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Free-Field Motions for Postulated Heavy Load Drop on Shallow Rock Site

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ABSTRACT

Nuclear plant regulations require assessment of the effects impact loads from credibly postulated accidental drops during heavy rigging operations. For plants sited on rock, these impacts produce wave motions which excite nearby safety related utilities mounted on or entrenched in the rock. As such, it is necessary to define the rock motion in order to evaluate the safety related component. For a very high energy drop, such as that of a steam generator from an outside lift system, the severity of the rock response is sufficient to crush, fracture, and crack the rock in the near vicinity of the impact and to propagate waves in a classical sense at distance. This investigation addresses the characterization of rock motions resulting from high-energy impacts of dropped pressure vessels as needed for evaluation of affected ductbanks, pipelines, etc.

To evaluate the utility response of an entrenched or surface-mounted utility, an estimate of the peak particle velocity at the utility location is required. For high-energy pressure vessel drops on sound rock, the absorption of energy by vessel deformation during impact can, by an energy balance approach, be associated with an interface forcing function and corresponding peak interface pressures. These pressures, for steam generator end-on and side-on impacts, typically produce interface pressures which are less than the compressive strength of the impacted rock. However, the rock stress wave in the vicinity of the impact location likely exceeds the rock tension threshold. As such, substantial crushing occurs in the immediate proximity of the loading and farther away, radial and tangential cracks propagate. Analytical prediction of wave propagation response at distance must integrate the effects of localized crushing, softening due to cracking, and crack propagation at intermediate distances and elastic wave propagation at distance. These behaviors, in combination, invalidate the usual attenuation approaches and are difficult to simulate using even the most advanced nonlinear finite element methodologies.

This investigation utilizes solutions for the wave propagation impact response of an elastic half-space to establish the rock principal stress field and thereby estimate the distance from the impact load footprint at which the rock tension threshold is exceeded. Beyond this distance, classical wave propagation characterizes the rock response and the peak particle velocity is attenuated in accordance with the appropriate attenuation coefficient for sound rock. An equation is developed for the distance r_T at which the rock tension threshold σ_T is exceeded. The values r_T and σ_T are used to establish the peak particle velocity (ppv) vs. scaled distance "square-root" attenuation relation for Rayleigh waves outside of the fractured region, where

$$\mathrm{ppv}(r) = \mathrm{ppv}(r_T)\sqrt{\frac{r_T}{r}}$$

1.0 INTRODUCTION

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 utilities for the effects of postulated accidental impact loads in the form of dropped loads, crane boom drops, etc. For plants sited on shallow rock, the entrenched or rock-surface mounted utilities near such postulated drops experience motions potentially severe enough to inhibit their nuclear safety functions. This investigation addresses the characterization of rock motions resulting from high-energy impacts of dropped pressure vessels as needed for design input to evaluate the affected ductbanks, pipelines, etc.

Evaluation of the response of an entrenched or surface-mounted utility requires an estimate of the peak particle velocity at the utility location. For high-energy pressure vessel drops on sound rock, the absorption of energy by vessel deformation during impact can, by energy balance and dynamic equilibrium approaches, be associated with an interface forcing function and corresponding peak interface pressures. End-on or side-on impacts from a large dropped pressure vessel, may produce interface pressures which are more or less than the compressive strength of the impacted rock. In either case, the stress wave in the vicinity of the impact location exceeds the rock tension threshold. As such, fractures occur in the immediate proximity of the loading and farther away, radial and tangential cracks propagate (Fig. 1).

