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Evaluating rate effects using high and low energy blows for a pipe pile in clay

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ABSTRACT: There are still uncertainties in models for assessing rate effects on soil resistance in SRD models. One technique to assess these models is to perform signal matching of blows during driving at two, significantly different, energy levels. Pile Driving Analyzer (PDA) data were obtained from several test piles at a clay site in Fargo, ND, USA. The piles, of diameter 0.61 m and wall thickness 19 mm were driven approximately 12 m through glacial lake clays and an additional 3 m into glacial till. At the end of driving into the glacial till, and also during restrike of some piles, blows with hammer impact energies ranging between approximately 80 kNm and 20 kNm were recorded, allowing for assessment of rate effects at similar times during driving. Signal matching analyses are presented using both Smith and continuum soil models at multiple energy levels for two of the test piles. The results provide insight not only into rate effects for blows with different maximum velocities, but also into the relative magnitudes of driving resistance estimated using the two different models for dynamic pile-soil interaction.

Keywords: PDA, clay, stress wave

1 INTRODUCTION

Assessment of pile drivability and back analysis of stress-wave data from dynamic tests on piles is generally conducted using one-dimensional models of the pile together with dynamic interaction models between pile and soil. These endeavour to capture the velocity dependency of the pile-soil resistance that arises from inertial effects and the viscous nature of most soils.

The most widespread pile-soil interaction model is the simple Smith model (Smith, 1960), which adopts a linear dependency of resistance on the pile velocity resulting from viscosity. Alternatively, a continuum model for pile-soil interaction may be adopted, capturing radiation damping due to the soil inertia (Novak et al., 1978; Lysmer and Richart, 1966; Randolph, 2000). Following failure, viscous enhancement of the shaft friction can be included.

The rate dependency of pile-soil interaction forces is difficult to assess with confidence. For the Smith model, viscous damping parameters for drivability assessment are based on experience, with typical values ranging from about 0.3 to 0.6 s/m. For back-analysis of stress-wave data from dynamic load tests, quake and damping values for the Smith model are generally optimised within the analysis software, which may lead to values outside the normal range.

For the continuum model, while the radiation damping component is derived scientifically in terms of the soil shear modulus and density, the viscous enhancement is still entirely empirical, generally using a relationship that varies non-linearly with the relative pile-soil velocity.

This paper presents data from dynamic tests conducted both at the end of driving (EoD) and during restrike (Rst) tests. Unusually, the tests were conducted at varying hammer energy levels and so offer the potential to explore dynamic pile-soil interaction values in more detail. The tests have been analysed with both CAPWAP (Rausche et al., 2010; PDI, 2014), using the Smith model, and IMPACT (Doherty et al., 2022; Randolph and Doherty, 2024), using the continuum model.

2 SOIL CHARACTERISATION

Data used in this paper are from the Wild Rice River Structure (WRRS), part of the Fargo-Moorhead Metropolitan Area Flood Risk Management Project (FMM Project). Pile driving at the site typically consisted of H-piles; however, open ended pipe piles were used to support six approach walls leading to the flood control structure. The location of the approach walls and soil investigations in the area of the structure are shown in Figure 1.

The original ground surface was approximately at elevation 278 m. Soils were excavated for construction of the control structure to approximately El. 268 m. The excavated ground surface for monoliths A1 and A4 was approxiamtely elevation 268m and was elevation 269 m for monoliths A3 and A6.

Subsurface stratigraphy consisted of (i) Sherack Formation; (ii) Brenna Formation; (iii) Argusville Formation; and (iv) Till. A CPT profile at the site is shown in Figure 2. Soils above the Till are generally high plasticity glacio-lacustrine Lake Agassiz clays, with a liquid limit (LL) between 50 and 100. The Till – Lake clay boundary was at approxiamtely elevation 256 m for the CPT shown, but varied by ±1.5 m across the site.

