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Free-Field Sub-Surface Soil Response to Surface Impact Loads

W. Johnson
Principal Engineer, Bechtel Power Corporation, Frederick, Maryland, USA

S. Malushte
Senior Principal Engineer and Bechtel Fellow, Bechtel Power Corporation, Frederick, Maryland, USA

ABSTRACT

Nuclear power plant regulations require evaluation of safety related underground utilities such as buried piping, tunnels, and ductbanks for credible postulated accidental load drops during construction and maintenance operations. The dynamic structural response of these components is calculated using the free-field wave motions produced by source impacts resulting from dropped elements. These wave motions are characterized by peak particle velocity data which have been collected for various impact phenomena such as pile driving, construction equipment vibrations, and blasting, represented by peak particle velocity as a function of scaled distance, a parameter which depends on the drop energy and the distance from the source of a receiver on the ground surface. Where the utility is deeply buried, peak particle velocities taken from these data can substantially overestimate the ground response. This investigation presents a method for estimation of the response below ground from measured available data at the ground surface by using existing non-dimensionalized elastic half-space analytical solutions for surface and interior response to surface impact loads. Subsurface responses are shown to be conveniently represented by parallel shifting of the surface log-log peak particle velocity vs. scaled energy plots. Limitations for applicability of the method, on the impact radius and on the temporal variation of the impact loading, are provided.

1.0 BACKGROUND

The heavy rigging operations necessary at nuclear plant sites during construction, routine maintenance, and special activities such as steam generator replacement require assessment of safety related buried utilities for the effects of postulated accidental impact loads in the form of dropped loads, crane boom drops, etc. [19]. The conventional system response methodology is to estimate the free-field stress wave amplitude resulting from the surface impact loading (in the form of peak particle velocities) and, neglecting dynamic soil-structure interaction, to apply these free field responses to the buried pipeline or ductbank and determine the structural response using methods such as those available in [1-6]. The free-field velocity due to impact loading is, however, difficult to determine analytically, primarily due to the unavailability of utilitarian solutions to the elastic half-space surface impact load problem. As such, nuclear plant structural engineers have utilized data collected for various impact phenomena, such as pile driving, construction equipment vibrations, blasting, soil compaction, etc. This data has been typically presented in the form of surface peak particle velocities as a function of the distance from the impact or as ppv vs. scaled energy [8-10]. Data for measurements beneath the surface are rare, first because the purpose of this data is generally for use in evaluating the potential for damage to surface mounted structures such as buildings, and secondly because of the difficulty and expense of acquiring reliable undisturbed in-situ data below the surface. For evaluation of nuclear plant buried safety related components, conservative data for the surface soil response has been used at locations below the surface.

The extent of this conservatism becomes evident when one considers the large attenuation of the response-dominating Rayleigh wave horizontal and vertical components. An idea of the velocity amplitude attenuation is provided (Richart et al [11]) in Fig. 1, which depicts the variation of the Rayleigh wave amplitude (roughly 70% of the impact energy is in the Rayleigh wave) with depth. From a construction operations standpoint, relaxation of this conservatism provides significant economic returns. The outage duration for conventional nuclear plant maintenance activities, and especially for steam generator replacement work is significantly influenced by the constraints on construction lift paths and load lift magnitudes, which are in turn a function of the capacity of underground utilities to withstand postulated dropped loads. For a postulated high energy load drop such as a steam generator from an outside lift system or an outside lift system header beam from a crawler crane, onto or near safety-related utilities serving a sister on-line unit, these considerations can be substantial enough to dictate the layout and design of the rigging equipment. Increased flexibility to perform construction operations and improved scheduling is afforded if conservative assumptions for the impact loadings from postulated component and construction element drops are relaxed.

