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PREDICTION OF IMPACT FORCE-TIME HISTORY IN SANDY SOILS

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Abstract: A dynamic problem that is represented by impact acting on a soil medium (short-period dynamic load) is rather different from the case of impact acting on a structure such as a beam or a pile. In the case of a pile, the resulting impulsive wave as per Clough and Penzien (2003) shows a standard amplitude, shape, frequency, and duration. Therefore, the impulsive load wave is almost of an ideal shape. However, in the case of an impact load acting on a soil medium neither the shape nor the amplitude can be evaluated by any existing methodology. An experimental study on the behaviour of dry dense, medium, and loose sandy soils subjected to a single impulsive load is carried out. Sand models were tested under different impulsive energies caused by different falling masses from different heights. Tests were conducted using the falling weight deflectometer to provide the single pulse energy. The behaviour of sandy soils was evaluating using different parameters, these are; footing embedment depth, diameter of the impact footing, density of the sand medium and the applied energy. It was found that the amplitude of the resulting force-time history is a function of the degree of confinement on the footing, the embedment depth, footing area, density of soil in addition to the energy of impact (falling mass and height of fall). The shape of the impulsive wave was found to be, therefore, of mostly a single pulse; with or without a negative phase. Moreover, it could be of an ideal half sine wave or a part of half sine wave with a nonzero residual inelastic force (represented by the falling weight).

1 Introduction

Dynamic load on a soil can be developed due to different sources such as earthquake ground motion; blast; machine vibration; and traffic movement. Machine foundations with impact loads are common powerful sources of industrial vibrations. These foundations are generally transferring vertical dynamic loads to the soil and generate ground vibrations which may harmfully affect surrounding structures or buildings. The impact of a hammer on a foundation produces a transient loading condition in the soil, as shown in Figure 1. The load typically increases with time up to maximum value at $t = t_1$ and drops to zero after that. Such a load-time history is only an assumption needed to be verified.

The main objective of this research is to predict soil behaviour under impact loads. Conducting an experimental investigation on sandy soils was established to study the behaviour of these soils under the effect of impact loads with different applied kinetic energies. Several factors taken into account include; embedment depth and diameter of the foundation, soil density and energy of the impact load.

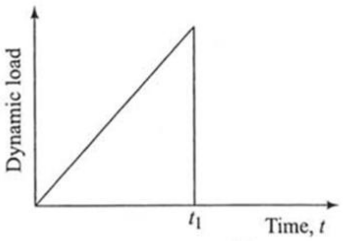


Figure 1: Typical loading diagrams: (transient loading due to single impact of a hammer) (Das and Ramana, 2011).

2 Experimental Work

A small scale model is implemented to simulate a physical model of a foundation resting on a dry soil media under impact loads. The tests were performed in dense, medium, and loose sands under impact load caused by different falling masses (5kg or 10kg from height of fall 250 mm or 500 mm). Two footing sizes were adopted (100mm and 150 mm diameters). Tests were performed at the surface of the soil and at depths of 0, 0.5B, B, and 2B (where B is the diameter of the footing).

3 Description of the soil model

Figure 2 shows the setup that was used to carry out tests. It consists of a steel box with walls made of 2 mm thick plates and a base as a soil container which is supported by a rigid reinforced concrete raft, and the falling weight deflectometer (FWD) to apply impact loads to the soil model with a base bearing plate of two sizes which represents a shallow foundation in the soil. The steel box consists of two parts having; a length of 1200 mm, width of 1200 mm and a total combined height of 800 mm. Each part of the steel box has a height of 400 mm whose walls are strengthened at the outside by 2 hoops of 40X40X2 mm steel angles.

The "raining technique and tamping" was used to deposit the soil in the testing tank while making the sand achieve a known uniform density. The device consists of a steel hopper, with dimensions of 1200 mm in length, 300 mm in width and 450 mm in height. It ends with an inclined funnel mounted above the testing tank and used as a hopper to pour the testing material from different heights through two rollers. In order to facilitate the horizontal movement of the steel hopper, a simple sliding system was used.