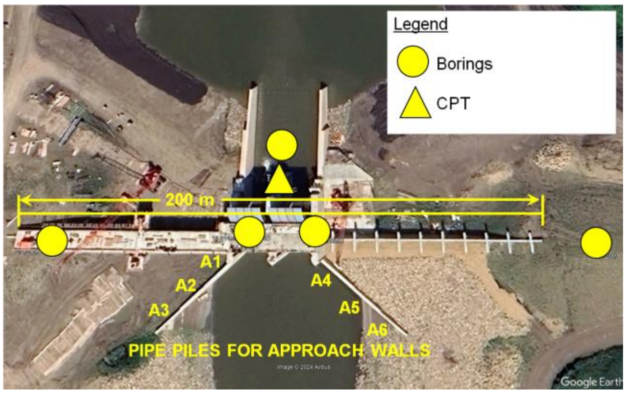

Figure 1. Location of investigation relative to approach walls (A1 through A6) for the WRRS

Pipe piles were generally tipped in the Clayey Till, which had a fines content of approximately 40% and existed to an elevation of approximately 251 m. Below elevation 251 m, the fines content dropped to approximately 20%. The Till consisted of approximately 1.5 m of 'weathered' lower resistance till, overlying stronger clayey Till. The weathered till had a LL of 35, a PI of 18, and CPT tip resistance on the order of 5 to 10 MPa. The underlying Till tended to have a LL of 17, and PI of 4, with CPTs typically meeting refusal at a tip resistance of approximately 45 MPa shortly after entering this unit, generally due to excessive rate of inclination of the cone.

Estimates of soil stiffness were made from pressuremeter and dilatometer data in the area. Lake clays had a pressuremeter unload-reload shear modulus of approximately 10 MPa, increasing to approximately 400 MPa in the Till soils. Shear modulus estimated from the Dilatometer was 3 MPa in the Lake clays, but the DMT met refusal at the top of the Till layers.

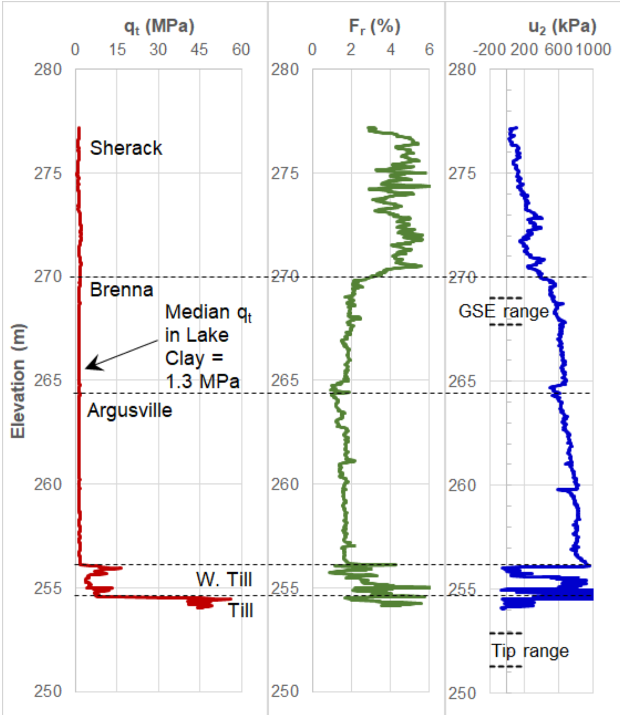

Figure 2. CPT profile at Wild Rice River Structure

3 MEASURED PILE BEHAVIOUR

3.1 Pile Properties

The open-ended piles used for the approach walls were 0.61 m diameter with wall thickness of 19 mm. Young's modulus and density were assessed as 207,000 MPa and 7.88 Mg/m^3 respectively, giving a wave speed of 5,123 m/s.

Ten of the piles were monitored with a pile driving analyzer (PDA) during initial driving. A PDA restrike was performed at 7 days after driving on one of the piles that was monitored during initial driving. At final penetration into the Till, transmitted hammer energy generally ranged between 50 and 80 kN/m, with sets of 5 to 9 mm. Essentially, all piles drove in a relatively similar manner and with similar final elevations in the Till, but rather deeper than the elevation of CPT refusal shown in Figure 2.

Here, attention is focused on two of the piles, A1.2.1G and A4.1.1G, for which dynamic tests were conducted at transmitted energies ranging from around 20 to 80 kNm. Results from end of drive tests are reported for both piles, while results from four restrike tests are reported for pile A4.1.1G.

3.2 Overview of Dynamic Test Responses

Table 1 summarises the eight dynamic tests considered here. Identifiers of EoD (end of drive) and Rst (restrike) are used, together with qualifiers that indicate the energy level (low, medium and high) and, for the restrike tests, the blow number.