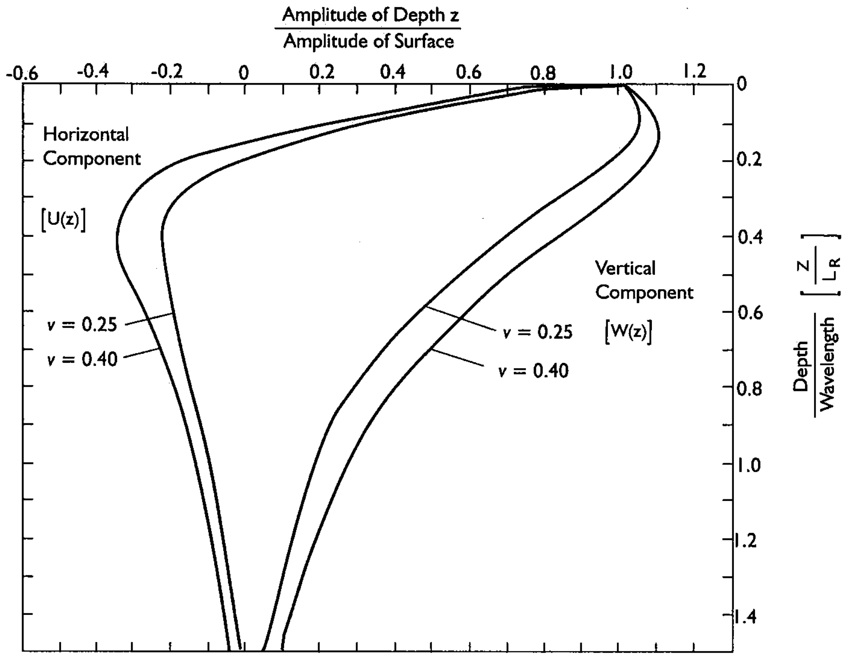

Figure 1. Rayleigh Wave Amplitude Variation with Depth (Richart et al [11])

2.0 EXTRAPOLATION OF SUB-SURFACE RESPONSE

In principle, the free field, off-axis sub-surface soil response can be approximated by solving the linear problem for the dynamic response of an elastic half-space to a time dependent impact loading p(r)F(t), either by analytical solution of the partial differential equation formulation or by an axisymmetric finite element solution. These approaches, for application to design, compound a number of difficulties. Firstly, development of the impact loading function requires address of the soil local material nonlinearity. Given the loading function, general analytical solutions must numerically invert the Laplace-Hankel transform, a formidable task, requiring either numerical complex integration with extremely refined localized meshes at singularities or the numerical evaluation of numerous real integrals. Such solutions have been published in the literature [12,13], but only for special and limiting loadings (step functions) and for specific response locations (surface or axis). In some cases, the simplifying assumptions required to achieve a solution, render results (such as infinite velocities for finite loadings) unsuitable for design application. Gakenheimer [14] and Georgiadis et al [15] have addressed the off-axis, sub-surface response problem. The finite element formulations are problematic in that there are insufficient aforementioned analytical results to benchmark against.

As noted in Sec. 1, the commonly used approach to determine subsurface response to surface impact loading is based on field measurements of surface velocities produced by various energy sources. These data are available for different soils in the form of peak particle velocity vs. scaled distance plots (Fig. 2) and represent the velocity at the surface only. The data are represented as straight lines on log-log plots. In the design application of these data to off-axis sub-surface impacts, either the surface ppv directly above the point of interest is used (on the basis that the Rayleigh wave dominates the response and the Rayleigh wave response is near its maximum at the surface) or the distance from the impact point on the surface to the sub-surface location is calculated and this distance is used to calculate the "scaled distance" (scaled distance is defined as $[d/E^{1/2}]$,where E is the drop energy and d is the distance from source to receiver) for determination of the ppv ordinate. Development of a more appropriate design application of the ppv surface data, to off-axis sub-surface locations, based on extrapolation in accordance with the theoretical half-space solutions provided in the literature, is the objective of the remaining sections.

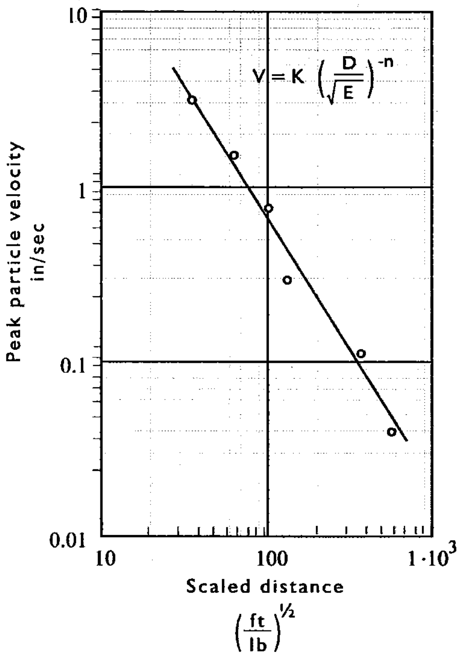

Figure 2. Typical Plot of Peak Particle Velocity vs. Scaled Distance (Wiss [8])