This behavior has been demonstrated, experimentally and reported by Ahrens et al in [1] for small scale rock specimens subject to high velocity impacts from metal projectiles. Radial, concentric and conical fractures were observed as shown in Fig. 1. Similar rock response behavior to confined underground blasts [2] has also been observed, with a blast-fractured zone consisting of crushed rock in the cylindrical or spherical concentric region nearest the blast, radial and tangential cracks further out, and at distance, a "seismic zone" where the stress is below the tensile "elastic limit" and no fragmentation or cracking occurs. In both [1] and [2], spall fractures (parallel to free surfaces) in the vicinity of the impacting or blast loads are noted. These are caused by tensile stress resulting from "interference between the tail portion of an incident compressional wave and the front of the same wave which has been transformed on reflection at the free surface into a tensional wave" [2]. Ahrens et al [1] have also noted that for high velocity impacts, the maximum depth of shock-induced cracking corresponds closely to the radius at which the amplitude of the decaying shock wave is approximately equal to the rock dynamic tensile strength.

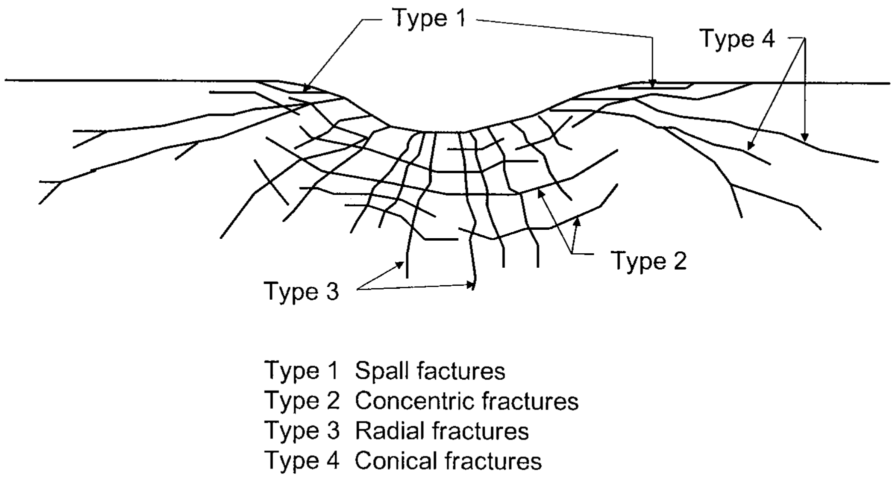

Figure 1. Failure of Impacted Rock

Based on these and similar observations and experience with impacted rock, in the region outside the fracture zone, the rock stress responses are within the strength limits and the material behavior remains elastic. Waves propagate in the classical sense there. At the boundary of this fracture zone, the rock material is at its tensile threshold limit. This condition applies without regard to the impact energy magnitude. Its application in design has the benefit of limiting peak particle velocities to values attenuated from a rock tension threshold located at some to-be-determined distance from the source. Thus, to predict rock response at locations outside the fracture or damage zone, the extent of the zone is estimated and the threshold wave stress is imposed at the defined boundary. Beyond this boundary, the wave response is attenuated as for sound, non-fractured rock.

2.0 EVALUATION OF STRUCTURES, SYSTEMS AND COMPONENTS FOR POSTULATED HEAVY LOAD DROP – ROCK VS. SOIL

Evaluation of sub-surface or surface-mounted structures, systems and components (SSCs) on soil sites is typically based on the use of measured peak particle velocity (ppv) vs. scaled distance data as shown in Figure 2 (the scaled distance is the distance from the source to the receiver divided by the square root of the drop or impact energy). These data, collected from various impact phenomena such as pile driving, construction equipment vibrations, etc. reflect hard, non energy absorbing impacting elements and are therefore directly applicable to the calculation of soil responses to hard missiles. A corresponding approach to either hard or deformable missile impact on rock is problematic for a number of reasons:

1) Such data are generally unavailable for rock, particularly at the high energy levels applicable to nuclear plant heavy load drop evaluations.

