# IMPACT: cloud-based software for stress-wave and drivability analysis of driven piles

James P. Doherty[i], Mark F. Randolph [ii] and James A. Schneider [iii]

i) Associate Professor, School of Engineering, Civil, Environmental and Mining Engineering

UWA Oceans Institute, The University of Western Australia, Crawley, Western Australia, Australia.

ii) Senior Honorary Fellow, UWA Oceans Institute, The University of Western Australia, Crawley, Western Australia, Australia.

iii) Civil Engineer, US Army Corps of Engineers, St. Paul, Minnesota, USA



## ABSTRACT

The dynamic analysis software, IMPACT, was originally developed some 30 years ago for drivability assessment and stress-wave matching of driven piles. The software has recently been launched as a web-based application, which brings major advantages in terms of speed of analysis and the potential to run the app remotely in batch mode from appropriate code. Dynamic pile-soil interaction is implemented using a continuum approach, although the traditional Smith models are retained as an option, with the internal soil plug treated independently from the external soil. Pile-soil interaction parameters may be derived from CPT data, either from in-built published recommendations or from user-input algebraic expressions for a range of different soil behaviour types. For drivability analysis, friction degradation is allowed for automatically using in-built or user-supplied relationships. The paper illustrates application of the web-app to an example field study, showing how measurements of hammer energy and blowcount data may be combined with intermittent stress-wave analysis of specific blows in order to refine pile-soil interaction parameters and their relation to CPT data.

**Keywords:** pile driving analysis, stress-wave matching

## 1 INTRODUCTION

The dynamic analysis software IMPACT has recently been launched as a web-based application, bringing major advantages in terms of accessibility and speed of (parallel) computations. The software uses a continuum model for the soil, with shear modulus and soil density used instead of the Smith model quake and damping parameters. The Smith model is also included as an alternative though. Initial estimates of pile-soil interaction parameters may be derived from CPT data using (user-modifiable) published correlations. For drivability studies, friction degradation is automatically taken into account.

The paper first discusses the cloud architecture used to develop the IMPACT web-based application, followed by a discussion of the algorithm used to quantify the quality of fit for stress wave matching. CPT based drivability analysis and stress wave matching features of the application are illustrated with a case history of driving a closed ended pile through lake clays into glacial till.

## 2 IMPACT CLOUD ARCHITECTURE

IMPACT is a loosely coupled scalable web based applications that runs on Amazon Web Services. The web interface is hosted on a regular virtual web server (EC2). However, the core IMPACT calculation algorithm is run on AWS as a Lambda function. AWS Lambda is a serverless compute platform, which creates and runs an instance of the IMPACT function in response to each calculation request. There is no practical limit to the number of parallel simulations Lambda can run. Within the IMPACT web interface, users can submit up to 150 calculation sequences. For example, because IMPACT has a built in SRD algorithm, multiple pile depths can be analysed in a single run. For each depth, the web server creates separate input files that trigger independent Lambda functions. Therefore all depths are analysed in parallel. This results in significant speed up of the calculation time. For example, a single IMPACT simulation may take 20 seconds. If 100 depths were run in series, this would take over 30 minutes to compute. With the IMPACT cloud architecture, each Lambda function takes around 0.5 seconds to trigger in series. Therefore, the simulation for the 100th depth would start around 50 seconds after the first depth and all calculations would be complete 20 seconds after this. Therefore, more than 30 minutes of calculations can be completed in just over 1 minute.

To further exploit this architecture, an application programming interface (API) has been made available. This allows users to 'script' simulations with IMPACT while achieving the same computational speed up generated on the web interface. With reference to Figure 1:

1. Users create or modify an IMPACT input file on a PC and upload the file to an S3 bucket using the AWS Software Development Kit (SDK) (available for common programming languages, including Python).
2. The input file is save with a postfix ".json".
3. An S3 event then automatically triggers a Lambda function which reads the file and runs a simulation.
4. Results are saved to output files back to the S3 bucket.