Estimation of the response below the ground surface from measured available data at the ground surface can be performed by using the existing elastic half-space response solutions for surface impact loads. Of interest is the interior vertical ppv component to which all of the stress components can be related [16]. The vertical component of motion is dominant at distance from the impact and generally not phased with the horizontal components [1]. Consider a general impact type loading p(r)F(t) applied to the surface of an elastic half space as shown in Fig. 3. The vertical, horizontal or resultant peak particle velocity at any point, due to a given axisymmetric loading p(x)F(t) can be represented as a positive surface which fixes the ratio of peak particle velocities for any two points (r_1, z_1) and (r_2, z_2) of interest (Fig. 4).

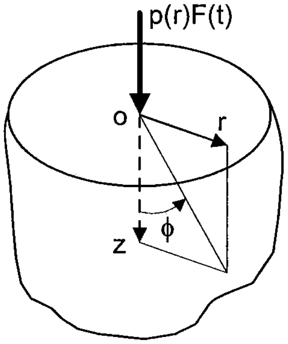

Figure 3. Impact Load Applied to Elastic Half-Space

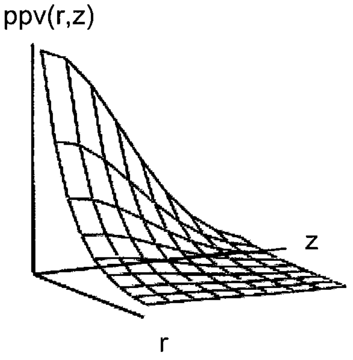

Figure 4. Peak Particle Velocity Variation

The function ppv(r,z) can be established from the rigorous solutions for the partial differential equations of motion available in the literature. The development used here follows the work of Georgiadis [15]. The locations of interest in this investigation are the half space off-axis interior points. Stresses on the z axis can be determined directly, without calculating a ppv using the relation (1) established by Mayne and Jones [17].

$$\sigma_z^{\max} = \frac{V_s\sqrt{WHB}}{(B+z)^2} \tag{1}$$

where V_s = soil shear wave velocity W = weight of the missile, H = height of drop, B = width of weight = a$\sqrt{\pi}$, a = radius of missile and z = depth beneath surface. Peak dynamic stresses predicted by formula (1) have been confirmed in [17] with field measurements for various soils. Measured responses at locations on the surface, in the form of either ppv vs. scaled distance plots, are assumed to be available, as it is these from which response within the half space will be generated. Georgiadis, in [15], using a high-accuracy numerical solution technique for inversion of the Laplace-Hankel transform, has calculated the response at interior points of an elastic half space subjected to an impact load. The governing differential equations and their development for Lamb's problem, provided in [15], are well known and will not be repeated here. Detailed, non-dimensionalized results for off-axis, surface and sub-surface displacements are provided for $\nu = 0.25$ and a symmetrical triangular impulse function with Dirac delta spatial distribution, $p(r) = \delta(r)$. The normalized displacement as a function of normalized time is defined as

$$u_z^{norm}(\tau) = -\frac{\pi\mu}{F}\left(r^2+z^2\right)^{1/2} u_z(t) \quad \text{and} \quad \tau = \frac{c_2 t}{\left(r^2+z^2\right)^{1/2}} \tag{2}$$

where $u_z(t)$ and t are corresponding dimensionalized variables, μ is the Lame constant, F is the peak value of the impact forcing function $F(t)$, c_2 is the shear wave velocity and r and z are as defined in Fig. 3. By the differentiation chain rule,

$$\frac{\partial u_z(t)}{\partial t} = \frac{\partial u_z}{\partial u_z^{norm}}\frac{\partial u_z^{norm}}{\partial \tau}\frac{\partial \tau}{\partial t} = \frac{-Fc_2}{\pi\mu\left(r^2+z^2\right)}\frac{\partial u_z^{norm}}{\partial \tau} \tag{3}$$

the expression for the velocity at any location, on or below the surface, is determined as a function of the corresponding normalized velocity. The expression for peak particle velocity is then

$$ppv(r,\phi) = \max_{t\in[0,t_1]}\left|\frac{\partial u_z(t)}{\partial t}\right| = \left|\frac{-Fc_2}{\pi\mu\left(r^2+z^2\right)}\right|\left[\max_{\tau}\left|\frac{\partial u_z^{norm}(\phi,\tau)}{\partial \tau}\right|\right] \tag{4}$$

