the elevation of the fall was doubled (from 5.0 to 10.0kg or from 250.0mm to 500.0mm).

- The vertical displacements in soft soil are approximately 78% greater than in the stiff soil at the depth of 0B from the topsoil surface.
- The excess pore water pressure inside the topsoil is shown as a result of three important parameters: impact energy (hammer weight and elevation of drop), size of foundations exposed to the impactor, and soil type. For soft clay soils with constant impact energy, increasing the impact area causes the excess pore water pressure to decrease. In that instance, a 125.0% increase in the plate area (from 100.0 to 150.0mm in diameter) causes a 30–40% drop in the pore water pressure.
- This approach makes sense, given that the excess pore water pressure of stiff clay in comparison to soft clay was decreased by almost 100.0 %, as a result of the decrease in the water content ratio and the increase in the density of clay particles. Conversely, in the case of soft soils.

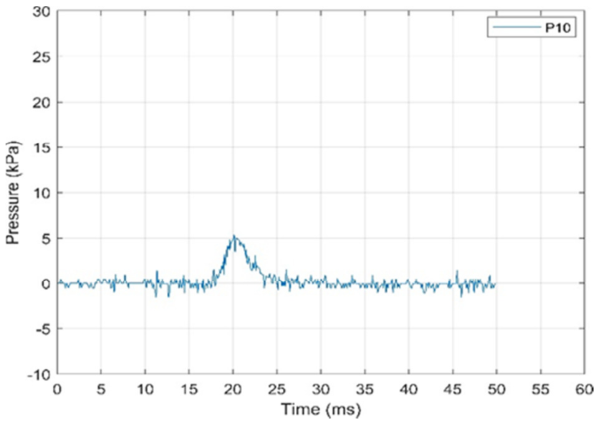

Fig. 14. Pressure-time history of excess pore water at depth B for the SOsP10M5H25 model.

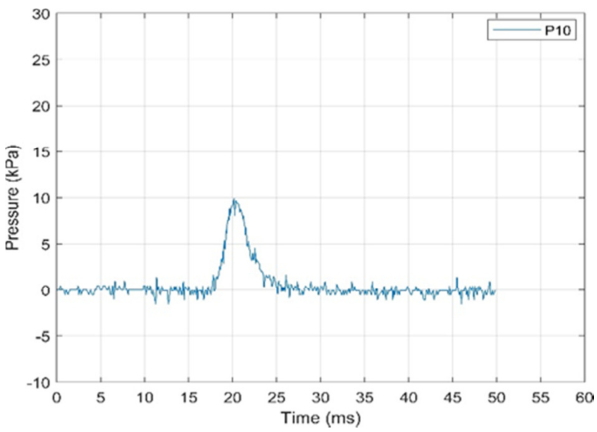

Fig. 15. Pressure-time history of excess pore water at depth B for the SOsP10M5H25 model.

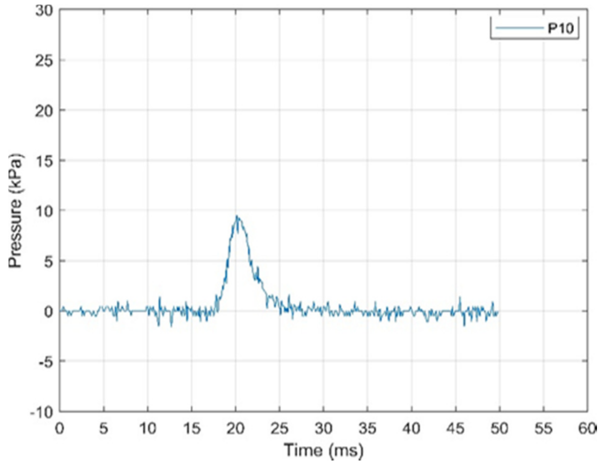

Fig. 16. Pressure-time history of excess pore water at depth B for the SOsP10M10H25 model.

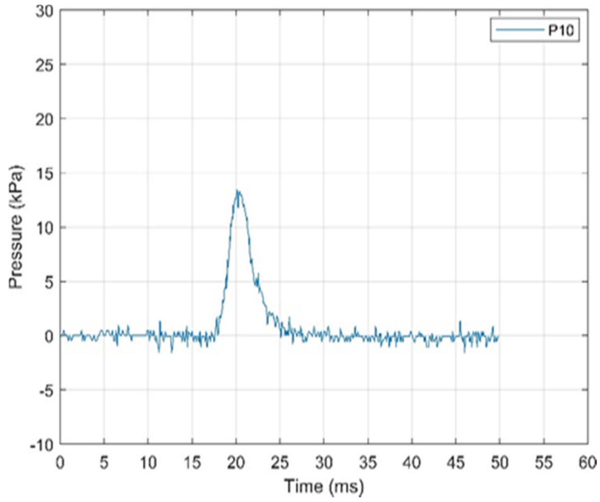

Fig. 17. Pressure-time history of excess pore water at depth B for the SOsP10M10H50 model.