Table 1. Summary of eight dynamic tests back-analysed

Pile number	Test identifier	Transmitted energy kNm	Measured final disp. mm
A1-2-1G	EoD HE	83.4	5.2
	EoD ME	31.2	0.45
A4-1-1G	EoD HE	73.8	8.9
	EoD ME	29	0.7
	Rst 1 ME	32.3	1.1
	Rst 2 HE	78.6	4.1
	Rst 20 HE	79.3	5.2
	Rst 23 LE	22.2	0.4

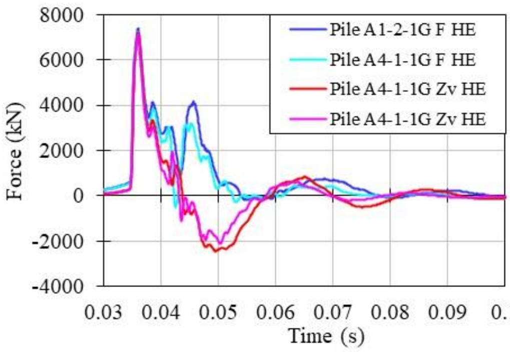

Figure 3. Force and factored velocity responses for high energy tests at end of drive

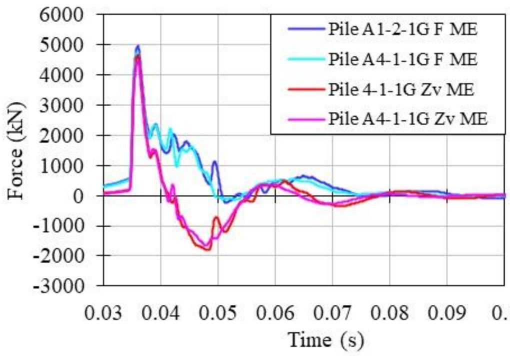

Figure 4. Force and factored velocity responses for medium energy EoD tests

Figure 3 and Figure 4 respectively show the measured force (F) and factored velocity (Zv) stress waves for the higher energy and medium energy tests at end of drive, where Z is the pile impedance (1,424 kNs/m). The stress waves for the two different piles are very consistent.

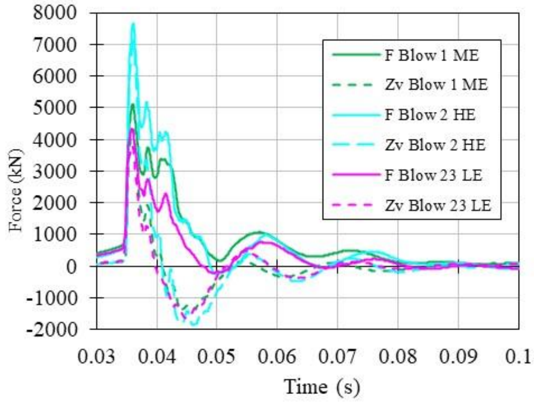

Figure 5. Force and factored velocity responses for restrike tests on Pile A4.1.1G at different energy levels

Figure 5 shows corresponding stress waves for restrike tests on Pile A4.1.1G at three different energy levels. The peak forces and velocities decrease as expected with decreasing transmitted energy. For context, the peak velocities range between 2.67 m/s for the lowest energy, to 5.19 m/s for the highest energy.

4 PDA ANALYSIS

4.1 Modelling Rate Effects

Although rate effects are modelled slightly differently in CAPWAP and IMPACT, the basic principles are illustrated in Figure 6.

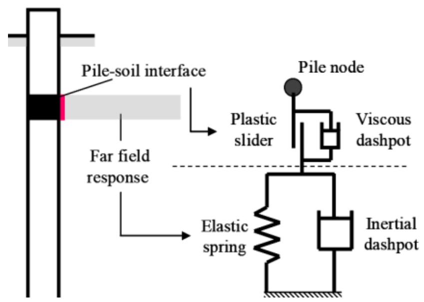

Figure 6. Model for dynamic pile–soil interaction along shaft

IMPACT distinguishes between the pile-soil interface where plastic shearing takes place and the limiting static friction τ_s is enhanced by viscosity to give a dynamic friction τ_d, as shown in Equation (1). The viscosity is controlled by two parameters α and β as shown, with Δv being the relative pile-soil shear velocity and v_{ref} is a reference velocity taken as 1 m/s.

$$\tau_d = \tau_s \left[1 + \alpha \left(\frac{\Delta v}{v_{ref}} \right)^{\beta} \right] \qquad (1)$$

Prior to yield, the resistance is determined by the far-field response with an inertial dashpot acting in parallel with an elastic spring. The spring and dashpot magnitudes are expressed in terms of the soil shear modulus and density together with the pile diameter (IMPACT, 2024). For open-ended piles IMPACT can model the pile-soil interaction along the soil plug independently of the external interaction, but to aid comparisons here, the soil plug resistance was set to a very low value.

