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Numerical modelling of drop load tests

R. Colombero [a,*,1], S. Kontoe [a,2], S. Foti [b,3], D.M. Potts [a,4]

[a] Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[b] Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy

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ABSTRACT

Assessment of the attenuation of induced vibrations in the ground plays an important role in evaluating comfort and structural safety. Analytical and empirical wave attenuation relationships of increasing complexity and detail are presented in the paper, as well as a numerical model that accurately reproduces wave attenuation for a well-documented site, namely the one of the Tower of Pisa, Italy. A new source model is calibrated on near-field data and used as input for the dynamic coupled consolidation finite element analysis to achieve a satisfactory simulation. The accuracy of simpler analytical and empirical approaches is then comprehensively assessed through comparison with the validated numerical model and the field data obtained from geophones at various distances from the impact source.

1. Introduction

Ground vibrations caused by human activities may have an adverse effect on structural safety and comfort. Numerical analyses of induced vibration can play an important role in establishing the expected amplitude of ground vibrations for a variety of circumstances such as for example construction works, soil improvement by compaction, blasting, and industrial activities. In this paper, drop load tests are used to calibrate a numerical model and study the expected attenuation of ground vibration.

It is generally difficult to establish the reduction of the vibration amplitude with distance. Both geometrical and material attenuation are of great importance in the soil response, as well as soil layering, groundwater conditions and the surrounding environment. Geometrical wave spreading, material damping and scattering due to heterogeneities in the soil all contribute to vibration attenuation in the ground: the first component follows a power law with distance, the latter two follow an exponential law [2]. In this study, the decay of peak particle velocity with distance of impact-induced vibrations is thoroughly analysed and the power trend is found dominant in many empirical vibration attenuation laws. Data collected in Pisa, Italy, are reviewed to evaluate the capabilities of wave amplitude vs. distance relationships.

Drop load sources are often used in surface wave analysis for site characterisation [11]. These tests are non-intrusive and can be used to obtain shear wave velocity and material damping profiles at a site. Several analytical expressions have been developed in the past to reproduce the source pulse generated by the drop load test [1,22,24]. However, only a few of these provide a good match to real data. A more refined expression for the source signal is proposed herein, based on experimentally recorded signals, to be used as input for the numerical simulation. It implicitly considers the influence of the characteristics of the drop load apparatus on the resultant seismic wave field. This approach can be easily extended to calibrate the source model for other activities inducing ground vibrations on the basis of experimental data collected in the vicinity of the source.

Previous numerical simulations of Spectral Analysis of Surface Waves (SASW) tests were performed to evaluate the potential influence of the test setup and soil stratigraphy on the ground frequency response in terms of dispersion curves through comparison with experimental tests [12]. For this study, numerical simulations of the Pisa field tests were carried out. The layered soil profile was modelled in detail and the drop load was simulated with the newly proposed expression for the source pulse. The velocity time histories were computed at several distances from the falling weight and compared to the experimental recordings. Focus was given to the wave decay with distance. As a realistic peak particle velocity (PPV) decay with distance was obtained, the finite element model is deemed to be

* Corresponding author. Tel: +44 78 3370 0742.
E-mail addresses: raffaella.colombero12@alumni.imperial.ac.uk (R. Colombero), stavroula.kontoe@imperial.ac.uk (S. Kontoe), sebastiano.foti@polito.it (S. Foti), d.potts@imperial.ac.uk (D.M. Potts).
[1] Permanent address: Atkins Ltd., The Wells, Church Street, Epsom KT17 4PF, UK.
[2] Tel.: +44 20 7594 5996.
[3] Tel.: +39 011 090 4896.
[4] Tel.: +44 20 7594 6084.

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reliable in reproducing the dissipation of the energy generated by drop load tests. This approach may be a useful tool in place of the empirical expressions for wave attenuation if a sufficient knowledge of the site is available.