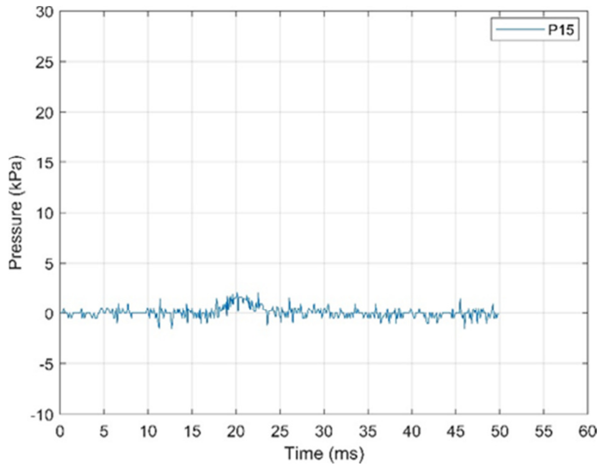

Fig. 18. Pressure-time history of excess pore water at depth B for the SOsP15M5H25 model.

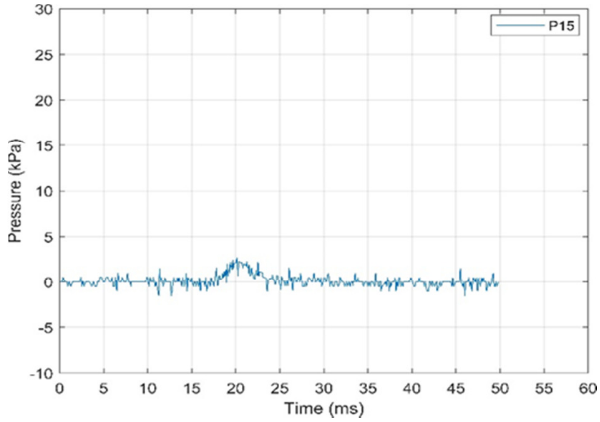

Fig. 19. Pressure-time history of excess pore water at depth B for the SOsP15M5H50 model.

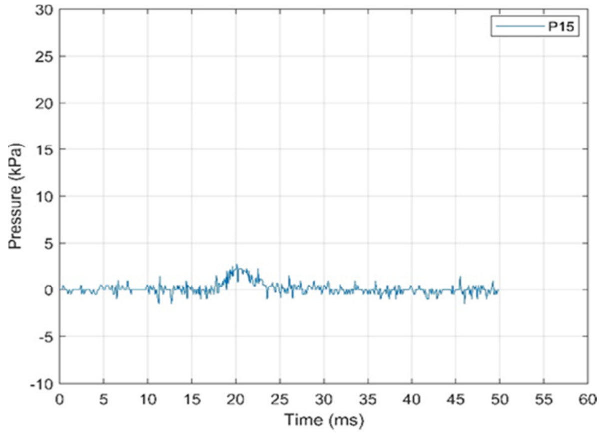

Fig. 20. Pressure-time history of excess pore water at depth B for the SOsP15M10H25 model.

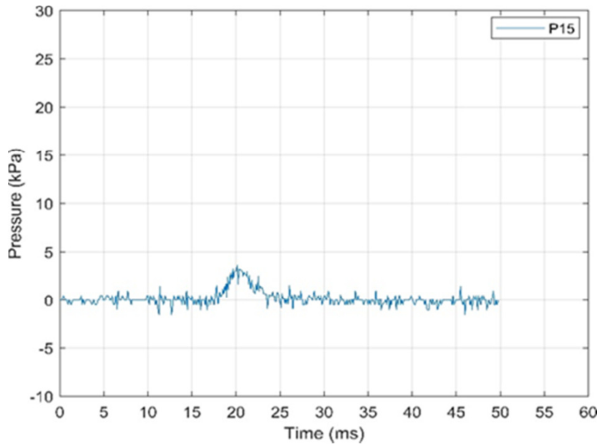

Fig. 21. Pressure-time history of excess pore water at depth B for the SOsP15M10H50 model.

IV. CONCLUSIONS

The experimental results can be seen in Figures 6-21. The main conclusions from the results of the current study are:

- The average stiff to soft soil reduction percentage in maximum displacement reaction was 80% under the same impact load, because stiff soil has 49% stresses generated by a rising in the contact surface than soft soil.
- The excess pore water pressure of soft soil is increased in comparison to stiff soil. Due to the little water content in stiff soil, there was no measured effect of pore water pressures.
- Compared to stiff clay, the amplitude of the force-time history in soft clay is reduced by 40-57%. This reduction happens since the voids are filled with water, causing fewer contact points between particles.
- The frequency ratio (frequency of the impact/frequency of the vibration foundation-soil system) is an important factor in impact load-related concerns.
- The ideal amplitude of the force-time history for stiff soil under impact stress is a single pulse.
- Once the operation frequency increases, the amplitude of displacements on the foundations, total stress, and pore water pressure increased for soft clay circular foundations at the soil's surface.
- The maximum displacement increased with increasing operational frequency and dynamic load.
- The dynamic response increases rapidly with the degree of damage, which in turn affects the transmission of damage in the foundation and the soil due to the higher stresses concentrating near the foundation regions. From the computational analysis of the dynamic features of soil damage, it can be observed that as damage rises, the effects of hammer blows on the surface and depth of the soil near the foundation become more important. This enables the development of a method for managing the damage and its progression in a damaged material, as well as the dynamic response of a damaged structure.

Following these conclusions, it is advised that pile foundations in saturated clay soils can be used in future works with the same standard specifications.

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