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Title of paper: Comparison of dynamic and static test results for cast in situ bored piles

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Title: **Comparison and dynamic and static test results for cast in situ bored piles**

by Michael Long, UCD.

Synopsis: Due to increasing time, cost and transportation difficulties, Irish contractors are seeking an alternative to conventional static pile load tests. As a result several firms have adopted dynamic testing techniques to supplement and in some cases to replace conventional static tests. In order to assess the reliability of the systems and to address the concerns of owners and consulting engineers, a database comprising 43 pairs of static and dynamic tests on piles from 24 sites around Ireland has been assembled. The database was limited to medium to large diameter continuous flight auger (CFA) piles, typically 450 mm to 600 mm in diameter. Comparisons between actual measured settlement in static tests and predicted settlement for dynamic tests showed a clear pattern of underestimation of settlement by the dynamic tests, with the ratio between the two values typically varying between 0.4 and 1.2, with an average of about 0.8. This is due to the limited energy being imparted to the pile in the dynamic test. The results were best for piles in rock and worst for piles in clay. Scatter in the results increased with increasing pile load. However as all of the measured settlements were modest, the absolute numerical difference between the actual and predicted values was typically less than 3 mm, which may not be significant in many practical cases. For piles supporting non - sensitive structures, in areas where the ground conditions are well know, and provided the ratio the drop weight to the pile weight and to the pile SWL is at least 50% and 1.5% respectively, it seems possible that static tests can be replaced by dynamic ones. However for structures sensitive to settlement or for those in areas where ground conditions are uncertain, then it is suggested that the dynamic test should be calibrated by at least one static test.

1. INTRODUCTION

Conventional maintained load, static, pile tests using kentledge are used in Ireland. Providing a reaction with tension piles is used less often for cost reasons on small projects. However due to increasing time and cost pressures, particularly with the difficulties associated with transporting kentledge into congested city centres, the lack of space on many sites contractors are seeking an alternative system for pile testing.

Most piles constructed in inner city areas are bored cast in - situ piles. Driven piles are not permitted due to noise and vibration limitations. The tendency is for contractors to use dynamic techniques in order to supplement conventional static tests. In some cases static tests have been omitted completely. There remains however a degree of reluctance amongst consulting engineers and owners to accept the dynamic test results in isolation.

In order to investigate the performance of these dynamic techniques Long[1] assembled a database of some 46 pairs of static and dynamic tests from 32 sites around Ireland. The piles were generally small with the majority being less than 300 mm in diameter. In each case the SIMBAT® dynamic technique was employed. He found that:

- A dynamic test result is likely to lie in the range of -50% to +100% of the true static behaviour.
- Correlation was best for piles in sand and gravel compared to those in clay or in rock.
- Dynamic tests will increasingly underestimate the results as pile diameter and length increases possibly due to insufficient energy being transmitted.
- The process mobilises sufficient load to give an adequate factor of safety.

- The technique was able to reliably identify defective piles.

Since this database was collected in 2000, there have been some significant changes in the piling industry and in the application of dynamic tests, namely:

- There is increasing pressure to dispense with static tests due to time pressures.
- Piles tend to be larger.
- There have been some improvements in the implementation of the systems.
- There are now three techniques used in Ireland for dynamic testing.

With these changes in mind and particularly with the tendency of increasing pile diameter, a new database was assembled in order to primarily investigate the relationship between settlement predicted by the dynamic tests and the measured settlement in static tests.

The objective of this paper is to describe briefly the test techniques involved, to discuss the result of the survey and to provide recommendations for future use. Details of the background geology, pile construction techniques and static testing methods can be found in Long and Collins[2] and Collins and Mitchell[3].