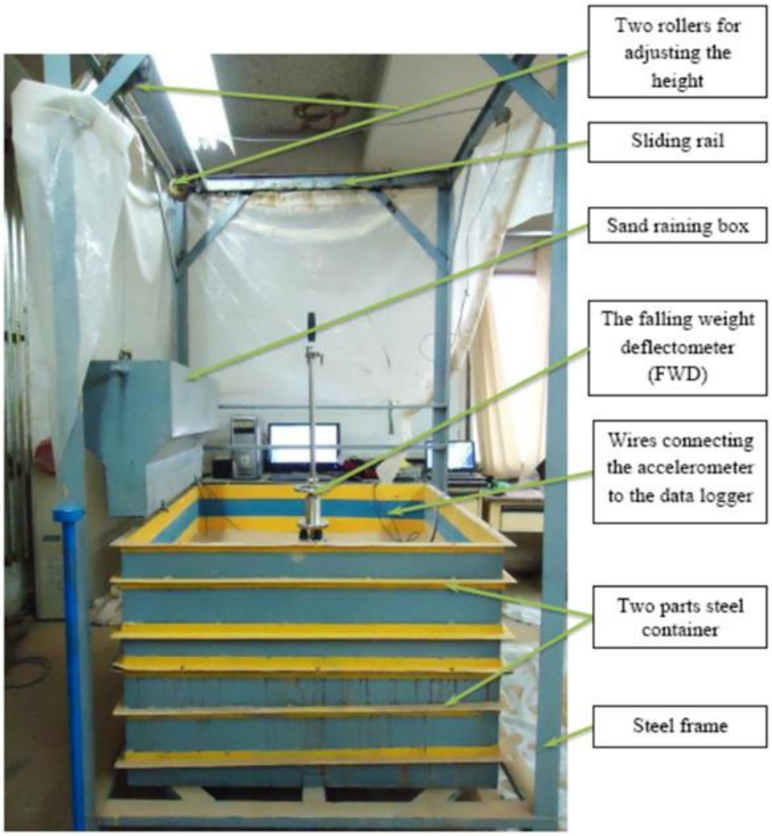


Figure 2: The setup of the soil model

4 The Soil Medium

The soil used for the test models is pure Iraqi sand, passing through sieve No. 10 (2 mm) and retaining on sieve No. 100 (0.15 mm). Physical properties of the sand are presented in Table 1. Figure 3 shows the grain size distribution of the test sand.

Table 1: Physical properties of the sand used.

Property	Value	Unit	Standard of the test
Specific Gravity, Gs	2.65	----	ASTM D 854
Coefficient of gradation, C_c	0.79	----	ASTM D 422 and ASTM D 2487
Coefficient of uniformity, C_u	2.94	----	
USCS-soil type	SP	----	
Maximum dry unit weight, γ_{dmax}	17.8	kN/m^3	ASTM D 2049-69
Minimum dry unit weight, γ_{dmin}	14.9	kN/m^3	ASTM D4254-00
Maximum void ratio (e_{max})	0.7447	----	---------
Minimum void ratio (e_{min})	0.4605	----	---------

