Investigation of dynamic soil resistance on piles using GRLWEAP

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ABSTRACT: GRLWEAP is a pure analysis program for the prediction of pile response and blow counts of a pile driven by an impact hammer. GRLWEAP was shown to predict good results in the hammer and pile behavior. For accurate predictions, a good knowledge of both the static and dynamic soil resistance behavior must also exist. However, several researchers have recommended that the damping models, originally proposed by Smith, be changed to an exponential or another more complex law. The paper investigates various damping models and compares results. It computes GRLWEAP calculated force versus history and evaluates the sensitivity of the bearing graph results relative to the various damping models. The results from this study tend to resemble one of the GRLWEAP programs. Recommendations for the application of the expanded soil model options are developed, demonstrated, and presented in the paper.

1. INTRODUCTION

An analysis of impact pile driving by the traditional wave equation method has become well accepted in many countries. In general, the approach yields satisfactory results provided that the soil is considered to be linear elastic. This assumption is acceptable only if the amplitude of movements is small. Recent work by many researchers has challenged this view. It is generally agreed that a nonlinear analysis is required for heavily loaded piles. In this case, a nonlinear soil model is necessary for proper analysis. The dynamic wave equation is the most common approach used for nonlinear analysis.

2. BASIC TERMS AND RELATIONSHIPS

In order to avoid confusing terminology, the following definitions are proposed:

1. Static soil resistance, \( R_s \), is a function of the relative displacement of the pile to the soil and is assumed to be present both during static and dynamic loading. While \( R_s \) is a function of displacement and therefore varies with time, the relative static resistance is a constant (\( R_s < R_d < R_a \)).

2. The dynamic resistance, \( R_d \), is that portion of the soil resistance which is not present during static load application. It varies in time and is commonly thought to be related to pile velocity.

3. The total resistance, \( R_t \), is the sum of the dynamic resistance, \( R_d \), and the static resistance, \( R_s \).

4. The slip layer is a zone in the pile-soil interface where one commonly expects the relative motion between pile and soil to occur.

GRLWEAP has been widely accepted and used in many countries around the world. No serious reservations to the damping resistance in calculated according to tygge's original approach and includes a proposed damping parameter which yields reasonable results with a beam theory solution. Most of these values are realistic to those originally proposed by Smith. However, there are some obvious links between Smith's model and standard geotechnical soil test parameters. Several investigators in the dynamic behavior of pile have reported concern that the current approach is unavailable for either previously summer soil conditions or certain extreme conditions (e.g., very high or very low pile velocities) for which no empirical basis exists. Limited dynamic laboratory tests (Cottin, Coley 1968; Hearn 1978; Lithin, Fokkink 1980) also indicated that the damping forces are not very linearly with pile velocity as is nor-

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3 DISCUSSION OF DAMPING APPROACHES

3.1 Smith damping

Smith represented the resonant excited in the pile-soil interface by an elastic-plastic spring to represent static resistance and a quasi-linear dashpot to model the damping resistance (Figure 1). He also assumed that the soil mass beyond the slip layer was infinitely rigid. Thus, energy actually transmitted to the deforming and moving soil was exactly included in the losses represented by spinging and dashpot. Smith expressed the total resistance force exerted by the soil on the moving pile as follows:

\[ R = R_s(1 + L) \]

(2a)

with \( R_s \) being Smith's damping factor and \( L \) the pile velocity. Actually, Equation 2 cannot be directly used for calculations since the damping force would assume a sign given by the product of the static resistance and the velocity. A meaningful result would only be obtained if the damping force had the sign of the velocity, wherefore, one calculates the Smith damping resistance using the absolute value of \( R_s \) and the total resistance then becomes

\[ R = R_s R_f \]

(1b)

Equation 2 shows both components of the total resistance very clearly and therefore is the preferred form.

3.2 Gibson and Copet

Gibson and Copet (1989) published results of modal tests at the Texas A&M University which compared the total damping resistance with the static values at various velocities. The authors concluded that

\[ R = R_s R_f \]

(3)

Clearly, this power law was closely modeled after the original Smith approach. The experiments indicated power exponents of \( n = 5 \pm 2 \) for clay and \( n = 0.2 \) for sand.

