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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 stresses and blow counts of a pile driven by an impact hammer. GRLWEAP was shown to produce good simulations of 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 model, originally proposed by Smith, be changed to an exponential or another more complex law.

The paper investigates various damping models and compares results. It compares GRLWEAP calculated force - velocity histories and evaluates the sensitivity of the bearing graph results relative to the various damping models.

The results from this study lead to additional options of the GRLWEAP program. Recommendations for the applications of the expanded soil model options are developed, documented and presented in the paper.

1 INTRODUCTION

Analysis of impact pile driving by the so-called wave equation method has become well accepted in many countries. In general, the approach yields satisfactory stress predictions and, combined with observed blow counts from restrikes, reasonably accurate bearing capacity predictions. Even though good progress towards improved predictions has been made since the original concept was proposed by (Smith 1960), two main error sources remain: The first one is an unknown hammer performance, and the second is unknown dynamic soil behavior. The first error source can only be eliminated by measurements, the dynamic modeling of the soil may be improved either by well correlated damping and quake parameters or by a more realistic soil model. This paper investigates relationships between different formulations of one part of the dynamic soil representation in the wave equation approach, the damping model.

The commonly used wave equation program GRLWEAP is based on the earlier introduced WEAP program (Goble, Rausche 1976) and offers several options for soil damping calculations. This paper investigates the differences between four of these options and develops relationships between them. A review of related approaches described in the literature will precede the formulations contained in GRLWEAP.

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 therefore assumed to be present both during static and dynamic loading. While R_s is a function of displacement and therefore varies with time, the related R_u, i.e., the ultimate static soil resistance is a constant ($-R_u < R_s < R_u$).

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

3. The total resistance, R_t, is also often called the dynamic resistance. It is the sum of static and damping resistance. Of course, under static loads, damping resistance is zero and total resistance is then equal to the static resistance.

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

GRLWEAP has been widely accepted and used in many countries around the world. Its manual recommends that the damping resistance is calculated according to Smith's original approach and includes a few proposed damping parameters which often yield reasonably accurate results. Most of these values are identical to those originally proposed by Smith. However, since there are no obvious links between Smith's model and standard geotechnical soil test parameters, several investigators of the dynamic behavior of piling have expressed concern that the current approach is unreliable for either previously untested soil conditions or certain extreme conditions (e.g., very high or very low pile velocities) for which no experience base exists. Limited dynamic laboratory tests (Gibson, Coyle 1968; Heerema 1979; Litkouhi, Poskitt 1980) also indicated that the damping forces do not vary linearly with pile velocity as is normally assumed by the standard wave equation approach. Furthermore, there exists a discomfort about ignoring the forces and motions of the soil beyond the slip layer.

Acceptance of new soil models has been slow, probably because none of the researchers has been able to demonstrate an improved correlation between dynamic predictions and static test results compared to existing methods. In fact, a complete set of generally acceptable dynamic soil resistance parameters is still missing for the non-linear damping model. Also, it is not certain that a more realistic damping model would yield much improved predictions of pile bearing capacity with penetration per blow. After all, effects from capacity changes due to set-up or relaxation, residual stresses, differences between the dynamic and static failure modes, incomplete capacity activation (when the permanent set achieved by a hammer blow is small) are soil model deficiencies which often have a much greater influence on the analysis results than the choice of the soil damping model. However, the non-linear damping model could play an important role when soil behavior is characterized in an impact driving test performed at one particular hammer impact velocity and when these results are to be extended to other situations. For example, in an SPT test the hammer impact velocity is typically 3 m/s, while pile driving may be done at ram speeds of 5 m/s. Because of the non-linearity of the damping resistance, such differences may be important for a proper test interpretation.