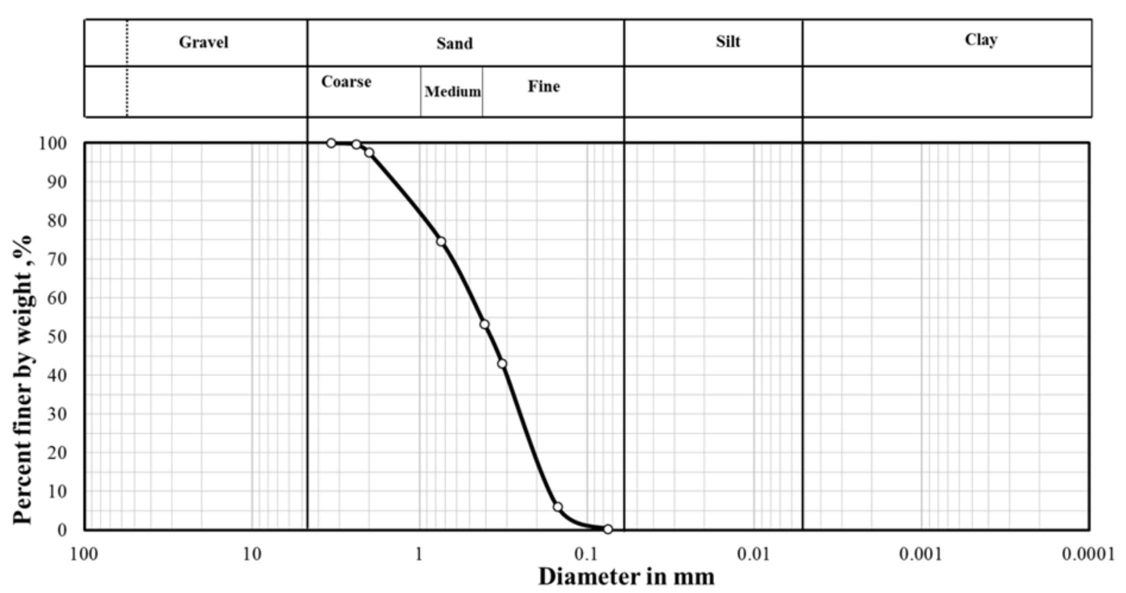


Figure 3: Grain size distribution of the sand.

5 Preparation of Sand Samples

The tamping and raining technique was used to prepare the sand in the test tank resulting in properties as given in Table 2. In order to achieve a uniform layer with a desired density, the raining technique was used to prepare the sandy soil model. This process was implemented using a pre-manufactured steel hopper and steel tank (manufactured by Al-Saffar, 2015) through repeated horizontal movement of the hopper which was controlled manually. Height of drop and rate of discharge of the sand mainly affect density of the sand layer in the raining method (Turner and Kulhawy, 1987).

Table 2: Physical properties of the sand used in the tests.

Property	Value	Unit
Dense state relative density, Dr, %	82.0	----
Medium state relative density, Dr, %	55.0	----
Loose state relative density, Dr, %	30.0	----
Dry unit weight in dense state	17.2	kN/m^3
Dry unit weight in medium state	16.37	kN/m^3
Dry unit weight in loose state	15.66	kN/m^3
Saturated unit weight in dense state	20.52	kN/m^3
Void ratio at dense state	0.5114	----
Void ratio at medium state	0.5881	----
Void ratio at loose state	0.6601	----

Three densities were to be tested; loose, medium and dense. The loose sand has a relative density of 30%, and is based on a height of the free fall of 200 mm. The soil medium was prepared in (6) layers each is of 100 mm thick, thus, resulting in a total thickness of (600 mm) measured from the bottom of container. The same procedure was followed for preparing a medium sandy soil having a relative density of 55% depending on the suitable height of free fall of sand as shown in Figure 4a. Preparation of dense sand was performed by using a 15 kg hammer tamping four times at the surface of each layer as shown in Figure 4b. The thickness of each layer was 5 cm to prepare dense sand with a relative density of 80%.

(a) (b)

Figure 4: Preparation of sand layer. a) Sand raining technique b) Preparation of dense sand using tamping.

6 Impact Test Procedure

The falling weight deflectometer (FWD) was used to apply impact loads on the soil model. The small FWD system with the standard set with optional Measurement/ Analysis Software TC-7100, additional weight (10 kg), and loading plate of 150 mm diameter were used. This equipment is capable of measuring the applied impact force-time history, displacement –time history at the soil surface.

The basic structure of the FWD system consists of the main unit with built-in accelerometer (KFD-100A) and the indicator (TC-351F) as shown in Figure 5. The indicator system is capable of obtaining a reading eat 0.05 msec intervals. This system drops the weight of the small FWD main body by free fall and measures the impact load and displacement using the load cell and the accelerometer.

