The effect of ram mass on pile stresses and pile penetration

Rausche, F.
GRL Engineers, Inc., Cleveland, Ohio, USA

Likins, G.
Pile Dynamics, Inc., Cleveland, Ohio, USA

Miyasaka, T.
Jibanshikenjo Co. Ltd., Tokyo, Japan

Bullock, P.
GRL Engineers, Inc., Gainesville, Florida, USA

ABSTRACT: Pile driving, and dynamic testing of cast-in-place piles, can cause potentially high compressive and tensile stresses in the pile. Higher compressive stresses are desirable to achieve an economic installation and to activate required test loads. However, tension stresses must be limited for concrete piles. Compressive stresses generally increase when ram mass and cushion stiffness increase. On the other hand, while tensile stresses also increase with cushion stiffness, they decrease with increasing ram mass when impact velocity is kept constant (energy increases linearly with ram mass). Therefore, no direct relationship exists between compressive and tensile stresses. Furthermore, the pile penetration increases with increasing ram mass at constant impact velocity and increases with cushion stiffness. Historically, these relationships have lead to consideration of the ram/pile weight ratio as an important variable. Indeed, experience teaches that for the same energy, a low ram/pile weight ratio can cause damage at the pile top or cracks along the pile, while a high ram/pile weight ratio may cause compressive overstressing at the pile bottom. The following paper examines these relationships based on both analysis and measurements. Examples include newly developed systems which bridge the gap between dynamic and rapid load testing. Also, consideration will be given to the effect of rise time and load duration, i.e. how quickly the force at the pile top increases and how long it lasts.

1 INTRODUCTION

The optimal pile driver should install the pile quickly, i.e. with reasonably low blow counts, and safely, i.e. within allowable dynamic stresses. A heavier ram accomplishes this goal, but is less economical as it requires higher transportation cost and more costly lifting equipment. A lighter ram, while easier to lift and handle, will not drive the pile as quickly. A lighter ram providing the same energy at impact as a heavier ram, will also require a greater stroke and impact velocity, resulting in greater impact stress that may damage the pile.

Preparations for, and selection of the drop weights for, dynamic load tests of non-driven piles, such as large drilled shafts, should be made considering similar physical laws and mechanical limitations. For this reason, loading systems were developed which transfer the necessary dynamic energy with relatively low dynamic forces and stresses over a longer time period than common during pile driving. This was accomplished using combustion pressures or soft mechanical springs (Miyasaka et al., 2006, Rausche et al., 2006, Rausche et al., 2007).

This paper investigates the relationship between ram weight, pile penetration into the soil, and stresses in concrete piles and drilled shafts, using mathematical simulations of the impact event by wave equation and by comparison of measurement results for piles of different size and rams of different weights. Based on these results, recommendations for the preparation of test programs will be formulated.

2 THE MECHANICS OF ENERGY TRANSFER DURING IMPACT

For several centuries it has been well known that the stress occurring in a pile during an impact event depends on (a) the size of the impact mass, (b) the magnitude of the impact velocity, and (c) the stiffness of the cushion system. Timoshenko (1951) presents a solution by Boussinesq from 1883 for the variation of compressive stress at the pile top versus time for a pile subject to the impact of a rigid body. Defining a relative ram weight as the ratio of ram weight, Wr, to pile weight Wp.

$$\alpha = Wr/Wp \tag{1}$$

Boussinesq's closed form solution for a rod fixed at its bottom end and hit directly on the top by a rigid mass clearly shows that the compressive stresses increase with the relative ram mass. In this solution, the pile length, L, is immaterial as long as α is the same. Based on earlier work (Timoshenko, 1951) the solution also introduced the speed of the stress wave:

$$c = (E/\rho)^{1/2} \tag{2}$$

with E being the elastic modulus and ρ the mass density of the pile material. The stress, σ_o, at the pile top at the time of impact in this ideal situation is merely a function of the ram impact velocity

$$v_o = (2gh)^{1/2} \tag{3}$$

(g is the gravitational acceleration and h the drop height of the ram)

$$\sigma_o = v_o E/c \tag{4}$$

The closed form solution indicates that stresses in excess of σ_o can only occur at and time after the time when the stress wave reaches the fixed pile bottom. At the top, the compression stresses can only exceed the impact stress σ_o if $\alpha = W_r/W_p$ is high and the pile toe is fixed.

Obviously, excessive dynamic compressive stresses can damage any type of pile, steel, timber or concrete, at the top, bottom, or in between. In addition, for concrete piles, tension stresses generated by stress wave reflections from the pile ends can lead to cracking, which in the presence of high compressive stresses after numerous hammer blows can lead to damage, i.e. an actual loss of concrete.