In CAPWAP, no distinction is made between the pile-soil interface and the far-field response, but alternative approaches may be chosen to differentiate between pre- and post-failure responses. Traditionally, for the Smith model, the interaction model comprises a spring and plastic slider in series, in parallel with a single dashpot. The shaft resistance per unit length T_d is then given by

$$T_d = Min\left(1, \frac{w}{Q}\right)\left(1 + Jv^n\right)T_s \qquad (2)$$

where w is the pile displacement, Q is the quake, i.e. the distance to mobilise the static resistance T_s, and J is the Smith damping factor. The power n must be taken as unity in CAPWAP.

4.2 Analysis Approach

The approach taken to analyse the dynamic tests was to first fit the stress-wave data using IMPACT. Two sets of CAPWAP analyses were performed; (i) one based on the distributions of soil resistance used in IMPACT; and (ii) where the automated algorithms within CAPWAP were used to adjust the shaft friction and end bearing resistance to optimize the match score. When using the auto quality improvement features within CAPWAP, only the quake and damping parameters were modified for the first CAPWAP model, although for blows of medium or low energy it was also necessary to reduce the base resistance to achieve lower (i.e. improved) match scores. For the second, automated, CAPWAP model resistances, quake and damping were optimized.

In the figures presented below, the first type of CAPWAP analysis is referred to as CAPWAP (IMPACT), while the second, unconstrained, analysis is referred to simply as CAPWAP.

In IMPACT, the dynamic response has been analysed using shear modulus G values of 200 times the local limiting shaft friction and 30 times the limiting unit tip resistance (with one exception, for the first restrike blow on pile A4.1.1G, where the ratio was taken as 20). The IMPACT viscous resistance parameters of α = 0.5 and β = 0.2 were used in all analyses.

In CAPWAP, the quake and damping values were optimised in order to obtain the best fit. The resulting values are summarised in Table 2.

4.3 Results of Analyses

Table 3 summarises the shaft, tip and total resistances deduced using IMPACT and CAPWAP, with the latter analyses conducted either forcing the same resistance profile as in IMPACT or with unconstrained (Auto) fitting. The quality of the fits is reflected in the SWIFT parameter for IMPACT (see IMPACT, 2024) or the Match Q parameter for CAPWAP. High quality fits are represented by SWIFT parameters of 80% or higher or Match Q values of less than 3.

For the high energy blows, it seems that the balance between shaft and tip resistance is similar for IMPACT and CAPWAP analyses of the EoD tests, but for the restrike tests IMPACT has a much greater weighting towards shaft resistance. IMPACT consistently gives greater total resistance although, for the HE tests, the difference is only about 10% for the EoD tests but larger for the restrike tests (especially for test 2 HE).

In the figures 7 through 10, the first type of CAPWAP analysis is referred to as CAPWAP (IMPACT), while the second, unconstrained, analysis is referred to simply as CAPWAP. The range of quake and damping values in Table 2 are quite large. There is some consitency between the CAPWAP (IMPACT) and unrestrained CAPWAP analyses, but large differences between HE and ME blows. These large differences in parameters is unexpected, since the soil conditions did not change between blows. Some similar relative values of quake and damping were observed for HE and LE restrikes values, however, the values were not entirely consistent with the implications of the EoD analyses.

Figure 7 and Figure 8 show contrasting comparisons for the HE and ME EoD tests on pile A1.2.1G. For the HE test, the unrestrained CAPWAP resistance is similar to that from IMPACT (4% difference). By contrast the unrestrained CAPWAP resistance for the ME test is only 63% of that from IMPACT and the CAPWAP analysis based on the IMPACT resistance profile shows a signficant negative reduction at the time of reflection from the pile tip.