7 Testing Program

The testing program consists of 64 tests. A special designation was assigned to each soil sample under testing such as $DP_{10}M_5H_{25}$, that is, $AB_aC_bD_c$. A refers to sand density (dense D, medium M, and Loose L), B refers to plate diameter (a is 10 cm or 15 cm). C refers to the falling mass (b is 5 kg or 10 kg) while D refers to height of fall (c is 25 cm or 50 cm).

8 Amplitude of the Impact Force

Results of impact force-time history are plotted and shown in Figure 6 for dense sands. Examining the figures reveals that:

a) The impact force-time curves are almost harmonic in nature, but of a single pulse, with or without a negative phase (though it is of a very short duration as compared to the positive pulse duration). This negative phase might resemble the rebound of the soil-structure to the falling mass. The system in such a case is acting as an elastic body responding to the impact load as in the case of beam impact or pile impact (Clough and Penzien, 2003).

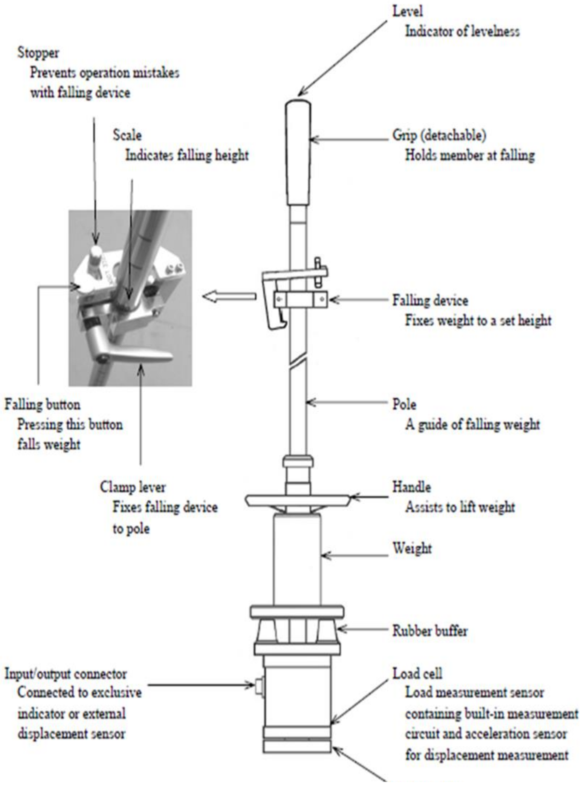


Figure 5: Small FWD main body KFD-100A.

b) When the plate diameter is relatively small (100 mm) and the falling mass is relatively low (having small height of fall), the system behaviour can be described as follows: if the plate is mounted at the top of the soil surface, the resulting pulse is of relatively smaller amplitude (the amplitude of the resulting pulse is relatively smaller) than all other cases of plate depth. For any other depth of the impact plate (0.5B, B, and 2B), the amplitudes and duration of the pulses are almost identical. This leads to an observation, that is, the active mass of the soil that is contributing to the response is less and no confining is encountered hence, the absorbed energy is expected to be of larger magnitude which results in lower values of the peak impact force amplitude.

If the plate diameter is relatively larger (150 mm), the falling mass is greater and the height of fall, at the same time, is also larger (500 mm), the foundation soil system responds similarly to the impact, thus, resulting in almost identical harmonic pulses. This means that the excited soil mass becomes larger enough to overcome the effect of confinement. This behaviour can be seen clearly when comparing the impulsive force-time history of two cases at the same time, that is, when the plate diameter is 150 mm. For the same falling mass and height of fall, it is observed that the impulse amplitudes are always larger than when the plate diameter is only 100 mm. This behaviour supports the justification of effects of the active mass reacting to the impact force. As an example, in case of $DP_{10}M_5H_{25}$ model, the maximum peak impact is about 2200 N but for $DP_{15}M_5H_{25}$ model, the peak is 2300 N, for $DP_{10}M_{10}H_{25}$ model, the maximum peak is almost 3600 N, while for $DP_{15}M_{10}H_{25}$ model, the peak is about 3700 N. The differences are small but they exist.

c) One common tendency can also be noticed, that is the amplitude of the impact pulse force increases with the increase of the energy of the hammer, i.e., the weight and height of fall.

d) The figures also highlight one more tendency, that is, the time for peak impulse to occur, is affected mainly by the magnitude of the falling mass rather than other factors, since it is noticed that the time for peak impulse in case of 10 kg falling mass is always more than that in case of 5 kg by about 12% in most cases. The height of fall has insignificant effect on the peak response time while the plate diameter has a minor effect on this time in case of low energy of the falling mass (250 mm).