2. TESTING TECHNIQUES

Up to now, the dynamic technique that has been used most often in Ireland is SIMBAT®. It was developed in France at the CEBTP in the late 1980's. In Ireland and the UK, SIMBAT® testing is carried out by Testconsult Ltd. (www.testconsult.co.uk). The method consists of instrumenting the pile top with two strain gauges, two accelerometers and a theodolite target (see Figure 1). The use of the theodolite is one of the significant beneficial changes that have been made to the system since the last Irish survey in 2000. A mass is dropped on to the pile and data from the instruments is captured by a high-speed data logger. As the resulting compressive wave reached “soil restraints”, part of the wave is reflected back up the pile shaft. The same happens at the pile toe.

Signal processing involves conversion of the strain to force, integration of acceleration to velocity, verification of this with the theodolite data, separation of forces into upward and downward components and measurement of dynamic reaction. The dynamic reaction is converted into static reaction and a load versus settlement plot is obtained.

Use is made of wave matching techniques and computer modelling in order to verify the result. Computer modelling comprises a “wave equation” analysis in which the pile is sub-divided into 20 or more discrete elements, which are connected by springs, dashpots and sliders to one another and to the ground. The model is subjected to the same load as the real pile and parameters are adjusted until the model behaves in the same way as the real pile (Stain and Davis[4], Ground Engineering[5]).

A similar method to SIMBAT® is offered by the Dutch Company Profound, through Independent Testing Services Ltd., in Ireland (www.profound.nl). Similar pile head measurements are made, except for the use of the theodolite and the results are analysed using the TNOWAVE software (Middendorp[6]). This differs from the analytical technique used in SIMBAT® in that the pile is assumed to be continuous instead of being made up of discrete elements and solution is by the method of characteristics.

The third dynamic load testing system for bored piles offered in Ireland by Lloyd Acoustics Ltd. (www.lloydacoustics.com) makes use of the well known PDA or “Pile Driving Analyser” technique. This was originally developed for dynamic testing of instrumented driven piles and is now well accepted worldwide, e.g. the “Case” or “CAPWAP” approach of Rausche *et al.*[7]. More recently post hammering on a driven pile, already in place, or a cast in - situ pile has been used to determine ultimate capacity.

3.0 STUDY BY OTHERS

Holeyman and Charue[8] report on an international prediction event carried out in association with a 30 pile testing program at a sandy soil site in Limelette, Belgium. Six different pile types were used. Dynamic testing included the SIMBAT®, Profound and PDA techniques. In general the dynamic techniques underestimated the measured static settlement with the predicted to measured average ratio varying between 63% and 122% with an overall average of about 85%. The SIMBAT® / Testconsult prediction was considered to be the "fittest for all piles" and achieved an average ratio of 91%.

4.0 2004 SURVEY

The five major indigenous contractors operating in the cast in situ bored pile market in Ireland were contacted and asked to supply dynamic test results, on piles from a site where static testing was also carried out, as well as some details of the pile construction technique and the ground conditions. Ideally the tests should be on the same pile but such occurrences were found to be rare. Four of the contractors supplied data. The fifth reported that they did not accept dynamic testing because they felt that the action of dropping the large mass on the pile damaged the bond between the pile shaft and the ground.

This new database comprises 43 pairs of tests from 24 sites around Ireland. In this case the focus was on medium to large diameter piles and these varied between 300 mm and 900 mm with the majority of the tests being in the range 450 mm to 600 mm. With only a few exceptions, the piles were constructed of concrete using the continuous flight auger (CFA) technique and were reinforced over their full length.

The ground conditions mostly comprised medium dense to dense glacial and fluvio-glacial gravels (SPT N typically equal to 40 blows / 300 mm). Three of the sites were underlain by very stiff glacial till and at three of the sites the piles were rock socketed. Details of the test piles and a summary of the test results are given on Tables 1 to 3.

5.0 DATA ANALYSIS

The results of a single static test were used as a basis and then the dynamic tests were compared with this. If both test types were carried out on the same pile (occurred for 6 piles) then these data were used in isolation. As was more often the case the tests were on different piles and then the average of all the dynamic tests in the relevant part of the site were used. The dynamic data were first scrutinised in order to eliminate anomalous results. In general it was found that the dynamic tests were very consistent and there were only small differences between the results of tests from the same part of each site.