2) Free-field rock responses are highly dependent on the missile stiffness for a given drop energy. Any representation of ppv vs. scaled energy data would require a description of this stiffness, unlike for soil, where a wide range of missile stiffnesses are essentially rigid. Large pressure vessels such as steam generators, for example, can have sufficient longitudinal and lateral stiffness to be considered as rigid impacting elements when impacting typical nuclear plant site structural backfill, but are essentially flexible when impacting rock. For impacts on soil, the soil absorbs the energy and for impact on rock, the missile may or may not absorb the energy, depending on the relative stiffness and resistance characteristics of the rock and missile.
3) Simplified power law type relations [3] for ppv vs. scaled distance, applicable over a wide range of drop energies, do not apply. These relations are consistent with Rayleigh wave propagation in an elastic half-space and are invalidated by the progressive crushing, fracture, and cracking which occur with increasing drop energies.
4) Analytical prediction of wave propagation response at distance must integrate the effects of localized crushing, softening due to cracking, and crack propagation at intermediate distances and elastic wave propagation at distance. These behaviors, in combination, invalidate direct application of the usual attenuation approaches [3] and are rather intractable by even the most advanced nonlinear finite element methodologies as noted by Belytschko and Mish [4].

For the nuclear plant postulated load drop onto a shallow rock site a two-step approach is taken in which the impulse loading applied to the rock is calculated based on deformation behavior of the impacting pressure vessel (or on the rock compressive strength if it is less than the resistance of the impacting element). It is then necessary to determine the attenuation of the impact stress to the receiver location. Using the conventional attenuation coefficients for rock, together with stresses and associated peak particle velocities at the boundary of the impact footprint will always overestimate the response at the receiver. The method proposed herein, and described in Figure 3, locates the tension threshold boundary based, conservatively, on elastic wave propagation throughout the entire rock medium. This location, together with the threshold principal stress, then anchors the conventional square-root attenuation curve for response beyond the tension threshold location.

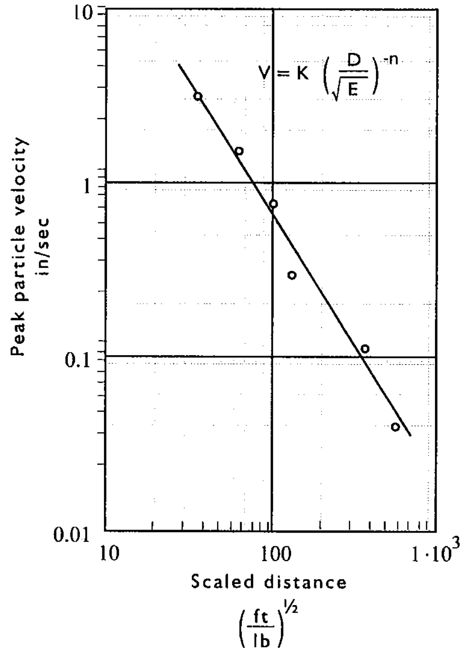

Figure 2. Typical Plot of Peak Particle Velocity vs Scaled Distance (Wiss [8])