3 DISCUSSION OF DAMPING APPROACHES

3.1 Smith damping

Smith represented the forces exerted in the pile-soil interface by an elasto-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 tacitly included in the losses represented by spring and dashpot. Smith expressed the total resistance force exerted by the soil on the moving pile as follows:

$$R_t = R_s(1 + J_s v) \qquad (1.a)$$

with J_s [s/m] being Smith's damping factor and v the pile velocity. Actually, Equation 1.a cannot be directly used for calculations since the damping force would assume a sign given by the product of the temporary static resistance and the velocity. A meaningful result would only be obtained if the damping force had the sign of the velocity. Therefore, one calculates the Smith damping resistance using the absolute value of R_s and the total resistance then becomes

$$R_t = R_s + |R_s| J_s v \qquad (1.b)$$

Equation (1.b) shows both components of the total resistance very clearly and therefore is the preferred form.

3.2 Gibson and Coyle

Gibson and Coyle (1968) published results of triaxial tests at the Texas A&M University which compared the total dynamic resistance with the static values at various velocities. The authors concluded that

$$R_t = R_s + R_s J_T v^N. \qquad (2)$$

Clearly, this power law was closely modeled after the original Smith approach. The experiments indicated exponents of N = 0.18 for clays and N = 0.20 for sands.

3.3 Case damping

Goble and Rausche (1976) included the non-dimensional Case damping approach in the WEAP program. This

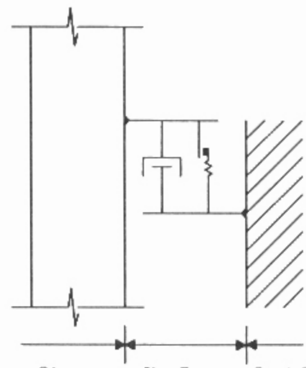

Fig. 1 Smith's soil model

approach had earlier been used for Case Method and CAPWAP capacity calculations (Rausche, Moses, Goble 1972). The soil resistance calculation is simplified to

$$R_t = R_s + J_c(Z)v \qquad (3.a)$$

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

$$R_t = R_s + R_u J_{s2} v. \qquad (3.b)$$

In Equation (3.b), R_u is the ultimate static resistance which, of course, is constant and J_{s2} is a "Smith-2" damping factor. Since the product of R_u and J_{S2} [s/m] is a constant, the equivalent Case damping factor becomes

$$J_c = J_{s2}(R_u)/Z. \qquad (3.c)$$

Thus, the actual velocity multiplier is a constant ($J_s R_u$) and the damping force is linearly viscous.

3.4 Heerema's tests

Heerema (1979) used a flat metal 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,

$$R_t = R_s(a + J_H v^{0.2}) \qquad (4)$$

where "a" [1] and J_H [$(s/m)^{0.2}$] depend on the shear strength of the soil.

3.5 Litkouhi and Poskitt

In 1980 these authors performed model pile tests (model pile size 10 mm diameter by 260 mm length) and determined for skin and shaft separately the ratio R_t/R_s for various pile velocities and soil types (Litkouhi, Poskitt 1980). The author's then used the Gibson-Coyle approach and calculated both for skin and toe the parameter J_T and exponent 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 just before full static resistance activation and also later during unloading (or pile rebounding). For a quantitative evaluation of this difference, three comparison runs were performed (Table 1). They included a large offshore steel pipe (75 m long, 1830 mm diameter and 50 mm wall thickness), and both a small (275 mm square, 15 m long) and a large (900 mm square, 15 m long) concrete pile. As per the GRLWEAP recommendations, the quakes were all set to 2.5 mm except the toe quake for the large concrete pile which was the recommended 900/120 = 7.5 mm. Since the large quake caused a relatively slow increase of R_s, 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 1. Input details of Case study

Case	Pile Type	Area m2	Length m	Hammer	Quakes Skin/Toe mm
1	72"Pipe	0.2750	75	MHU 1700	2.5/2.5
2	275mmPC	0.0756	15	5-ton drop	2.5/2.5
3	30"PSC	0.8100	15	D 62-22	2.5/7.5

"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 result. 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 2, for example, shows calculated pile top velocities from analyses according to both Equations 1.b and 3.b. Figure 2 also includes damping forces as a function of time. These forces are the sum of all skin and toe damping values. The usually observed dampened behavior of the pile top velocity is obviously better represented by the Smith-2 analysis. For this reason, CAPWAP 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 best modeled with slowly increasing damping factors until the full static resistance has been activated. 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 since the maximum activated resistance force, R_a, which has exactly these properties may be used as a multiplier instead of R_s or R_u.