This API interface is likely to be useful for parametric studies or Monte Carlo simulations. For stress wave matching studies, the IMPACT output file includes a measure of the match between the input signal and the calculated response (SWIFT) which is suitable for use as objective function in optimisation algorithms. Program workflow and soil resistance to driving (SRD) calculations are discussed by Doherty et al. (2020).

## 3 STRESS-WAVE MATCHING USING SWIFT

The Stress Wave Impact FiT (SWIFT) function was developed to assess the quality of signal matching of stress waves at a given depth. It is broadly similar in concept to the CAPWAP match score, although is based on a scale of 0 to 100 with 100 being a perfect match and has a different weighting when assessing the match quality.

At present the SWIFT weighting is a function of normalized time t/(2L/c), which avoids limiting the match to 25 ms after the return time. This may prove problematic, since the match score depends slightly on pile length and type. However, for offshore piles the stress wave perturbations can continue for a long time and the match weighting needs to extend far enough to capture the soil response near the base of the pile.

An example IMPACT SWIFT weighting function is shown in Figure 2, combining a sinusoid with an exponential function. The corresponding CAPWAP weighting function (GRL, 2013) is shown for comparison, scaled to give a maximum weighting of unity. This particular example was for a pile of length 17.1 m below the stress wave measurement instrumentation, with a return time of 2L/c = 6.67 ms.

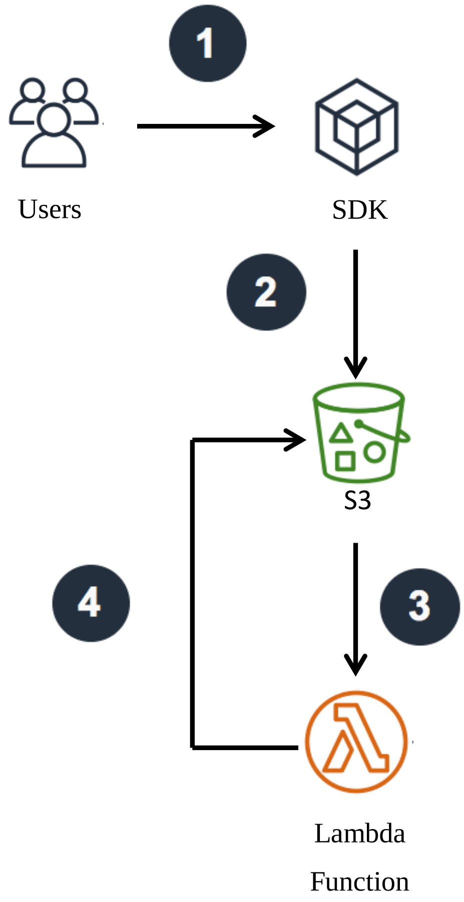


Fig. 1. IMPACT cloud architecture

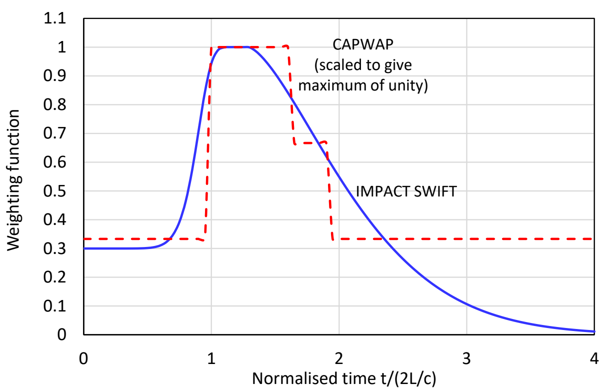


Fig. 2. Comparison of weighting functions for SWIFT and CAPWAP match score

## 4 CASE HISTORY, FARGO, ND

Data discussed in this paper were collected as part of a pile test program performed in 2012 in Fargo, ND, USA. The site is 10 km east-southeast of a second load test site where driving of 0.61 m diameter open ended piles is discussed by Schneider et al. (2022).