For the dynamic tests the predicted settlement at 0.5, 1.0 and 1.5 times SWL (specified pile working load) together with the maximum mobilised resistance in the pile were chosen for comparison. For the static tests the measured settlement at the same loads were chosen. If a number of load cycles had been carried out, then the settlement for the final load cycle, where that loads was applied and maintained, was used.

6.0 COMPARISON OF MEASURED AND PREDICTED SETTLEMENT

6.1 Ratio $\delta_{dynamic} / \delta_{static}$

The ratio of predicted settlement for the dynamic test ($\delta_{dynamic}$) and the measured settlement in the static test (δ_{static}), for 0.5, 1.0 and 1.5 SWL are plotted against pile weight on Figure 2. Despite some scatter the clear pattern that emerges from the data is one of the dynamic tests under predicting the measured static settlement. A summary of the results is presented on Table 4.

This overall finding of under prediction by the dynamic tests is perhaps not surprising given the limited amount of energy that can be imposed on the pile by dropping a weight a relatively modest height. The dynamic tests seem to perform best for piles in rock and worst for piles in clay. Again this is not surprising as a pile founded on rock presents a much “stiffer” system for the transfer of compression waves than the relatively “soft” pile – clay system. Creep settlements will also be significant for static pile tests in clay, whereas the dynamic tests will not be able to recognise these effects. Other factors which may influence the dynamic test results, particularly for piles in clay are:

- rate of loading effects,
- drainage time available,
- age of piles (piles often older and hence stiffer when static test takes place).,

Although the average values of $\delta_{dynamic}$ / δ_{static} for piles in gravel and rock are relatively encouraging, any consideration of these data must also take into account the relevant scatter.

6.2 Absolute values of settlement

Any discussion on the relative behaviour of the static and dynamic tests must take into account the actual value of the settlements, as this after all is the main consideration of the engineer. In general all of the pile tests results presented here are for piles which behaved well. Settlements were modest and generally less than 10 mm. Therefore the actual differences between δ_{static} and $\delta_{dynamic}$ are small. For example for the piles in gravel, at SWL, the absolute difference between δ_{static} and $\delta_{dynamic}$ static varied between 0.2 mm and 8.6 mm with an average of about 3.0 mm.

6.3 Other findings

Some other findings from the results presented in Tables 1 to 4 and on Figure 2 are as follows:

- As the load increases from 0.5 SWL to 1.5 SWL, the scatter in the ratio $\delta_{dynamic} / \delta_{static}$ increases.
- $\delta_{dynamic} / \delta_{static}$ is independent of pile weight in the range available.
- There is no clear difference between the results from the SIMBAT® and Profound tests (although the data from the latter technique are limited).
- There is insufficient data to comment on the effect of whether the dynamic or static test is carried out first.

6.4 Effect of drop weight

It would be expected that an improvement in the result could be achieved by increasing the drop weight relative to the pile weight. The results for $\delta_{dynamic} / \delta_{static}$ at SWL are plotted against the ratio of drop weight to pile weight and drop weight to SWL on Figure 3.

From the limited data available it seems that $\delta_{dynamic} / \delta_{static}$ is independent of drop weight once this is greater than about 50% of the pile weight. This finding is consistent with experience from driving precast concrete piles where the driving drop is normally specified to be about 50% of the pile weight.

Also $\delta_{dynamic} / \delta_{static}$ seems to be independent of the ratio between drop weight and SWL within the range 1.0% to 2.0%. Typically it is recommended that this ratio should not be less than 1.5%. In practice the maximum drop weight that can be handled easily is about 5 tonnes. This implies testing up to SWL of 3,500 kN.

6.5 Mobilised load / safety factor

A plot of the mobilised "factor of safety", i.e. the ratio between the calculated mobilised static resistance and the SWL is shown on Figure 4. It can be seen that in all cases the FOS is greater than 1.0, with a minimum value of about 1.4. Typically static tests on working piles are taken to 1.5 SWL and therefore these values seem reasonable.