Table 2 Deduced CAPWAP quake and damping values

Pile number	Test identifier	IMPACT fit Q_{shaft} mm	IMPACT fit Q_{tip} mm	IMPACT fit J_{shaft} s/m	IMPACT fit J_{tip} s/m	Auto fit Q_{shaft} mm	Auto fit Q_{tip} mm	Auto fit J_{shaft} s/m	Auto fit J_{tip} s/m
A1-2-1G	EoD HE	1.63	9.81	0.35	0.11	1.66	9.61	0.43	0.21
	EoD ME	4.95	4.85	1.08	0.46	3.48	4.74	0.61	0.66
A4-1-1G	EoD HE	1.00	6.41	0.08	0.14	1.53	10.33	0.15	0.27
	EoD ME	5.00	5.00	1.30	0.87	5.36	5.46	1.10	0.64
Restrikes	Rst 1 ME	1.00	1.00	0.78	0.11	1.00	3.00	1.56	1.37
	Rst 2 HE	1.65	5.00	0.47	0.08	2.20	7.11	0.32	1.13
	Rst 20 HE	1.00	5.10	0.36	0.09	1.08	6.69	0.72	0.11
	Rst 23 LE	2.00	2.00	0.52	0.10	2.78	2.46	1.31	1.43

Table 3 Summary of resistances and qualifiers from IMPACT (IMP) and CAPWAP (CAP) analyses

Pile number	Test ident.	IMP R_{shaft} kN	IMP R_{tip} kN	IMP R_{total} kN	IMP SWIFT %	CAP (IMP) R_{total}# kN	CAP (IMP) *Match Q*	CAP (Auto) R_{shaft} kN	CAP (Auto) R_{tip} kN	CAP (Auto) R_{total} kN	CAP (Auto) *Match Q*
A1-2-1G	EoD HE	2238	2822	5060	85.2	5060	3.02	1846	3035	4881	2.46
	EoD ME	2238	2822	5060	82.6	3138#	3.43	1560	1624	3184	2.81
A4-1-1G	EoD HE	1964	2822	4786	86.4	4786	5.48	1913	2113	4026	3.44
	EoD ME	1964	2822	4786	79.5	2764#	3.10	1437	1280	2717	3.10
Restrikes	1 ME	5003	564	5568	90.9	5553#	4.78	1878	835	2713	2.16
	2 HE	5003	762	5765	82	5765	5.70	2054	1724	3778	2.91
	20 HE	4670	762	5432	86.6	5235#	4.61	2063	2556	4620	2.33
	23 LE	4344	621	4965	85.3	4965	5.82	1593	1187	2780	2.45