The sites consist of approximately 18 m of lake clays underlain by clayey glacial till. Site characterization included piezocone penetration tests (CPTU), pre-bored pressuremeter tests (PMT), standard borings and index testing, as well as laboratory triaxial and oedometer tests. Cone penetration testing near the test piles discussed in this paper met refusal at the top of the till. Scaled measurements from the CPT data in the till discussed by Schneider et al. (2022) were therefore used in these analyses. The median PMT limit pressure and un-load reload stiffness in the till were both 1.6 times higher at the site discussed by Schneider et al. (2022) as compared with those at the site in this paper. The available CPT tip resistance and sleeve friction was therefore reduced by a factor of 1.6 for applicability to pile drivability below 19.4 m in this paper. The CPT profile used in the analysis is shown in Figure 3.

Three piles, 219 mm in diameter with a 16 mm wall thickness, were driven with a Delmag D30-32 diesel hammer. The piles were closed ended, with a flat pate welded at the tip. TP-2 was driven to a depth of 21.5 m with PDA monitoring. TP-8 was driven to a depth of 22.8 m with PDA monitoring, and a dynamic restrike was performed 26 days after initial driving. TP-4 was driven to a depth of 22.4 m without PDA monitoring.

### 4.1 Drivability Analysis

The cone penetration test (CPT) based Alm & Hamre (2001) pile drivability method was used for the analysis. Hammer efficiency was varied with depth in the IMPACT sequence options from 0.375 to 0.5 to match PDA energy measurements. Measured blowcount, hammer efficiency, and calculated blowcounts are shown in Figure 4. The agreement is reasonable, but calculated blow counts slightly overestimate the measured. The reasons for this are explored in more detail using the signal matching options within the application.

### 4.2 Signal Matching for End of Driving

The drivability analysis showed a reasonable match to blowcounts using the input CPT profile and Alm & Hamre (2001) drivability method. Following up this analysis with more detailed signal matching can provide additional insight into the factors influencing the soil resistance to driving. The quality of the SRD profile is quantified in the signal matching process using the SWIFT function, described in Section 3.

The IMPACT web-based application allows for linear changes to seven parameters that dominate SRD calculations. The five parameters relevant to driving closed ended piles are shown in the first five columns of Table 1. It is noted that for signal matching analyses the hammer efficiency is kept at unity, as the downward travelling stress wave is used as the input to the matching analysis, and should not be scaled. For open ended piles, plug length and plug resistance are also scalable.

Table 1 summarises how the SWIFT factor changes due to changes in (i) residual base stress; (ii) base resistance; and (iii) shaft resistance. The best fit occurred by multiplying the Alm & Hamre shaft friction by a factor of 0.85. For this case of a relatively slender pile, L/D = 104, in a predominantly clayey soil, adjustments to residual base stress or end bearing had only a small effect on the overall fit.