7.0 CONCLUSIONS

The main objective of this paper was to review the reliability of dynamic tests by comparing the results of dynamic and static tests on piles from the same site. Here the emphasis was on CFA bored pile, typically 450 mm to 600 mm in diameter. The following conclusions can be drawn:

1. There is a clear trend of the dynamic tests underestimating settlement. The ratio between $\delta_{dynamic}$ / δ_{static} typically varies between 0.4 and 1.2, with an average of about 0.8.
2. These findings are consistent with those of the Belgian study reported by Holeyman and Charue[8].
3. Correlation seems best for piles in "stiffer" material such as rock and sand and gravel and weakest for piles in "softer" clays.
4. The scatter in the data increases as the load increases from 0.5 SWL to 1.5 SWL.
5. The results seem independent of pile length and diameter at least in the range of available data.
6. Despite the above, the absolute numerical difference between the actual and predicted values was typically less than 3 mm, which may not be significant in many practical cases.
7. The dynamic tests seem to mobilise sufficient load for the purposes of proof testing a working pile up to 1.5 SWL.

8. Due to practical considerations concerning the drop height, it does not seem possible to determine the ultimate capacity of the piles using the dynamic tests.

8.0 RECOMMENDATIONS

1. For piles supporting non - sensitive structures, in areas where the ground conditions are well known, it seems possible that static tests can be replaced by dynamic ones. However the ratio the drop weight to the pile weight and to the pile SWL must be at least 50% and 1.5% respectively.
2. However for structures sensitive to settlement or for those in areas where ground conditions are uncertain, then it is suggested that the dynamic test should be calibrated by at least one static test.
3. There seems to be a strong relationship between the drop mass and the test result. Further data should be gathered to investigate this more fully.

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Location / Test pile	Number of tests static (dynamic)	Dynamic test type	Test pile diameter (mm)	Test pile length (m)	SWL (kN)	**STATIC*** δ at SWL (mm)	δ at 1.5SWL (mm)	**DYNAMIC*** δ at SWL (mm)	δ at 1.5SWL (mm)	Avg. mob. resis. (kN)	Hammer wt. (t)
Blackpool business park, Cork											
Block A - 1A	1 (9)	SIMBAT	800	6.5	1800	5.5	6.9	5.3	8.1		
Block C - 69C	1 (6)		600	10.4	1200	3.8	5.8	3.8	5.9		
UCC Art Gallery - Pile 39	1 (6)	SIMBAT	450	14.12	1200	4.41	8.1	5.3	8		
Camden Quay, Cork- Pile 126	1 (10)	SIMBAT	600	9.8	1300	6.62	9.54	4.1	6.8		
An Post, Little Island - Pile 305	2 (16)	SIMBAT	350	18.3	1000	12.24	23.8	2.8 - 7.1	5.1 - 11.4		0.9
Pile 14			350	18.1	1000	10.64	16.24	2.8 - 7.1	5.1 - 11.4		0.9
Pile 579	1 (7)		300	25	450	3.22	4.95	2.4 - 4.2	3.9 - 7.3		0.9
Pfizers, Ringaskiddy, Cork - A4	2 (23)	SIMBAT	450	7.9	700	0.95	1.78	1.5 - 5.2	2.8 - 7.4		0.9
GB4			450	2.7	700	1.37	2.3	1.5 - 5.2	2.8 - 7.4		0.9
Pile 3	1 (16)		450	7.2	600	1.38	2.69	1.8 - 4.4	3.4 - 7.5		0.9
Glencastle bridge, Co. Mayo											
South abutment	1 (6)	Profound	600	14	800	6	15	2.9	8.5	1200	1.0
North abutment	1 (6)		600	12.2	800	3	8	2.2	11.9	1200	1.0
Tesco, Youghal	1 (10)	?	450	18	800	6.27	9.96	1.9 - 2.8	3.2 - 4.5		
Hanover Quay, North Lot - PTP2	4 (15)	SIMBAT	450	11.4	1000	3.47	4.57	3.9 - 5.2	4.6 - 7.4		
PTP3			450	7.5	1000	8.68	9.77	3.9 - 5.2	4.6 - 7.4		
WP375			450	7	1000	6.58	15.79	3.9 - 5.2	4.6 - 7.4		
WP215			450	11	1000	8.36	10.68	3.9 - 5.2	4.6 - 7.4		
Project Cuba, Waterford - TP138	2 (?)		450	12	550	2.46	4.27				
TP180			450	12	550	3.06	6.12				
PTP600	1 (?)		600	14.1	1500	5.17	6.34				
WIT, Waterford	1 (4)	PDA	450	15.9	1000	2.8	5.7			1540	
Canada St., Waterford - Pile 364	1 (18)	Profound	450	18	700	2.59	4.2	0.8 - 1.8	1.5 - 2.9	1050	2.5
Pile 451	2 (3)		600	18	1100	3.17	4.59	1.6 - 2.5	2.6 - 5.8		2.5
Pile 251			600	16	1100	3.44	4.88	1.6 - 2.5	2.6 - 5.8		2.5