Since the height of falling mass was found to have insignificant effects on the global behaviour of both impulse-time shape and the displacement (qualitatively not quantitatively), it was preferred to take into account the case of 500 mm height of fall only. Plots of the experiment results are presented in Figure 7 for medium and loose sands.

Examinations of these figures show the behaviour presented here after:

1. The impact load-time history is also of a single pulse but has no ideal sine shape. In case of medium sand, it almost vanishes or becomes of negligible value at the end of the impulse-time history when the impact plate is embedded at large depths while it ends at a magnitude equals or near to the magnitude of the weight of the falling hammer when the footing is placed at the top surface or embedded at a shallow depth.

2. When the impact load acts on a footing resting on loose sand, the impulse force-time history ends at values near to the weight of the falling hammer irrespective of other parameters (magnitude of the hammer weight or the footing diameter).

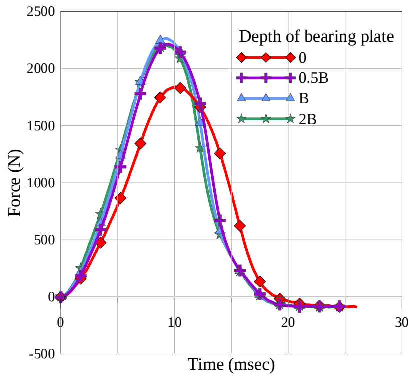
This tendency ensures the idea that, no reflection of the impulsive wave from the far boundaries is encountered (for both medium and loose sands), so that, the boundaries act as a free support (at the base) having no or negligible stiffness.

3. The amplitude of the impulsive wave was found to be:

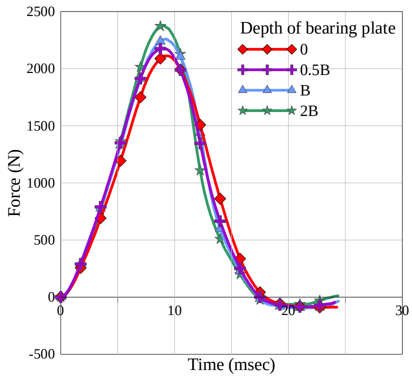
a. Decreasing as the density of supporting medium (soil) decreases. Lower amplitudes of the impulsive wave are found to be in models of loose soil for all cases of impact plate diameter, weight of the falling mass and height of fall of the hammer. In case of 100 mm diameter of impact plate, the reduction in impulse force amplitude from dense to loose sand ranges between 60%-70% (keeping other parameters unchanged) while in case of 150 mm impact plate, the reduction is about 45%-55%. This tendency is a common behaviour of impulsive force amplitude magnitude since the magnitude of impulse is stiffness dependent. Stiffer soils tend to act as solids with high rebound capability.

b. As the impact plate diameter increases, the magnitude of the impulsive amplitude increases also by about 30-40% in case of medium sand and by about 50-60% in case of loose soil. This tendency is attributed to the fact that the soil stiffness is related to two factors; degree of confinement which increases with the footing area and the magnitude of the excited mass which depends, also upon the footing area.