2. Amplitude–distance attenuation laws

2.1. Theoretical framework

Any disturbing source acting on a medium generates a complex wave field within it. The amplitude of such waves decays with distance as the waves propagate away from the source. It is well established that three main mechanisms influence the attenuation of impact-induced wave fields, as reported in many studies after the pioneering work of Lamb in 1904 (e.g. [2,28]):

Geometrical attenuation. Waves generated at a point propagate in the soil with a continuously expanding front, a hemisphere and a cylinder for body waves and Rayleigh waves respectively. Neglecting dissipative components, the wave energy remains constant along the wave front; hence the energy per unit area of the wave front decreases as the wave travels from the source point. As the peak particle amplitude attenuation is linked to the energy decay, the amplitude–distance relationship is based on the elastic wave energy conservation and follows a power law $A \propto r^{-n}$, where A represents the amplitude of a recorded quantity of the wave motion (e.g. velocity or acceleration) and r is the distance from the source position. The exponent n is equal to 0.5 and 2.0 respectively for surface and body waves produced by a surface point load.

Material attenuation. The hysteretic behaviour of the soil leads to a second attenuation component, exponentially dependent on the distance, $A \propto exp(-k_M \cdot r)$, where the attenuation coefficient k_M can be expressed as a function of the soil damping ratio ξ, the wave frequency ω and Rayleigh wave propagation velocity V_R.

Scattering in non-homogeneous media. In heterogeneous media, due to a change in the material properties at the interfaces between successive layers, the waves are reflected and refracted. As a consequence of this, the distribution of wave energy is locally modified and the wave amplitude reduces. Similarly to the material damping relationship, the scattering attenuation with distance follows an exponential law, where the attenuation coefficient k_S is inversely proportional to the shear wavelength λ_S.

Fig. 1. Drop load test apparatus used for experimental tests in Pisa.

Auersch [2] proposed the following peak particle amplitude attenuation law which incorporates all three mechanisms:

$$A_j = A_i \left(\frac{r_j}{r_i}\right)^{-n} exp\left[-k_M \cdot (r_j - r_i)\right] exp\left[-k_S \cdot (r_j - r_i)\right] \quad (1)$$

where A_i and A_j are the amplitude of the wave motion at two points i and j; r_i and r_j are the corresponding distances from the source location; and n, k_M and k_S are the attenuation coefficients.

2.2. Drop load tests and analytical representation of disturbing sources

Drop load tests are often carried out as part of Spectral Analysis of Surface Waves (SASW) tests. They consist of a falling heavy weight hitting a plate or directly the ground, generating a wave field (Fig. 1). Particle velocity signals are captured at different distances from the source by geophones (Fig. 2).

A vertical point load acting on the surface of a half-space represents a good approximation of the falling mass used in drop load tests. Lamb [16] presented a first attempt to evaluate the soil response due to a surface point force, representing the disturbance by a vertical impulse. Based on Lamb's work, several authors deduced complete analytical solutions in terms of particle displacements, velocities, accelerations and strains due to the application of an arbitrary excitation. For example, Pekeris [24] assumed the source to be a Heaviside step unit function (Fig. 3a), while Mooney [22] considered a Dirac Delta function (Fig. 3b). However in both cases the resulting velocity response reached non-realistic infinite values. Hence Mooney [22] suggested an arbitrary sinusoidal function (Fig. 3c), able to better predict the generated wave field. Abe et al. [1] suggested a new sinusoidal expression (Fig. 3d), which accounts for the effect of the drop load apparatus characteristics on the wave field by assuming the amplitude of the source signal to be proportional to the momentum of the weight before the impact (given by the product of mass by velocity just before the impact).

Although the expression proposed by Abe et al. [1] is quite representative of a drop load test action, it results from a parametric analysis of the influence of the standardised drop load tests setup on the recorded source signal. Therefore a more realistic approximation of the source pulse is still needed. Force identification procedures [13,19] would provide a consistent framework to formulate an appropriate source model. Nevertheless, they require the solution of a rather complex inverse problem especially in the case of a drop-load test in which a significant plasticisation is expected in the impact zone. The solution of the inverse problem would be in this case very computationally intensive and time consuming. Moreover, the non-uniqueness of the solution would represent a very serious issue. A simpler but efficient approach is proposed herein. The new source function is directly formulated on the basis of near-field observations of particle velocity time histories recorded by geophones positioned

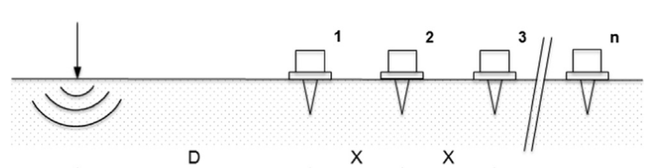

Fig. 2. Experimental setup for multistation SASW tests.