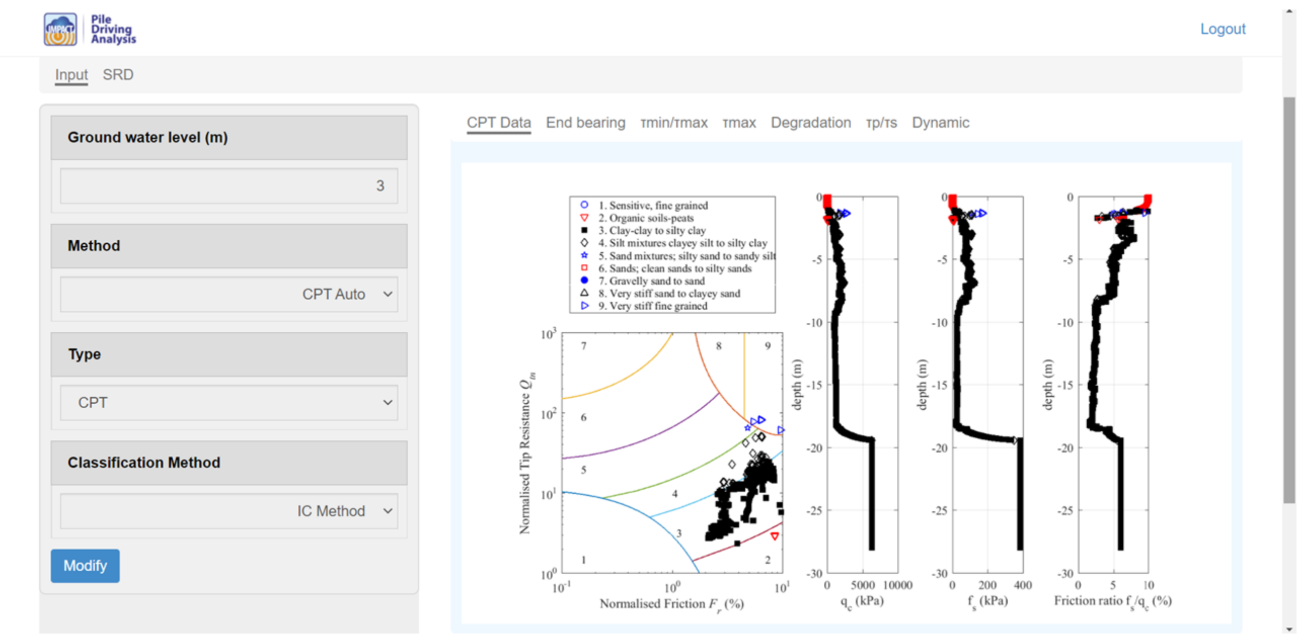


Fig. 3. Impact CPT profile and Soil Behaviour Type interpretation for Fargo RRS PDA site

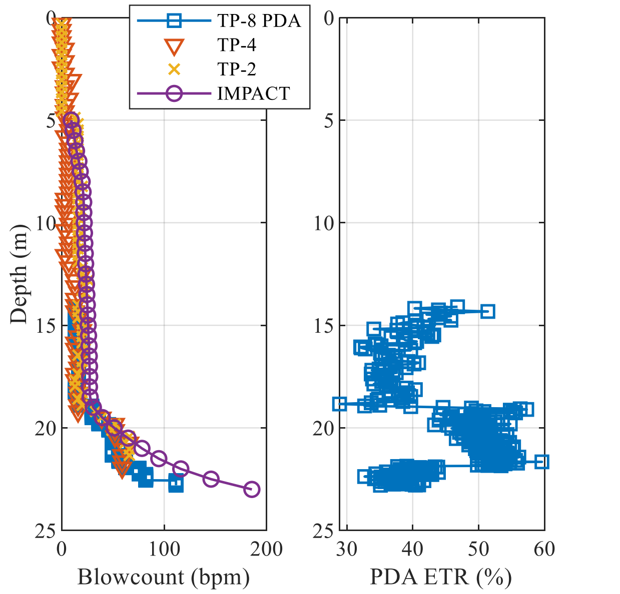


Fig. 4. Comparison of measured blowcounts and Impact CPT based calculations for Fargo closed ended pile

Calculated and measured upward travelling stress waves, $F_{up}$ (see, for example, Randolph 2003 for definition) are plotted against normalized time (where t is time, c is the wave speed and L is the pile length) in Figures 5 through 7 for the end of driving condition. Note that the peak input (i.e. downward travelling) force occurred at a normalised time of t/(2L/c) = 4.2. Results of parametric studies are presented in Table 1. Recorded blow number 293 was used for analyses.

- Figure 5 – baseline SWIFT = 70.5 Alm & Hamre (2001) case
- Figure 6 – best fit SWIFT = 77.4 shaft factor of 0.85, other factors = 1
- Figure 7 – poor performing SWIFT = 40.2, shaft factor = 0.5, base factor = 1.25, residual base stress = 0.6

Table 1. Signal Matching Parametric Studies for end of driving.

| Pile Embed (m) | Hammer Efficiency | Residual Base / Ultimate Base | Base Fact. | Shaft Fact. | SWIFT |
|---|---|---|---|---|---|
| 22.75 | 1 | 0 | 1 | 1 | 70.5 |
| 22.75 | 1 | 0 | 1 | 1.25 | 59.6 |
| 22.75 | 1 | 0 | 1 | 0.85 | 77.4 |
| 22.75 | 1 | 0 | 1 | 0.75 | 73.6 |
| 22.75 | 1 | 0 | 1 | 0.65 | 61.6 |
| 22.75 | 1 | 0 | 1 | 0.5 | 36.9 |
| 22.75 | 1 | 0.6 | 1 | 0.85 | 76.8 |
| 22.75 | 1 | 0.6 | 1.25 | 0.85 | 76.9 |
| 22.75 | 1 | 0.6 | 1.25 | 0.5 | 40.2 |
| 22.75 | 1 | 0.6 | 0.7 | 0.85 | 76.4 |
| 22.75 | 1 | 0.6 | 0.7 | 0.5 | 33.0 |
| 22.75 | 1 | 0.6 | 2 | 0.85 | 76.2 |