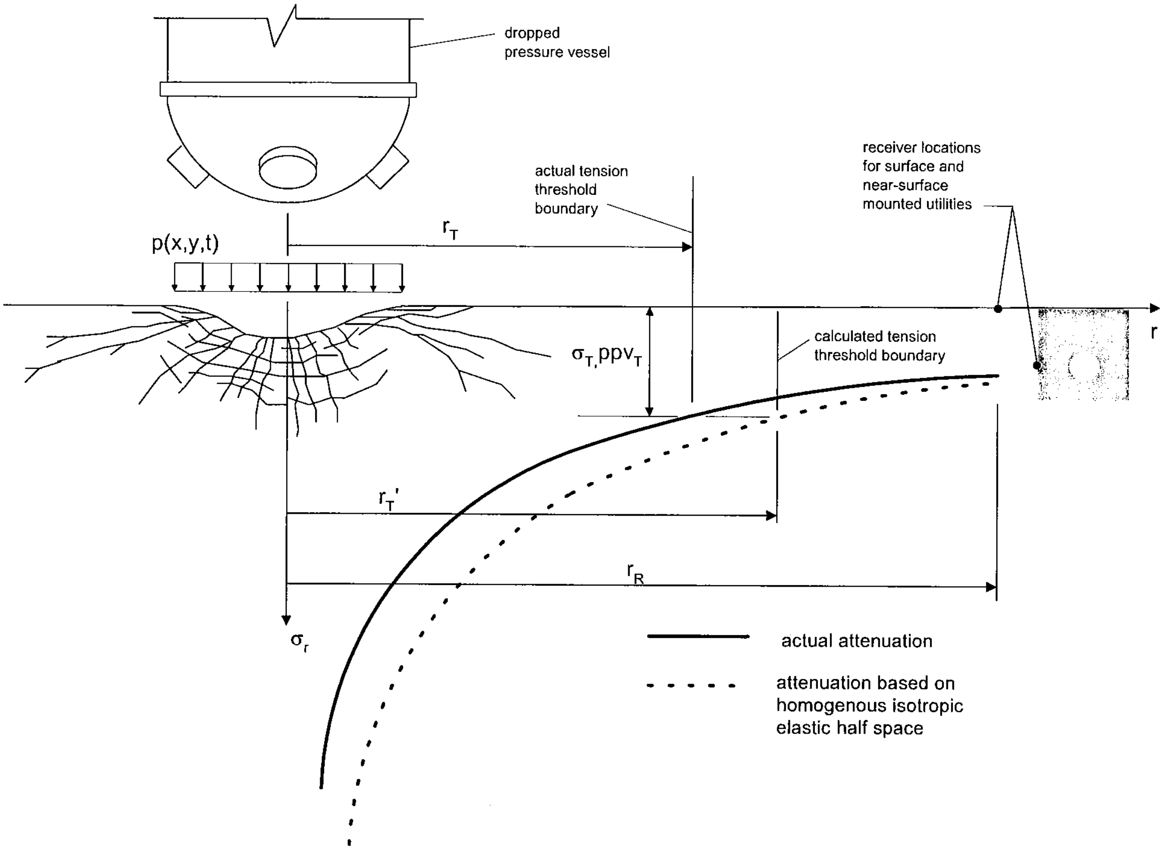

Figure 3. Attenuation of Impact Response from Postulated Steam Generator Drop

The steps for analysis of the overall postulated load drop to rock problem are summarized as follows:

1) Determine a resistance function for the impacting element, applicable for the range of expected deformations. For a pressure vessel, consider large deflection of the shell from a load applied by a rigid plate. The effect of internal stiffeners should be included in this evaluation. A steam generator channel-end resistance corresponding to shortening of the channel-end hemispherical shell in the direction of the steam generator longitudinal axis was found, by the authors, to roughly double when the internal stiffeners were included. Stolarski [9] and Zhong and Ruiz [10] provide resistance function calculation methods for shells impacting rigid surfaces and undergoing large displacements. The treatise by Simitses [11] addresses the case for thin shells when the resistance function is governed by buckling.
2) Compare the shell resistance with the rock compressive strength to determine whether the rock or shell resistance governs. This will depend, in general, on the amount of shell deformation or rock "penetration" and on the time dependent interface footprint. Governance of the resistance by the rock or shell could change during the application of the impact load due to time variation of the contact area. Such change could also result from increased confinement with penetration, where the penetration is deep. For the case of a pressure vessel drop onto rock, the effects of confinement are negligible since the missile profile is blunt and the corresponding penetration depth is small.
3) Based on the limiting resistance, develop the interface forcing function p(x,y,t) amplitude and footprint based on local contact mechanics and energy balance considerations.
4) Determine, by the methodology of Sec. 4.0, the location where the rock dynamic response is equal to its dynamic tension threshold. Beyond this location, classical wave propagation characterizes the rock response.
5) Attenuate from the tension threshold location to the receiver location, using the appropriate attenuation coefficients for the rock material (Woods and Jedele[12]).