3.3 Case damping

Goble and返mae (1976) included the 3-dimensional Case damping approach in the WERAP program. This approach had earlier been used for Case Method and CASEWAP capacity calculations (Ronan, Mose, and Goble 1977). The soil resistance is calculated as simplified

\[ R = R_s + L/Z \]

(3a)

where \( Z \) (ksi/m) is the pile impedance \( Z = E/A \) where \( E \) is the pile's elastic modulus, \( A \) the cross-sectional area, and \( Z \) the strain wave speed. This simple concept can also be expressed in a Smith-type formula:

\[ R = R_s R_f \]

(3b)

In Equation 3b, \( R_s \) is the ultimate static resistance which, of course, is constant and \( R_f \) is a "Smith damping factor." Since the product of \( R_s \) and \( R_f \) [here as a constant, the equivalent Case damping factor becomes]

\[ L = R_s R_f Z \]

(3c)

Thus, the actual velocity multiplier is a constant \( R_s R_f \) and the damping force is linear viscous.

3.4 Hearn's tests

Hearn (1979) used a flat steel plate in contact with a soil sample and also concluded that a power law should be used to calculate the total soil interface force. Thus, with the current definition

\[ R = R_s R_f + L/A \]

(4)

where \( L/A \) is the impedance \( Z \) depends on the shear strength of the soil.

3.5 Likithos and Poulies

In 1989, two batches of reinforced model pile tests (model pile size 10 mm diameter by 200 mm length) and instrumented for strain and shaft separately for the tests. The authors then used the Gibson-Copet approach and calculated both for and the parameter \( L/A \) and \( R_s \), and experiment N to obtain a best fit with observed data.
4 COMPARISON OF SMITH AND CASE (SMITH-2) DAMPING

Smith's approach gives lower damping resistance forces than the equivalent Case approach per below full static resistance activation and also less static unloading (or pile rebounding). For a quantitative evaluation of this difference, three comparisons were performed (Table 1). They included a large-scale offshore small pipe (76 in. long, 100 in. diameter and 90 mm thick), and two small (275 mm square, 15 m long) and a large (900 mm square, 15 m long) concrete piles. As per the (case) recommendation, the quakes were all set to 2.5 m except the toe quake for the large concrete pile which was the recommended 900/120 = 7.5 m. Since the large quake caused a relatively slow increase of $R_p$, somewhat different results were obtained for the large concrete pile with the two damping approaches. For the other two cases, the results were nearly identical, however, only because the

<table>
<thead>
<tr>
<th>Case</th>
<th>Pile Type</th>
<th>Area</th>
<th>Length</th>
<th>Hammer</th>
<th>Quakes</th>
<th>Min/Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>72&quot;Pipe</td>
<td>0.2755</td>
<td>55</td>
<td>MBU 1700</td>
<td>2.5/5.5</td>
<td>2.5/2.5</td>
</tr>
<tr>
<td>2</td>
<td>275mmPC</td>
<td>0.0759</td>
<td>13</td>
<td>S-son drop</td>
<td>2.5/2.5</td>
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</tr>
<tr>
<td>3</td>
<td>275PS</td>
<td>0.8100</td>
<td>13 D-0.12</td>
<td>D-0.52</td>
<td>2.5/5.5</td>
<td></td>
</tr>
</tbody>
</table>

"Smith-2" damping parameters were reduced by 10% compared to the standard "Smith-1" values. Table 2 lists results and indicates differences with respect to the standard Smith-1 small. These differences are generally small.