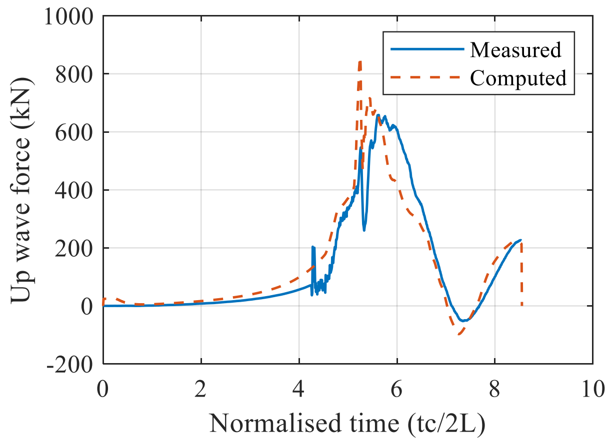


Fig. 5. Comparison of measured and calculated wave up using baseline Alm & Hamre (2001) method, SWIFT = 70.5

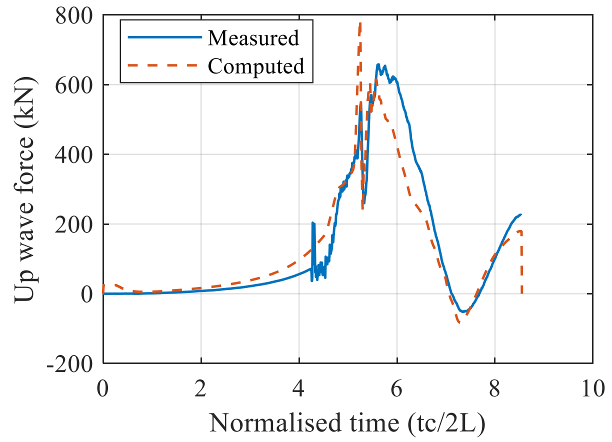


Fig. 6. Comparison of measured and improved calculated wave up using adjusted Alm & Hamre (2001) method with shaft factor of 0.85, SWIFT = 77.4

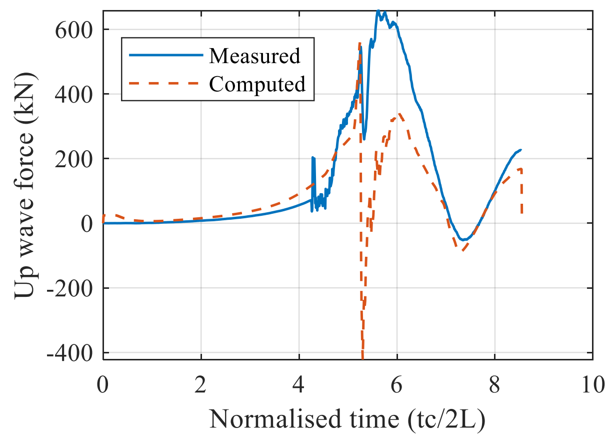


Fig. 7. Comparison of measured and poorly performing calculated wave up using adjusted Alm & Hamre (2001) method with shaft factor of 0.5, base factor of 1.25, and residual base stress factor of 0.6, SWIFT = 40.2

### 4.3 Signal Matching for Beginning of Restrike

A restrike was performed on pile TP-8 approximately 26 days after driving. The 4th blow of the restrike was analyzed. Significant increases in capacity with time after driving, or setup, was indicated by the restrike. Figure 8 shows the up wave profile for the restrike blow, as compared to the end of driving best fit from Figure 6. It can be seen that the resistance is underpredicted and the SWIFT factor drops to 45.2.