Reduced tip resistance compared with IMPACT but same shaft resistance profile

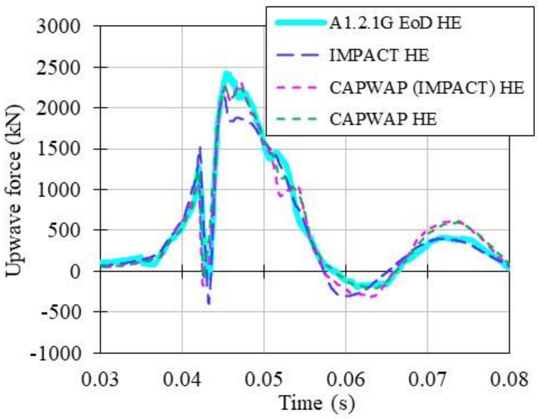

Figure 7. Comparison of upwave fits: A1.2.1G EoD HE

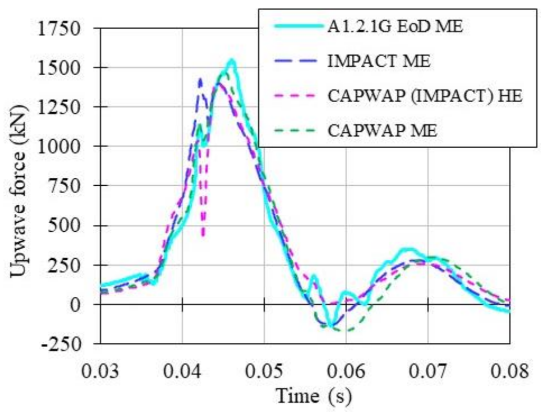

Figure 8. Comparison of upwave fits: A1.2.1G EoD ME

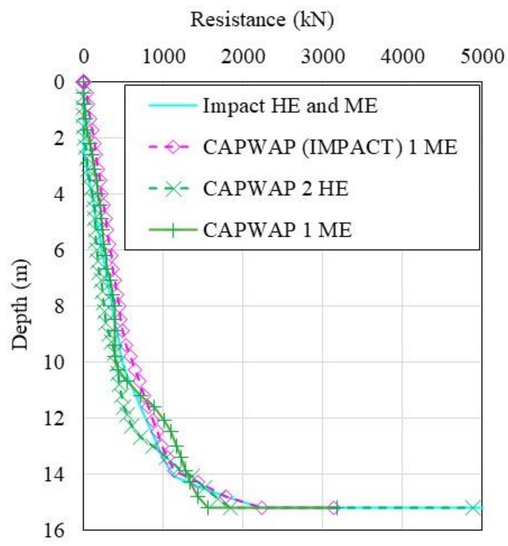

Figure 9. Comparison of resistance profiles: A1.2.1G EoD

These differences are highlighted in the profiles shown on Figure 9. The two unrestrained CAPWAP fits show slightly unexpected profiles, but overall with somewhat lower shaft resistance. For the HE test, the tip resistance is higher, while for the ME test the CAPWAP tip (and total) resistance is significantly lower than from IMPACT.

A possible explanation for the lower mobilised resistance for the ME tests for both piles lies in the more rapid mobilisation of resistance in IMPACT due to inertial effects, i.e. radiation damping. That leads to mobilisation of both shaft and base resistances in less than 1 mm for these piles. By contrast, the CAPWAP fits have very high quake values (see Table 2), with a strong trend for higher tip quakes the higher the transmitted energy.

For the restrike tests on Pile A4.1.1G, the upwave fits to the second blow, 2 HE, are shown in Figure 10. The IMPACT fits showed more than double the shaft resistance compared to that at the end of driving, but the increase in shaft resistance was much less from the unrestrained CAPWAP analyses (Table 3).

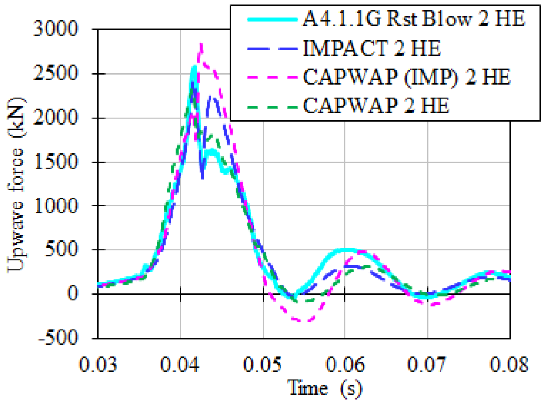

Figure 10. Comparison of upwave fits: A4.1.1G Rst 2 HE

The higher total resistance mobilised in IMPACT, when adopted in CAPWAP, leads to a characteristic overshoot of the peak upwave. As previously noted for EoD conditions, the deduced tip quake values show a trend of higher values for the higher energy tests (2 HE and 20 HE) compared with medium or low energy tests.

5 CONCLUSIONS

The dynamic load tests presented here have allowed rate effects to be explored by considering impact blows with different transmitted energy, hence different velocity levels. Two different software (IMPACT and CAPWAP) were used, with pile-soil interaction models based respectively on a continuum model of the soil or the traditional Smith model.

Large differences in quake and damping values for each CAPWAP analysis resulted, which, while leading to improved fits, were not a result of changes in soil conditions. This highlights limitations of the interaction model, with a tendency to overfit waveforms using standard CAPWAP procedures.

Overall, the study revealed significant differences in the mobilised soil resistance estimated from the two approaches, particularly for blows with moderate or low energy. The balance between shaft and total resistance was relatively similar for end of driving conditions for each software. However, for the restrike tests IMPACT gave a much higher proportion of shaft friction compared to CAPWAP.

Overall, the authors consider that the modelling of radiation damping and viscous rate effects in IMPACT is more scientific than the damping factors incorporated in CAPWAP. The greater resistance mobilised by IMPACT for low energy tests arises from more rapid mobilisation compared with the quake values in CAPWAP, but this needs further validation, perhaps through dynamic FE analysis.

AUTHOR CONTRIBUTION STATEMENT

Lead Author: Data curation, IMPACT analyses, First draft and editing text. **USACE Author**: Data procurement and curation, CAPWAP analyses, reviewing, editing text. **2nd UWA Author**: Software development (IMPACT), reviewing, editing of text.

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