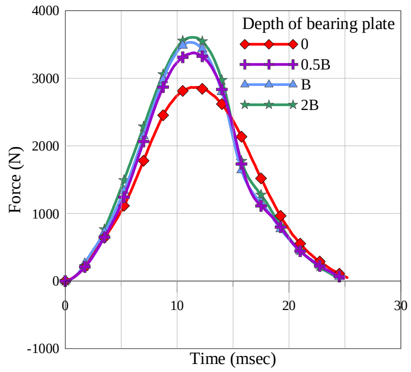
c. As the energy of impact increases (due to an increase in the weight of the falling hammer), the amplitude of the impact also increases. A 100% increase in the weight results in an increase in the impulse amplitude by about 55-80% in case of medium sand and by about 45-55% in case of loose sand. This tendency is related to the fact that the impulse amplitude is energy dependent. The energy, meanwhile, decreases as the density also decreases that is, looser soils contribute more in energy dissipation though the magnitude of dissipation is less than the increase associated with the mass of falling hammer.



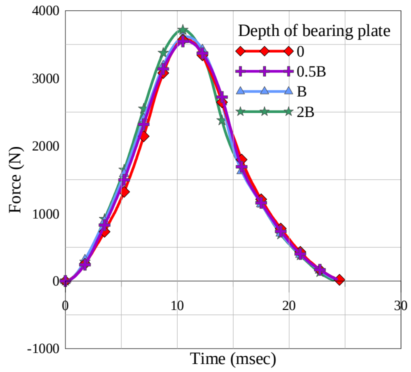
Test results for $DP_{10}M_{5}H_{25}$ model.



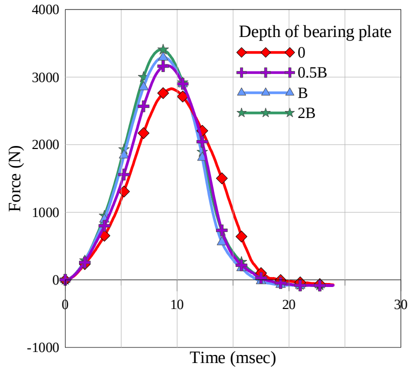
Test results for $DP_{15}M_{5}H_{25}$ model.



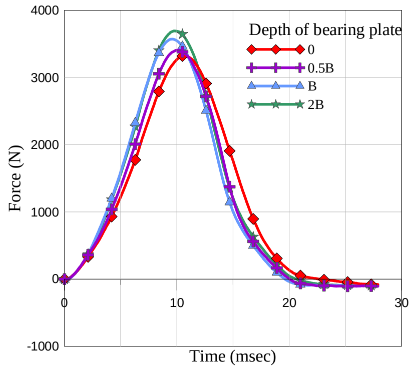
Test results for $DP_{10}M_{10}H_{25}$ model.



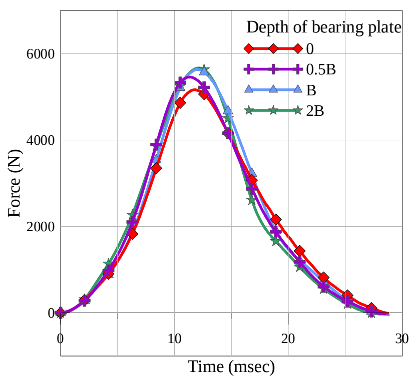
Test results for $DP_{15}M_{10}H_{25}$ model.



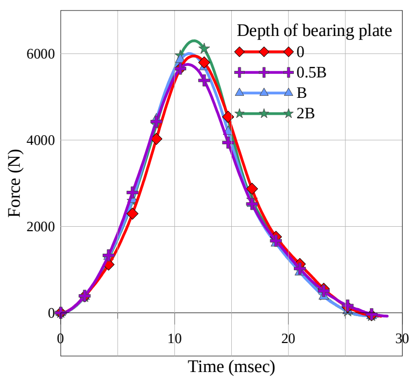
Test results for $DP_{10}M_{5}H_{50}$ model.



Test results for $DP_{15}M_{5}H_{50}$ model.