In this case, uniformly increasing capacity with a factor on the Alm & Hamre (2001) shaft friction of 2 (see Table 2), resulted in the SWIFT factor increasing to 84.8. Since the best fit shaft factor at the end of driving was 0.85, the setup was about 2.4 for this case. The adjusted calculated and measured up travelling waves are shown in Figure 9, with a reasonably good fit evident.

In some cases, a constant multiplier on the end of driving shaft friction may not result in the best fit. A manual soil profile option in IMPACT can be used to create the best fit in this case. The manual option allows input of $q_b$ and $\tau_f$ directly as well as more detailed adjustment of soil stiffness with depth

Table 2. Signal Matching Parametric Studies for beginning of restrike.

| Pile Embed (m) | Hammer Efficiency | Residual Base / Ultimate Base | Base Fact. | Shaft Fact. | SWIFT |
|---|---|---|---|---|---|
| 22.75 | 1 | 0 | 1 | 0.85 | 45.2 |
| 22.75 | 1 | 0 | 1 | 1 | 57.2 |
| 22.75 | 1 | 0 | 1 | 1.25 | 72.4 |
| 22.75 | 1 | 0 | 1 | 1.5 | 80.7 |
| 22.75 | 1 | 0 | 1 | 2 | 84.8 |
| 22.75 | 1 | 0 | 1 | 2.5 | 83.6 |
| 22.75 | 1 | 0 | 1 | 3 | 81.2 |

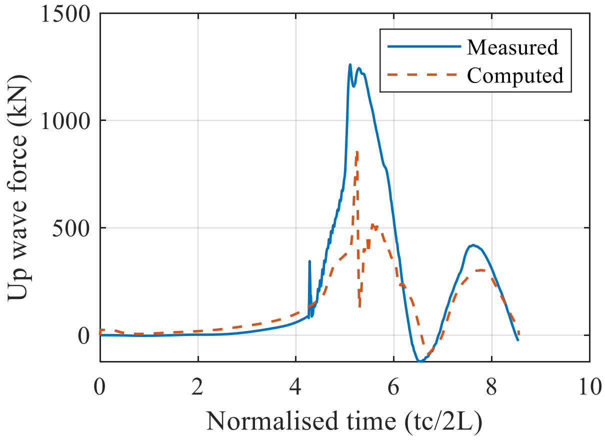


Fig. 8. Comparison of measured TP-8 restrike, and predicted capacity from end of driving using adjusted Alm & Hamre (2001) method with shaft factor of 0.85, SWIFT = 45.2

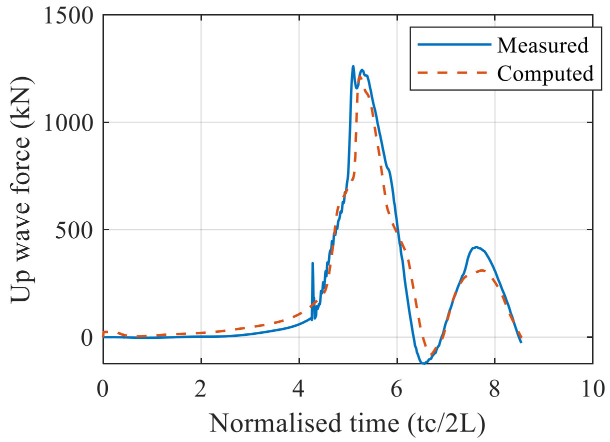


Fig. 9. Comparison of measured TP-8 restrike, and predicted uniformly increased capacity from end of driving using adjusted Alm & Hamre (2001) method with shaft factor of 2, SWIFT = 84.8

## 10 CONCLUSIONS

Combined drivability and signal matching analyses using IMPACT performed on the AWS Lambda serverless compute platform allows for rapid and rigorous evaluation of pile driving response. Analyses can be linked directly to CPT data using pre-programmed methods, linked to CPT data using custom algorithms, or SRD can be manually input. The case history in this paper shows reasonable agreement to installation blowcounts.

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