Expressing the ratio of peak particle velocity below the surface to the peak particle velocity at a location directly above,

$$R(r,\phi) = \frac{ppv(r,\phi)}{ppv(r,\pi/2)} = \frac{r^2}{\left(r^2+z^2\right)}\left(\frac{\max\limits_{\tau}\left|\dfrac{\partial u_z^{norm}(\phi,\tau)}{\partial \tau}\right|}{\max\limits_{\tau}\left|\dfrac{\partial u_z^{norm}(0,\tau)}{\partial \tau}\right|}\right) \tag{5}$$

The normalized velocities required for the implementation of (5) are determined from the displacement time histories in [15], provided in Fig. 5 of this paper. Note that the ratio shown in (5) depends on ratios determined from the normalized displacement/velocity functions, and not directly on material constants or the spatial/temporal characterization of the forcing function. Maximum slopes for the surface responses at $\phi = 30^\circ$ and at $\phi = 60^\circ$ are provided in Fig. 5. Substituting these into (5) leads to ratios $R(r, \phi = 30) = (0.5)^2(0.71/2.75) = 0.06$ and $R(r, \phi = 60) = (0.8660)^2(1.90/2.75) = 0.52$. The corresponding shifted ppv vs. scaled distance curves, applied to typical surface ppv data are shown in Fig. 5.

3.0 IMPACT LOADING – TEMPORAL AND SPATIAL CONSIDERATIONS

Based on recorded measurements using accelerometers attached to dropped weights, the impact forcing function can be reasonably approximated using a symmetrical triangular time history (Mayne and Jones [17]). The only available off-axis results in the literature for this kind of pulse are those from [15] for a symmetrical triangular time pulse of specific duration $t_o = r/2c_r$, where c_r is the Rayleigh wave velocity. Values of t_o in this range are typical of postulated load drop impact durations. Surface soils encountered in proximity to nuclear power block structures are usually high quality structural backfill with shear wave velocities ranging from 1000 to 2500 fps or 1750 fps on average, with corresponding Rayleigh wave velocity $c_r = 0.9194\ c_s \sim 1600$ fps. A missile dropped from 150 ft. penetrating the ground surface 12 inches would produce a uniform pulse duration of 0.02 sec and a triangular pulse duration of 0.04 sec. The radius at which the results from Fig. 6. would apply is then $2t_oc_r$ or 40 ft. Where $r/2t_o$ is approximated by, but not equal to c_r, the subject predicted ppv values serve as upper bounds ($r < 2t_oc_r$) or lower bounds ($r > 2t_oc_r$), respectively. The curves in Fig. 6, then, represent bounding rather than specific or general cases. To predict the response for the arbitrary case, computation of t_o and estimation of c_r, together with a parametric set of response curves, for various $t_o = r/2c_r$ (of the type developed in [15] and shown in Fig. 5) will be required. Estimates for $2t_o$ are readily calculated from the missile geometry and velocity for a nondeformable missile from the empirical penetration relations such as those provided by Young [20] and those in [7].

The solutions from [15] are based on the application of a concentrated load rather than a realistic spatially distributed one. Application of the St. Venant principle to the surface impact problem has been investigated by Awrejcewicz and Pyryev in [22] by comparing the response time histories at distance for various radii of the impacting load (step function in time). The comparison demonstrated that surface responses from concentrated and distributed loadings were indistinguishable at distance $r > 3r_o$, where r_o is the radius of load application. For response at distance, then, the St. Venant principle applies and it is unnecessary to consider the detailed effect of load spatial distribution on the ppv vs. scaled distance data.

4.0 SUMMARY

A method has been developed for extrapolation of surface ppv vs. scaled energy data to sub-surface locations based on elastic half-space solutions found in the literature. In the application of the method, either of the following approaches may be used: 1) where $r/2t_o \sim c_r$, the calculated response ratios may be used directly and 2) where $r/2t_o$ is not approximated by c_r, use of the method provides either upper or lower bounds for the response. Development of additional response curves, using the methods of [14] or [15], for a range of $r/2t_o$, will enable the concise response extrapolation for arbitrary pulse durations.