Dromroe Village, UL- Pile 72	2 (5)	SIMBAT	300	9	600	5.54	7.31	2.1 - 2.41	3.71 - 4.12		0.9
Pile 172			300	7.7	600	2.41	2.92	2.1 - 2.41	3.71 - 4.12		0.9
Pile 115	1 (3)		450	9.2	880	2.67	3.75	2 - 2.55	3.41 - 4.21		0.9
Thomond Village, UL - 110BlockA	2 (22)	Profound	350	5.8	800	6.98	11.09	0.8 - 3.9	1.2 - 7.5	3000	1.0
110BlockC			350	7	800	9	14.86	0.8 - 3.9	1.2 - 7.5		1.0
City Quay, Dublin	1 (11)	SIMBAT	900	12	3000	6.04	9.67	3.3 - 4.8	5.2 - 7.7	5630	4.0
Fitzwilliam Quay, Dublin - Test 142	2 (11)	SIMBAT	600	13.9	1925	12.66	30.37	4.5 - 8.4	6.9 - 12.8	3495	
Test 143			600	13.5	1925	6.4	10.13	4.5 - 8.4	6.9 - 12.8		
Bridge UB241 - Wexford / Roslare	1 (7)	SIMBAT	600	12.1	1000	12.08	13.45	2.8 - 4.2	4.3 - 6.6	2460	2.0
Barrow St., Dublin	1 (12)	SIMBAT	600	9.3	2000	8.11		4.6 - 8.9	7.3 - 14.4	3215	4.0
Ballycasey, Co. Clare - Pile No. 5	?	2 (21)	450	19.38	1500	4.78	8.69	3.9 - 6.4	6 - 11.5		
Pile No. 16			450		1500	4.93	8.79	3.9 - 6.4	6 - 11.5		

* Measured value for static tests. For dynamic test actual value given if tests on same pile, range given if tests on different piles.

Table 1. Piles in gravel

Location / Test pile	Number of tests static (dynamic)	Dynamic test type	Test pile diameter (mm)	Test pile length (m)	SWL (kN)	**STATIC*** δ at SWL (mm)	δ at 1.5SWL (mm)	**DYNAMIC*** δ at SWL (mm)	δ at 1.5SWL (mm)	Avg. mob. resis. (kN)	Hammer wt. (t)
Hanover Quay, North Lot - PTP	4 (47)	SIMBAT	450	6	1000	9.88	11.31	2.8 - 6.3	4.4 - 10.0		
PTP2			450	7.5	1000	11.25	12.8	2.8 - 6.3	4.4 - 10.0		
WP164			450	6.5	1000	10.47	16.34	2.8 - 6.3	4.4 - 10.0		
WP380			450	7.5	1000	9.91	16.62	2.8 - 6.3	4.4 - 10.0		
Hogan Place - Test pile 130	1(6)	SIMBAT?	450	11.3	800	4.54	8.38	1.9 - 3.8	3.1 - 6.5		
Limerick Main Drainage - Storm tank	1 (11)	SIMBAT	600	5.5	1400	3.36	6.05	1.69 - 2.54	3.45 -4.80	2065	2.50
Settlement tank	1 (12)		900	5.5	3200	2.62	5.45	1.9 - 3.5	4.65 - 8.1	4700	4.00

* Measured value for static tests. For dynamic test actual value given if tests on same pile, range given if tests on different piles.