4.0 LOCATION OF THE ROCK TENSION THRESHOLD

Considering an elastic isotropic half-space, Guan and Nowak [5] have determined surface vertical displacement time histories, $u_z(t)$, as a function of non-dimensional time, $\tau = tc_s/r$ (where t is time, c_s = shear wave velocity and r is the distance from source to receiver) for a suddenly applied loading, distributed uniformly over a square of dimension 2a x 2a (Figure 4). Figure 5 shows these surface vertical displacement time histories at locations $x = r = 2a$ and $x = r = 4a$ for a total pressure loading $Q = 4a^2q$.

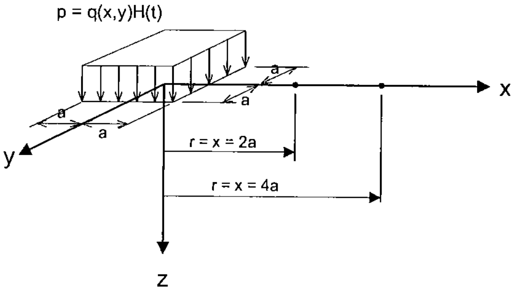

Figure 4. Uniform Rectangular Load Applied to Half-Space

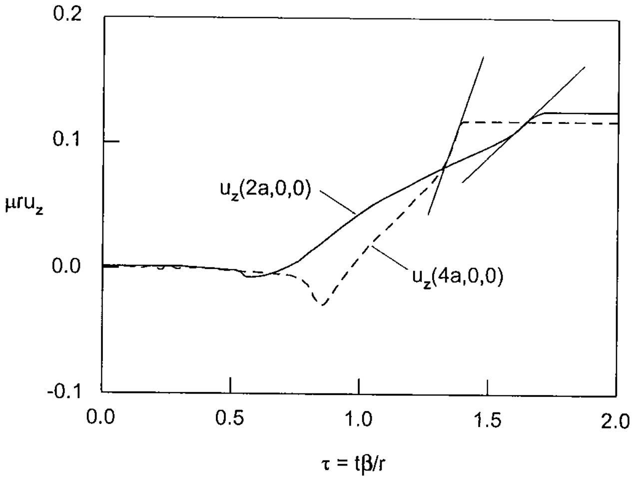

Figure 5. Nondimensional Displacement Response vs. Nondimensional Time for Rectangular Step Loading (Guan Novak [5])

Dimensional peak particle velocities, defined by slopes for the respective locations z = 2*a* and z = 4a occur at the departure of the Rayleigh wave. These velocities are, for unit total pressure loadings, $Q = 4a^2q = 1$,

$$\frac{\partial\left[\mu r u_z(2a,0,0,t)\right]}{\partial\left(tc_s/r\right)} = \left(\frac{\mu r^2}{c_s}\right)\frac{\partial u_z(2a,0,0,t)}{\partial t} = 0.21 \tag{1}$$

and

$$\left(\frac{\mu r^2}{c_s}\right)\frac{\partial u_z(4a,0,0,t)}{\partial t} = 0.63 \tag{2}$$

where μ = shear modulus (for $\nu = 0.25$) and u_z is the displacement per pound of total load $Q = 4qa^2$. The radial normal stress, $\sigma_{r,Q}$, for total pressure loading Q, is given by Uenishi and Rossmanith [6] in terms of Rayleigh wave vertical particle velocity as

$$\sigma_{r,Q} = \rho c_R g(\nu) Q \frac{\partial u_z}{\partial t} = BQ\dot{u}_z \tag{3}$$

where

$B = \rho c_R g(\nu)$, $c_R = 0.9194 c_S$ is the Rayleigh wave velocity and c_S is the shear wave velocity. From Eq. 8 and Figure 3 of [6], $g(\nu) \approx 2.14$. Substituting (3) into (1) and (2), using $c_S = (\mu/\rho)^{1/2}$ and simplifying,