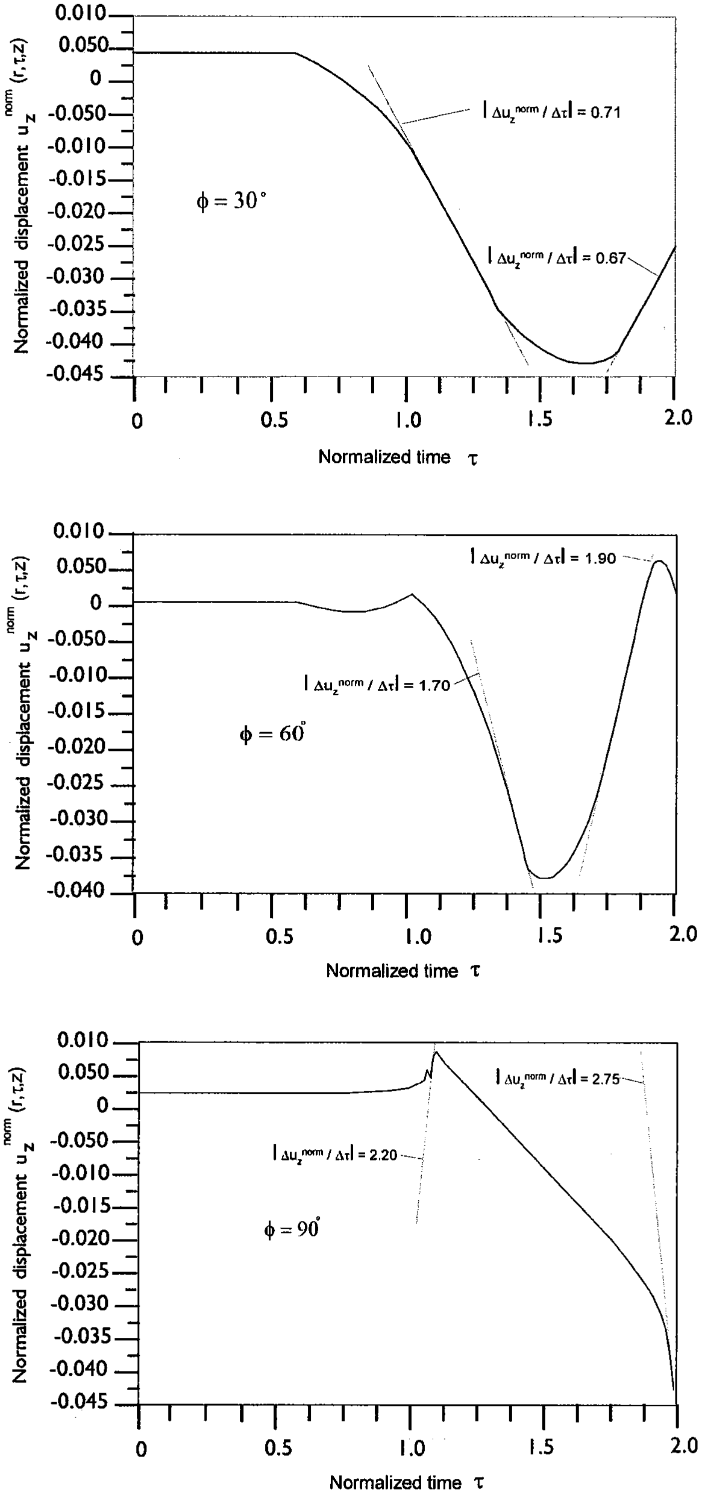

Figure 5. Velocity Slopes from Normalized Response Curves (Georgiadis et al [15])

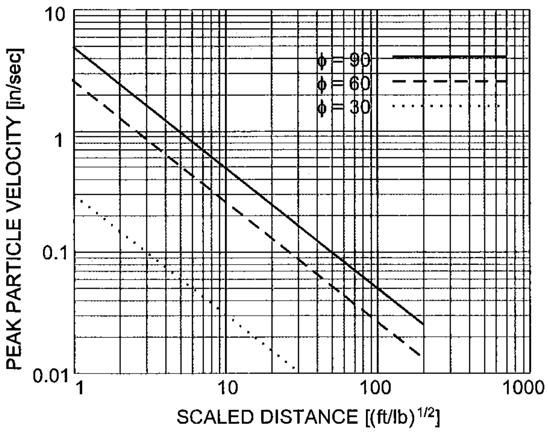

Fig. 6. Extrapolated Subsurface Responses

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