The original Smith damping approach yields small damping forces at the end of a hammer blow when the static resistance has decreased to small values. Figure 3, for example, shows calculated pile top velocities from analyses according to both Equations 1.1 and 3.b. Figure 2 also includes damping forces as a function of time. These forces are the sum of all site and toe damping values. The usually observed damped behavior of the pile top velocity is obviously better represented by the Smith-2 analysis. For this reason, CAPRAP analyses which must match actual measurements yield reasonable results only with either the Case or Smith-2 damping approach. The toe damping resistance of a large displacement pile is the only exception and is sometimes better modeled with slowly increasing damping forces until the full static resistance has been achieved. Therefore, ideally, a combination of both approaches would be chosen: Smith-1 until full static resistance activation is reached and Smith-2 thereafter. It is not complicated to use this combined resistance multiplier in damping calculations to get the maximum activated resistance term. $R_{\text{p0}}$ which has not yet these properties may be used as a multiplier instead of $R_p$ or $R_{\text{p0}}$. 5 DISCUSSION OF THE POWER LAW APPROACH

The experiments, leading to the exponential relationship between velocity and damping force, generally involved the measurement of a maximum damping force which occurred at that one instant when the sample was suddenly loaded.

![Fig. 2. Velocity force and damping forces over time for Smith-1 (top) and Smith-2 damping approach.](image-url)
<table>
<thead>
<tr>
<th>Case/Model</th>
<th>Damping Capacity at 1% Tension</th>
<th>Diff. Capacity</th>
<th>Diff. Max. Tension at 1%</th>
<th>Diff. Max. Capacity at 1% Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/Strain 1</td>
<td>0.167 36400 4550 11.0 288</td>
<td>0.167 36400 4550 11.0 288</td>
<td>0.167 36400 4550 11.0 288</td>
<td>0.167 36400 4550 11.0 288</td>
</tr>
<tr>
<td>1/Strain 2</td>
<td>0.153 30700 5600 6.0 270 0.7</td>
<td>0.153 30700 5600 6.0 270 0.7</td>
<td>0.153 30700 5600 6.0 270 0.7</td>
<td>0.153 30700 5600 6.0 270 0.7</td>
</tr>
<tr>
<td>1/Strain 3</td>
<td>0.252 2020 13.0 220 35.5 289 0.4</td>
<td>0.252 2020 13.0 220 35.5 289 0.4</td>
<td>0.252 2020 13.0 220 35.5 289 0.4</td>
<td>0.252 2020 13.0 220 35.5 289 0.4</td>
</tr>
<tr>
<td>1/Strain 4</td>
<td>0.303 2020 13.0 220 35.5 289 0.4</td>
<td>0.303 2020 13.0 220 35.5 289 0.4</td>
<td>0.303 2020 13.0 220 35.5 289 0.4</td>
<td>0.303 2020 13.0 220 35.5 289 0.4</td>
</tr>
<tr>
<td>2/Strain 1</td>
<td>0.25 1300 160 7.2 25.9</td>
<td>0.25 1300 160 7.2 25.9</td>
<td>0.25 1300 160 7.2 25.9</td>
<td>0.25 1300 160 7.2 25.9</td>
</tr>
<tr>
<td>2/Strain 2</td>
<td>0.25 1400 140 6.6 26.4 1.5</td>
<td>0.25 1400 140 6.6 26.4 1.5</td>
<td>0.25 1400 140 6.6 26.4 1.5</td>
<td>0.25 1400 140 6.6 26.4 1.5</td>
</tr>
<tr>
<td>3/Strain 1</td>
<td>0.25 980 100 5.0 25.9</td>
<td>0.25 980 100 5.0 25.9</td>
<td>0.25 980 100 5.0 25.9</td>
<td>0.25 980 100 5.0 25.9</td>
</tr>
<tr>
<td>3/Strain 2</td>
<td>0.25 1000 100 6.2 25.9</td>
<td>0.25 1000 100 6.2 25.9</td>
<td>0.25 1000 100 6.2 25.9</td>
<td>0.25 1000 100 6.2 25.9</td>
</tr>
<tr>
<td>4/Strain 1</td>
<td>0.25 1000 100 6.2 25.9</td>
<td>0.25 1000 100 6.2 25.9</td>
<td>0.25 1000 100 6.2 25.9</td>
<td>0.25 1000 100 6.2 25.9</td>
</tr>
</tbody>
</table>