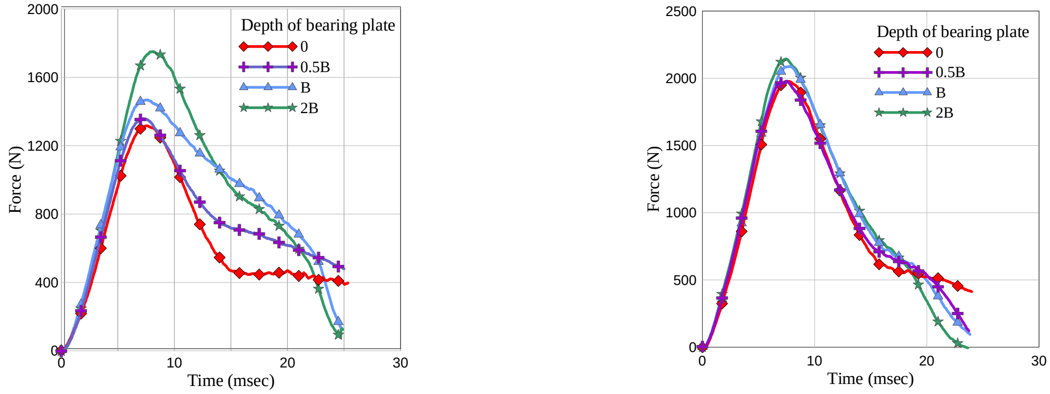


Test results for $DP_{10}M_{10}H_{50}$ model.



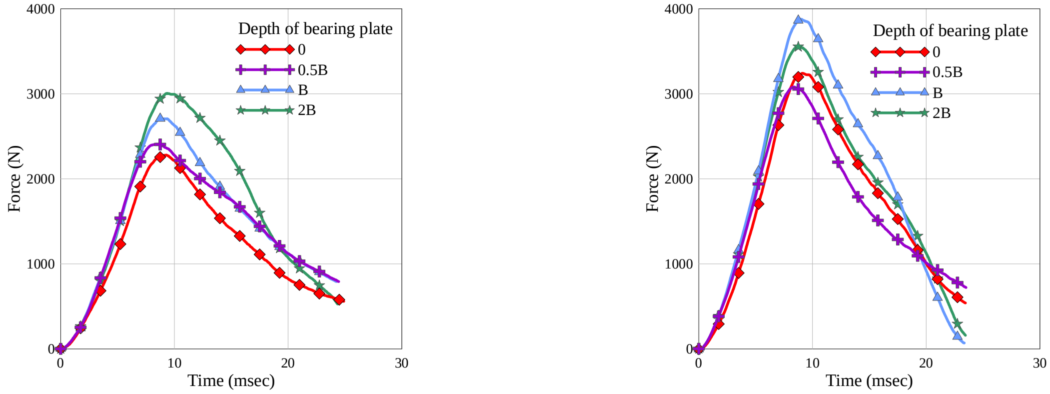
Test results for $DP_{15}M_{10}H_{50}$ model.

Figure 6: Force-time history for dense sandy soil.



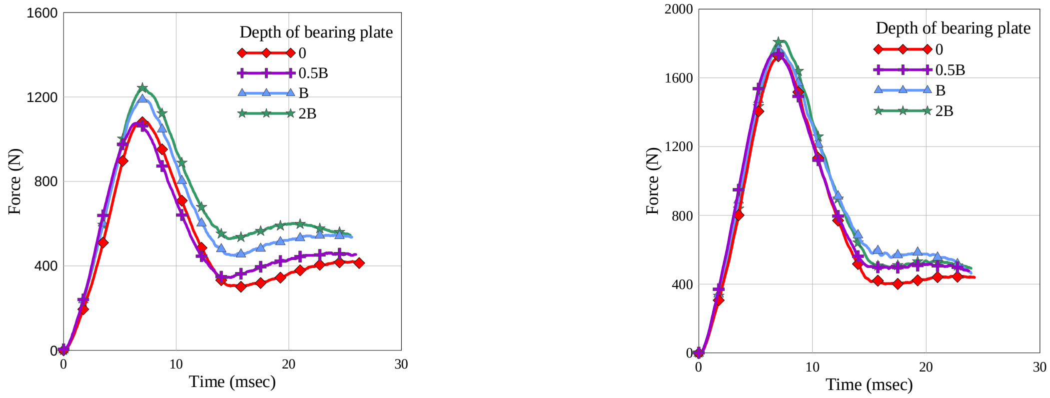
Test results for MP$_{10}$M$_{5}$H$_{50}$ model.