Table 2. Piles in clay

Location / Test pile	Number of tests static (dynamic)	Dynamic test type	Test pile diameter (mm)	Test pile length (m)	SWL (kN)	**STATIC*** δ at SWL (mm)	δ at 1.5SWL (mm)	**DYNAMIC*** δ at SWL (mm)	δ at 1.5SWL (mm)	Avg. mob. resis. (kN)	Hammer wt. (t)
Lough Ree power station - 62 UEB	1 (31)	?	600	6.7	2100	3.01	4.88	3.4 - 4.5	5.2 - 6.8		
PTP	1 (31)	?	600	18	2000	4.47	11.25	3.4 - 4.5	5.2 - 6.8		
Carlton, Henry St., Limerick - Pile 151A	1 (4)	Profound	305	5	1000	3.29	5.26	1.6 - 2.2	3.4 - 6.0	1500	1.00
Great Ship St.	1(3)	SIMBAT?	600	8.5	1000	2.16	3.78	2.7 - 3.0	4.5 - 5.0		

* Measured value for static tests. For dynamic test actual value given if tests on same pile, range given if tests on different piles.

Table 3. Piles in rock

	Gravel		Clay		Rock	
	Typical range	Average	Typical range	Average	Typical range	Average
0.5 SWL	0.6 – 1.1	0.86	0.6 – 1.0	0.86	n/a	0.7
1.0 SWL	0.4 – 1.2	0.8	0.5 – 1.1	0.58	0.6 – 1.3	1.0
1.5 SWL	0.2 – 1.4	0.87	0.6 – 1.1	0.64	0.5 – 1.2	1.0

Table 4. Summary of results for $\delta_{dynamic} / \delta_{static}$

Figures for: **Comparison of dynamic and static test results for cast in situ bored piles**

by Michael Long, UCD.

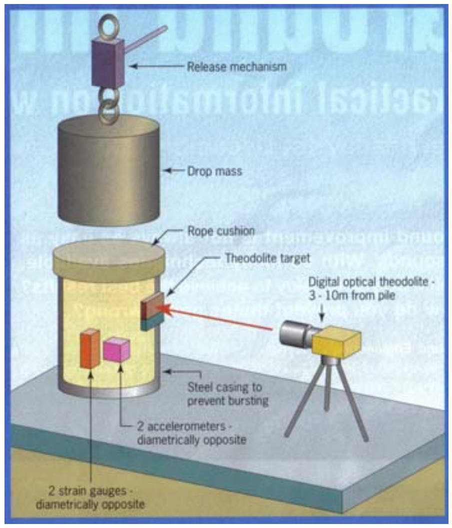

Fig. 1. SIMBAT® dynamic pile testing system (Ground Engineering[5])