Gibson and Loyd's equation cannot be used directly to calculate damping forces for all speeds using a harmonic flow. Modifications must be made to Equation 2 to (1) ensure velocity is positive for all values and (2) avoid multi-values. The equation would read:

\[ R_1 = R_2 + R_4 \sqrt{Q} \]  

The factor \( Q \) is the ratio of the sign of velocity \( \dot{v} \) to Equation (5.4). The "Smalls" of Gibson's option in EURAP. As will be shown, it does not yield satisfactory results (Figure 4.4). Obviously, the Gibson approach needs further modification before it can be used. First, the \( R_3 \) multiplier in (5.4) was replaced by \( R_3 \) as proposed earlier. Thus, the velocity \( \dot{v} \) in the power term was replaced by \( \dot{v} \).

The maximum velocity having occurred at a time in which \( R_1 \) is calculated. Equation (5.4) then becomes

\[ R_1 = R_2 + R_3 \dot{v} \quad (\text{5.5}) \]

The denominator minimum velocity \( \dot{v} \) is increasing before and constant after the absolute maximum velocity has been reached. It is never negative or decreasing which is an important feature of damping. Furthermore, since \( \dot{v} \) is constant throughout most of the analyzed time \( t \), is constant when the peak velocity is reached, a nearly linear equation approach results. Obviously, at the moment when minimum velocity is reached \( R_1 = R_1(\dot{v}_{\text{min}}) \) as recommended to Gibson and Copy. For ease of reference, Equation (5.5) will be referred to as the Gibson EURAP method. Both methods have been used to improve the examples.
discussed previously. Return was again measured in Table 2. The Gibson, Jp, and Gibson/GIRL (WEAP) Jp, damping factor was used daily on skin and has 0.055 and 1.25 (157) and the exponent N with 0.18 as for the day.

Three values correspond to recommendations contained in the literature. Two comparisons were also run for the same situation and N = 0.20 and 0.10 using the new approach. It can be concluded that, for practical purposes, there are no significant differences between these two experiments and N = 0.20 is undoubtedly accurate.

Table 2 (indications that Gibson's method yields low energies compared to the standard Smith approach which is situated to very high damping as low velocities both before and after maximum velocity (Figure 4). On the other hand, the new Gibson/GIRL approach yields very reasonable results. Furthermore, th Gibson's damping force versus time relationship indicates high frequency variations whereas the velocity approach term, Equation (3.4), produces a smooth and essentially damped relationship. This is demonstrated for the small concrete pile in Figure 4.

The new method would not be very useful without a set of recommended damping factors. Figure 5 provides a conversion from Smith to Gibson/GIRL damping factors with N = 0.2 and including a 10% correction for the R2 to R1 conversion. The figure gives corrections for various commonly encountered Smith/L damping factors. For example, for clay normally used 0.05 in a Smith damping factor. For this Smith value Figure 3 suggests 1.06 (157) for Jp, W = 5 m, and 5.5 = 3 m/s. For high velocity W = 5 m/s, the factor would be 2.17 (157). These conversions would approximately yield the same results from Smith and Gibson/GIRL. However, the purpose of using the new method would be to obtain valid results over the whole range of possible W values. It would, therefore, be reasonable to assume that Smith's provides relatively reliable results for average velocity maximum of 5 m/s, find the corresponding Lp, damping factor for this velocity, and the soil pile, and use that factor for all other, high, or low velocity situations.

6 SUMMARY

A new damping method has been developed and included in GIRL/WEAP. It has the advantage of 1. providing results in good agreement with the Smith approach which has been well correlated for a standard situation such as the case analyzed, 2. providing a well-damped pile behavior over long periods times which best matches measured pile velocities histories and 3. generating calculated damping forces which are physically possible. This new formula combines the past experience with wave equation and CAPWAP correlations with laboratory measured values. It appears that the approach may be directly used, even without additional experimental work. To accomplish this, the current standard Smith damping factors are to be easily converted to the Smith/L or WEAP Jp factors for any arbitrarily chosen reference velocity, e.g., Wp = 3 m/s (see also Figure 2).

The study also indicated that under normal circumstances Smith's damping factors may be replaced by Smith/2 values with a 10% decrease.
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