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,

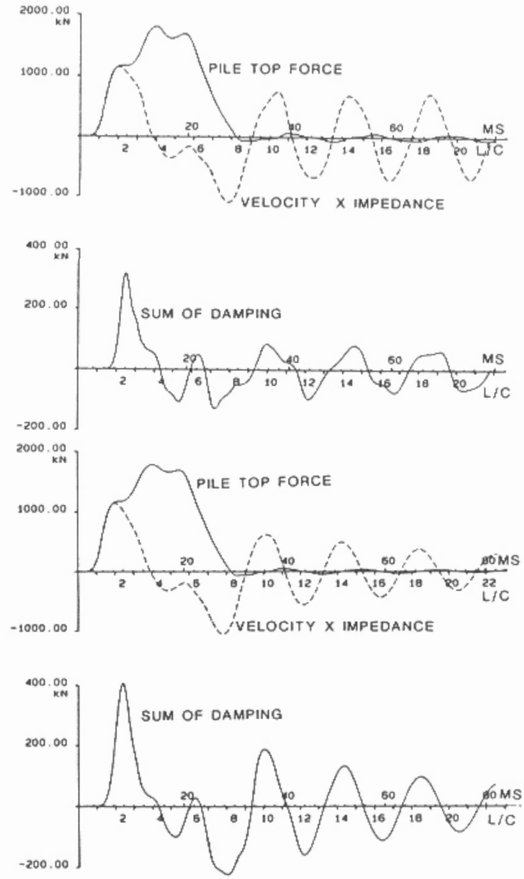

Fig. 2 Velocity force and damping forces over time for Smith-1 (top) and Smith-2 damping approach.

i.e., when the velocity was highest. However, under a hammer blow the velocity of a particular point along the pile increases to a maximum during a time period of several milliseconds, then relatively slowly decreases to smaller values and finally becomes negative during rebound. However, both before and after a pile segment reaches maximum velocity, the functional relationship between velocity and damping force was not determined by the experiments. Thus, it may be argued that the maximum damping force and associated maximum velocity define Gibson's damping factor, J_T. Under such circumstances, equivalent Smith damping factors can be calculated for maximum velocities which differ from a reference maximum velocity. Assuming that the reference maximum velocity is 3 m/s, the multipliers for equivalent Smith damping factors can be found in Figure 3. For example, if the maximum pile velocity is 1 m/s, the Smith factor should be approximately 2.4 times greater than normally assumed. Figure 3 may be helpful when determining standard Smith damping factors (for "normal" pile driving situations) from tests with very low (refusal situations) or high velocities (hammers with large drop heights). It also shows that the standard Smith damping factors could yield highly inaccurate results at very low maximum velocities.

Table 2. Comparison of GRLWEAP damping approaches with standard Smith damping results

Case/ Model	Damping Skin/Toe s/m	Capacity at 150 B/m kN	Diff. %	Capacity at 300B/m kN	Diff. %	Max. Tension Stress MPa	Diff. %	Max. Compres. Stress MPa	Diff. %
1/Smith 1	.6/.165	36400		43500		71.0		268	
1/Smith 2	.54/.15	36700	0.8	43600	0.2	76.0	7.0	270	0.7
1/Gibson (N=.18)	1.25/1.25	29250	-19.6	33500	-23.0	109.0	53.5	269	0.4
1/Gibson/GRL (N=.20)	1.25/1.25	39700	9.1	42600	-2.1	113.0	59.2	263	-1.9
1/Gibson/GRL (N=.18)	1.25/1.25	40000	9.9	42900	-1.4	115.0	62.0	263	-1.9
2/Smith 1	.165/.5	1390		1610		7.2		25.9	
2/Smith 2	.15/.45	1410	1.4	1620	0.6	7.0	-2.8	26.4	1.9
2/Gibson	.65/.65	980	-29.5	1170	-27.3	4.5	-37.5	26.0	0.4
2/Gibson/GRL	.65/.65	1370	-1.4	1560	-3.1	5.9	-18.1	25.3	-2.3
3/Smith 1	.165/.5	2600		3460		6.2		10.5	
3/Smith 2	.15/.45	2430	-6.5	3260	-5.8	6.2	0.0	10.5	0.0
3/Gibson	.65/.65	1660	-36.2	2400	-30.6	6.6	6.5	11.1	5.7
3/Gibson/GRL	.65/.65	2300	-11.5	3150	-9.0	6.4	3.2	10.6	1.0