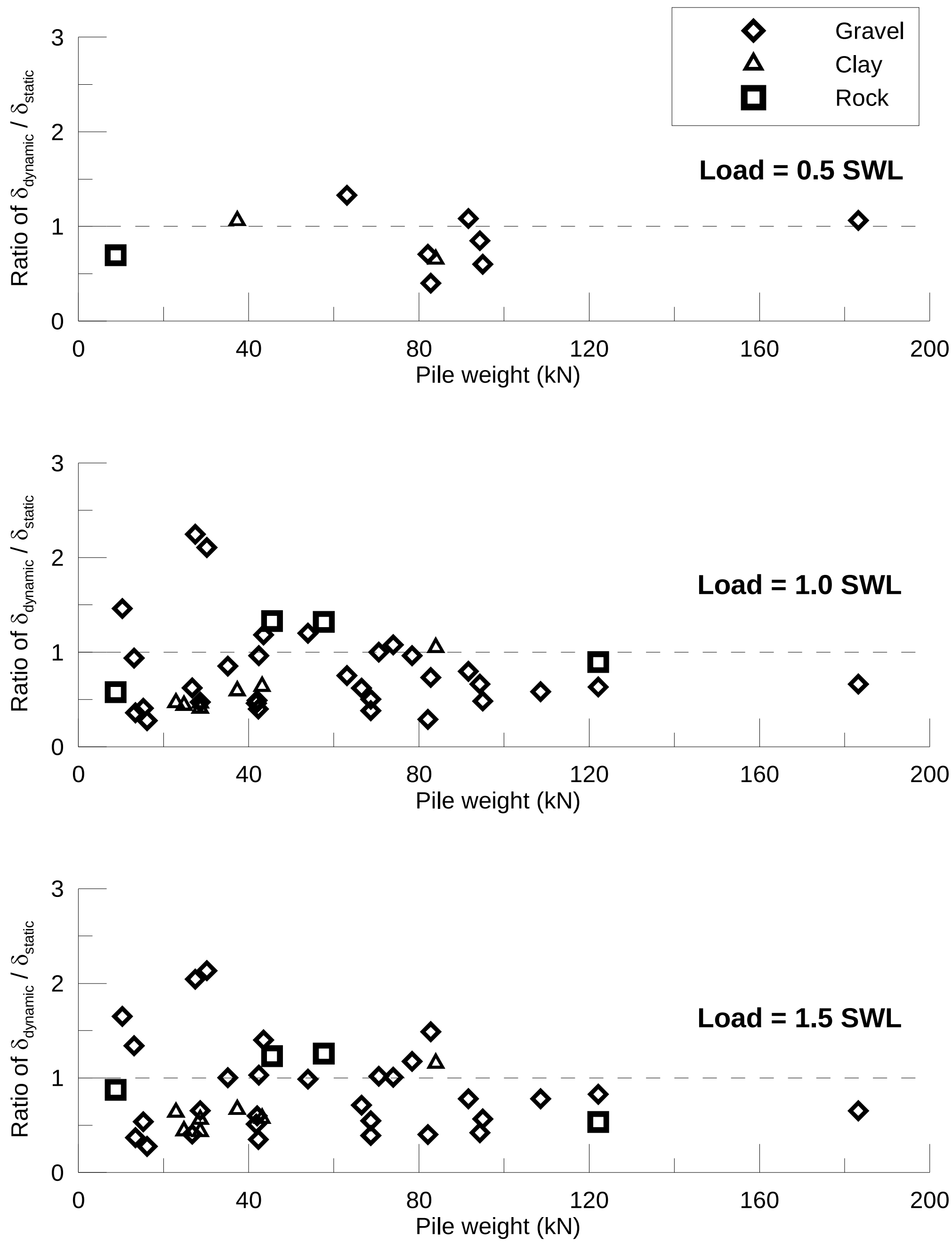

Fig 2. Ratio of $\delta_{dynamic}$ / δ_{static} for pile load = 0.5, 1.0 and 1.5 SWL