Test results for MP$_{15}$M$_{5}$H$_{50}$ model.



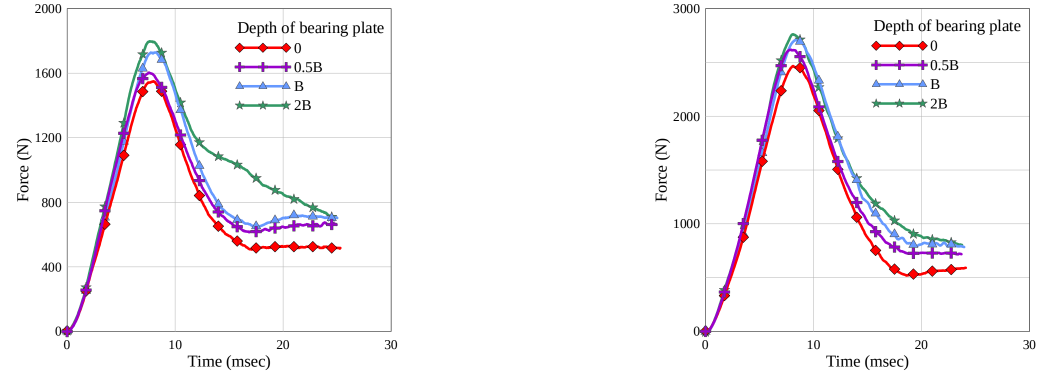
Test results for MP$_{10}$M$_{10}$H$_{50}$ model.

Test results for MP$_{15}$M$_{10}$H$_{50}$ model.



Test results for LP$_{10}$M$_{5}$H$_{50}$ model.

Test results for LP$_{15}$M$_{5}$H$_{50}$ model.



Test results for LP$_{10}$M$_{10}$H$_{50}$ model.

Test results for LP$_{15}$M$_{10}$H$_{50}$ model.

Figure 7: Force-time history for medium and loose sandy soil.

Conclusions

1. The amplitude of the force-time history in dense sandy soils under impact load is ideally harmonic of a single pulse, while in case of medium and loose sands, the impact load-time history is also of a single pulse but has no ideal sine shape. The impulse almost vanishes or becomes of a negligible value at the end of the impulse-time history in case of medium sandy soils while it ends at a magnitude equals or near to the weight of the falling hammer in case of loose sands.

2. Doubling footing embedment depth as compared to on-surface case results in an increase in amplitude of the force-time history by about 10-30% due to the increase in the degree of confinement as depth increases.

3. When the area of a bearing plate (footing) is increased by 125%, compared to the 100 mm diameter amplitude of the force-time history increases by about 50-60% for loose sand, 30-40% for medium sand, and 10-15% for dense sand. This tendency is attributed to the fact that the soil stiffness is related to two factors, degree of confinement which increases as the footing area does and the magnitude of the excited mass which depends, also upon the footing area.

4. Variation of sandy soil density leads to variations of the soil characteristics as follows:

a. When the falling weight of the hammer increases by about 100% (from 5 kg to 10 kg), the impulse amplitude increases by about 70-80% in case of dense sand, 55-80% in case of medium sand and by about 45-55% in case of loose sand. This tendency is related to the fact that the impulse amplitude is energy dependent. The energy, meanwhile, decreases as the density also decreases that is, looser soils contribute more in energy dissipation though the magnitude of dissipation is less than the increase associated with the mass of falling hammer.

b. In case of the 100 mm diameter impact plate, the reduction in impulse force amplitude when the sandy soil changes from dense to loose ranges between 60%-70%, while in case of the 150 mm impact plate, the reduction is about 45-55% since the magnitude of impulse is stiffness dependent. Stiffer soil tends to act as solids with high rebound capability.

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