Gibson and Coyle's equation cannot be used directly to calculate damping forces for all times during a hammer blow. Modifications must be made to Equation 2 to (a) assure velocity opposing damping forces and (b) avoid mathematically undefined values. A usable equation would read:

$$R_t = R_s + |R_s| J_T |v|^N \{v/|v|\}. \qquad (5.a)$$

The factor in {} is merely the sign of velocity v. Equation (5.a) is the "Smith-3" or Gibson option in GRLWEAP. As will be shown, it does not yield satisfactory results (Figure 4.a). Obviously, the Gibson approach needs further modifications before the power law approach can become useful. First the R_s multiplier in (5.a) was replaced by R_a as proposed earlier in this paper. Then the velocity, v, in the power term was replaced by v_x which is the maximum velocity having occurred prior to or at the time during a hammer blow at which R_t is calculated. Equation (5.a) then becomes

$$R_t = R_s + R_a J_W v_x^N \{v/v_x\} \qquad (5.b)$$

The temporary maximum velocity, v_x, is increasing before and constant after the absolute maximum velocity has been reached. It is never negative or decreasing which is an important feature as will be shown. Furthermore, since v_x is constant throughout most of the analyzed time (it is

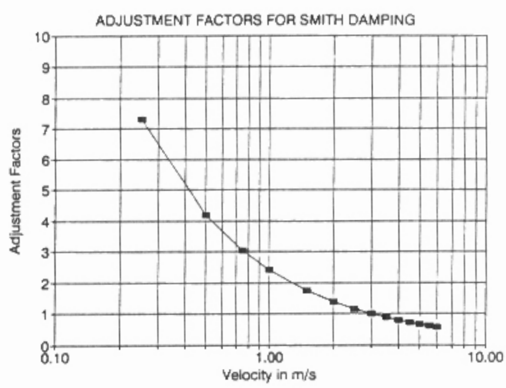

Fig. 3 Multipliers for conversion of Gibson to Smith-1 damping factors.

constant after the peak velocity is reached), a nearly linearly viscous approach results. Obviously, at the instant when maximum velocity is reached $R_d = J_T R_a v_x^N$ (since $v = v_x$) as exactly recommended by Gibson and Coyle. For ease of reference Equation (5.b) will be referred to as the Gibson/GRL method; it is the Smith-4 method in GRLWEAP. Both methods have been used to reanalyze the examples