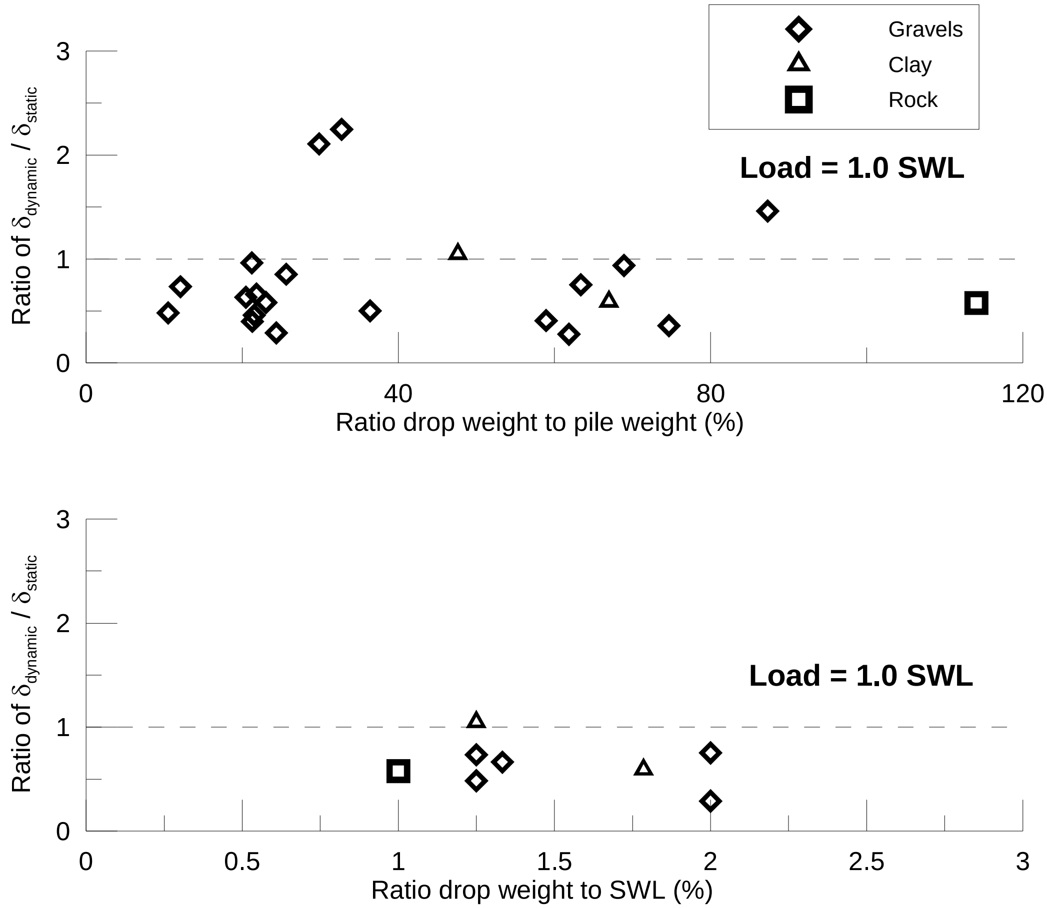

Fig. 3. Relationship between $\delta_{dynamic} / \delta_{static}$ and drop weigh

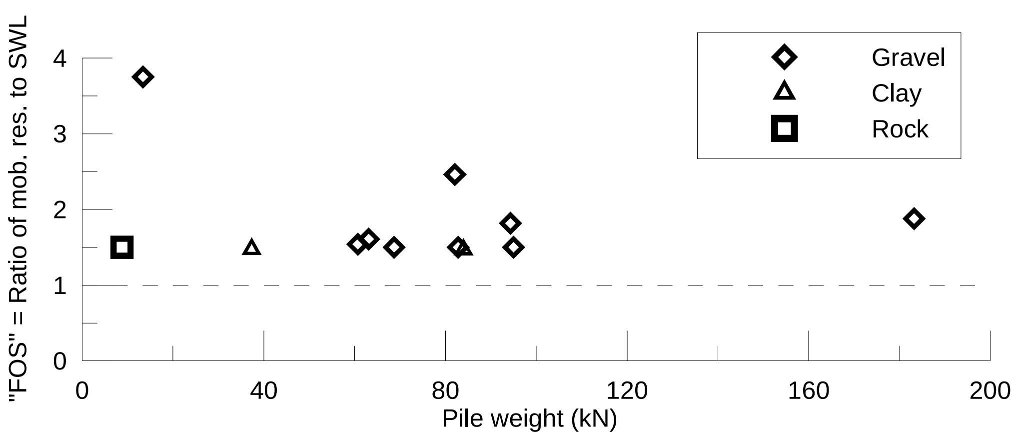

Fig. 4. Mobilised “factor of safety” in dynamic tests