$$\sigma_{r,Q} = \frac{AQ}{r^2} g(\nu)\left(\frac{c_R}{c_S}\right) \tag{4}$$

where at $r = 2a$, $A = 0.21$; at $r = 4a$, $A = 0.63$ and $c_R/c_S = 0.9194$ for $\nu = 0.25$. From relations (1) through (4) and these values,

$$\sigma_{r,Q}(2a,0,0) = \frac{0.103Q}{a^2} \tag{5}$$

$$\sigma_{r,Q}(4a,0,0) = \frac{0.077Q}{a^2} \tag{6}$$

From (5) and (6), a power law for the attenuation of elastic radial stress at the surface can be established [3]. Attenuation over the fractured region based on assumed elastic behavior there will provide upper bound or conservative stresses and peak particle velocities at distance.

$$\frac{\sigma_{r,Q}(4a,0,0)}{\sigma_{r,Q}(2a,0,0)} = \frac{\dot{u}_z(4a,0,0)}{\dot{u}_z(2a,0,0)} = \left(\frac{2a}{4a}\right)^{-n} \tag{7}$$

where

$$n = \frac{\log(0.103/0.77)}{\log(1/2)} = 0.4197 \tag{8}$$

With n defined, the attenuation curve is now anchored and the ppv and radial stress at an arbitrary distance r from the source are given by

$$\dot{u}_z(r) = u_z(2a,0,0)\left(\frac{2a}{r}\right)^n \tag{9}$$

$$\sigma_{r,Q}(r) = \sigma_{r,Q}(2a,0,0)\left(\frac{2a}{r}\right)^n = \frac{0.103Q}{a^2}\left(\frac{2a}{r}\right)^n \tag{10}$$

These stresses provide upper bound values for the actual stresses at distance when the response local to the impact is characterized by breakage, fracture and cracking of the rock. As the shear stress $\sigma_{r\phi}(r) = 0$ and $\sigma_{\phi\phi}(r) = \nu\sigma_{rr}(r) < \sigma_{rr}(r)$, $\sigma_{rr}(r) = \sigma_{r,Q}(r)$ is also the principal stress at r. Equating the dynamic tensile strength, σ_T to $\sigma_r(r)$ and solving for r, locates the boundary demarcating nonlinear response from classical wave propagation.

$$r_T = 2a\left(\frac{a^2\sigma_T}{0.103Q}\right)^{-\frac{1}{n}} \tag{11}$$

Neglecting the small material damping effects, the rock surface principal stress at distance r is then defined using the conventional "square-root" scaling attenuation formula for propagation of Rayleigh waves on the surface of an elastic half-space [3]

$$\sigma_r(r) = \sigma_T\sqrt{\frac{r_T}{r}} \tag{12}$$

Corresponding surface vertical particle velocity at r is given by (13), where ppv(r_T) is given by $\dot{u}_z$ in (3) with $\sigma_{r,Q} = \sigma_T$:

$$\text{ppv}(r) = \text{ppv}(r_T)\sqrt{\frac{r_T}{r}} \tag{13}$$

Horizontal radial particle velocity can be computed directly from the relations provided in Bedford and Drumheller [7] defining the ratio of horizontal to vertical rock particle velocity for Rayleigh waves. Typically, this ratio is around 2/3. The tangential normal rock stresses are given by the product of (12) and poisson's ratio. The tangential stress, the horizontal particle velocity computed from the relations in [7] together with equations (3) and (11) and (12) above describe the surface rock responses which can be used to evaluate structures located near the rock surface at distance from high energy impact sources.

5.0 SUMMARY AND CONCLUSIONS

The severe motions imposed by postulated high energy drops onto shallow rock nuclear plant sites are mitigated by several factors. These are the limited resistance of the impacting elements, the bounded compressive strength of the rock material, and the dynamic tension threshold of the rock. All of these effects limit the energy which can be transmitted from the source to the receiver. The tension threshold has been used to develop simple conservative formulas for the rock motion at the receiver location. The motion amplitudes described constitute input data useful in the analysis of nuclear plant equipment mounted on or near the rock surface.

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