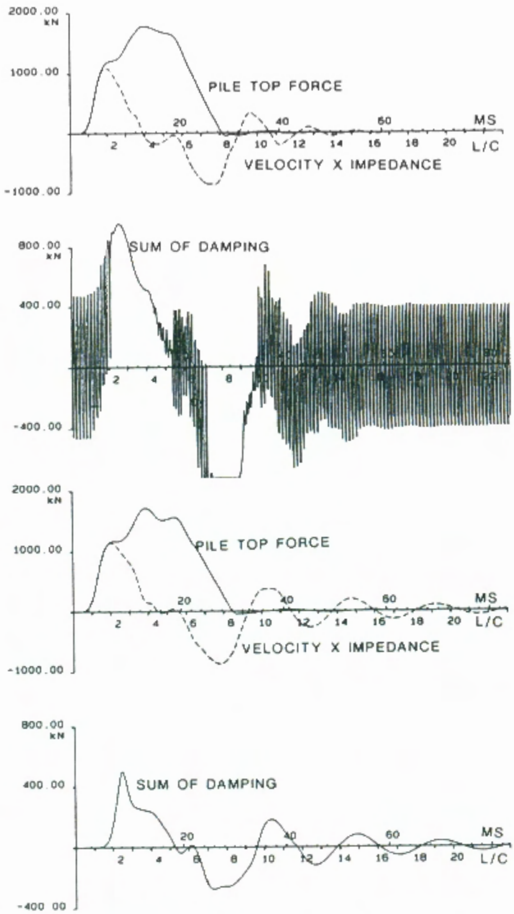

Fig. 4 Velocities, forces at pile top and damping forces as a function of time for Gibson and Gibson-GRL damping approaches.

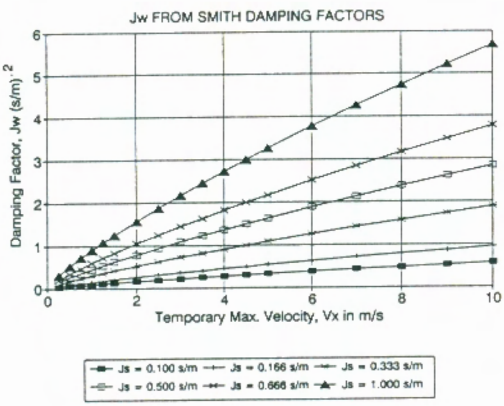

Fig. 5 Conversion of Smith to GRL damping factors.

discussed previously. Results were again entered in Table 2. The Gibson, J_T, and Gibson/GRL (WEAP), J_W, damping factors were used identically for skin and toe with 0.65 and 1.25 $(s/m)^N$ and the exponent N with 0.18 as for clay. These values correspond to recommendations contained in the literature. Two comparison analyses were also run for the same situation and N = 0.20 and 0.18 using the new approach. It can be concluded that, for practical purposes, there are no significant differences between these two exponents and N = 0.20 is sufficiently accurate.

Table 2 indicates that Gibson's method yields very low capacities compared to the standard Smith approach which is attributed to very high damping at low velocities both before and after maximum velocity (Figure 4.a). On the other hand, the new Gibson/GRL approach yields very reasonable results. Furthermore, while Gibson's damping force versus time relationship includes high frequency variations whenever the velocity approaches zero, Equation (5.b) produces a smooth and realistically dampened 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-1 to Gibson/GRL damping factors with N = 0.2 and including a 10% correction for the R_a to R_s conversion. The Figure gives corrections for various commonly encountered Smith-1 damping factors. For example, for clay one normally uses 0.67 s/m as a skin damping factor. For this Smith value Figure 5 suggests 1.44 $[(s/m)^{0.2}]$ for J_{GRL} at v_x = 3 m/s. For a high velocity v_x = 5 m/s, J_W would be 2.17 $[(s/m)^{0.2}]$. These conversions would approximately yield the same results from Smith-1 and Gibson/GRL. However, the purpose of using the new method would be to obtain valid results over the whole range of possible v_x values. It would, therefore, be reasonable to assume that Smith-1 provides relatively reliable results for an average velocity maximum of say v_x = 3 m/s, find the corresponding J_W damping factor for this velocity and the soil type, and use that factor for all other, high or low velocity situations.

6 SUMMARY

A new damping method has been developed and included in GRLWEAP. It has the advantage of

1. yielding results in good agreement with the Smith approach which has been well correlated for a standard situation such as the ones analyzed,

2. producing a well dampened pile top behavior over long analysis 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 of wave equation and CAPWAP correlations with laboratory measured values. It appears that the approach can be directly used, even without additional experimental work. To accomplish this, the current standard Smith damping factors may be easily converted to the Smith-4 or WEAP J_W factors for any appropriately chosen reference velocity, e.g., V_X = 3 m/s (see also Figure 5).

4. The study also indicated that under normal circumstances Smith-1 damping factors may be replaced by Smith-2 values with a 10% decrease.

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