Wave propagation theory can help derive a relationship between α and the tension stresses that would show that a larger relative ram mass leads to lower tension stresses. Indeed there are rules of thumb and specifications which require, for example, that the ram to pile weight ratio should be greater than 1.0. Such simplified formulae are, however, inaccurate and may lead to either costly damage or uneconomical foundation solutions. Closed form solutions of the basic equations governing dynamic pile penetration also yield unrealistic solutions as they are incapable of realistically representing such complex driving system features as diesel hammer compression, non-linear system components including soft pile cushions, and static and dynamic soil behavior. The numerical solution of the wave equation by Smith (1960), programmed conveniently in a user-friendly code, e.g., GRLWEAP (PDI, 2005), provide more realistic results of pile stresses with little additional analysis effort. However, even though such a simulation is invaluable before a pile is tested or driven, once the impact is applied more accurate solutions can be obtained with measurements taken at the pile top and evaluated by either the closed-form Case Method or the signal matching program CAPWAP (PDI, 2006).

Recently, the ‘‘Rapid Load Test’’ (RLT) has been introduced as an alternative to the dynamic load testing system. In one configuration, described by Middendorp, 2005, the ‘‘Statnamic’’ RLT develops a dynamic load on top of the pile by means of the combustion of a blasting component reacting against a mass placed above the pile. According to its developers, the advantages of this system include a longer force pulse which would avoid tension stresses. The combustion pressures, however, can only produce a force pulse of substantial duration, if the reaction mass is relatively large. A second configuration of RLT consists of a ram impacting against a soft cushion, again, to achieve a long lasting force pulse. The ‘‘Hybridnamic’’ system is one such RLT as reported by Miyasaka, 2007.

Both the combustive and the soft spring RLT systems require that either the reaction mass or the drop weight range between 5%, and 10% of the required test load. On the other hand, for dynamic load testing a drop weight of 1 to 2% of the test load is generally sufficient. For example, for a 4 MN dynamic test the drop weight should be 40 to 80 kN while the RLT requires 200 to 400 kN. Although these systems help reduce tension stresses, their large weights also increase the testing cost significantly. On the other hand, moderate tensions stresses applied 3 or 4 times during a dynamic test, and over a very short time period, are generally not detrimental to a pile. Even if tension stresses exceed the pile’s tension strength, additional concrete hydration following the test usually fuse the hairline cracks within a short time period. However, the discussion about tension stresses in concrete piles have been for centuries, and still are today, an interesting matter of discussion and will be further investigated in the following.

3 ALLOWABLE STRESSES

When an impact is applied to a friction pile, compressive stresses are highest at or near the pile top. When impacting an end bearing pile, compressive stresses may be highest either at the top or bottom. For pile driving, compressive stresses should be limited to 90% of steel yield strength or to 85% of concrete strength after subtracting prestress. Tensile stresses may occur either when resistance is very low or when a very high soil resistance causes the pile to rebound sharply. In either case a heavy ram can reduce the tension stresses. Again, for pile driving, the generally accepted practice maintains tension stresses below a level that causes cracks in prestressed concrete piles, generally less than the sum of the effective prestress and 50% of the concrete tensile strength. For regularly reinforced concrete piles tension forces during driving should be limited to 50% of the concrete tensile strength or 70% of the yield strength of the reinforcement bars.

During dynamic load testing, because of the limited number of impacts, it is the authors opinion

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that the allowable tension stresses in all types of concrete piles can be increased to the lesser of 100% of the strength of concrete (typically 3 MPa) or reinforcement (perhaps 3.5 MPa for each percent reinforcement by gross shaft area). The compression stress limits for pile driving are also reasonable for dynamic load testing.

4 WAVE EQUATION SIMULATION

To illustrate the relationship between pile and soil properties, ram weight, and pile cushion stiffness, we performed realistic simulations using a wave equation program. We assumed two different pile sizes: (a) a 15 m long concrete pile of 600 mm diameter and (b) a 30 m long concrete pile of 420 mm diameter making the pile weight in both cases roughly 100 kN. We also assumed a 147 kN ram striking a 5 kN steel plate, with a softwood pile cushion 75 mm thick and 38 mm thick for the shorter/larger and longer/smaller pile, respectively. In this way the stiffness of the cushion was the same in both cases. However, we also checked the influence of an unusually soft cushion of 750 mm thickness for the shorter/larger pile. To compensate for the energy lost in the thick cushion, we increased the ram drop height in that case from 2 to 4 m. The soil profile was assumed to consist of stiff clay over dense sand leading to a shaft resistance of 50% of the total capacity.

Fig. 1 shows the calculated maximum stresses as a function of the relative ram mass α, (ram weight divided by pile weight). These results were chosen for a soil resistance that would cause a permanent set, e, less than 15 mm although larger sets would only yield insignificant changes in stresses. The results are somewhat surprising as they show that tension stresses are modest and independent of pile length provided α is at least 0.5. Furthermore, in contrast to the results from Boussinesq which predict equal compressive stresses for the same relative ram weights, the calculated compressive stresses were higher in the more slender pile. Intuitively, this is of course reasonable and results in the more realistic situation from the consideration of cushion and helmet. Also, it is not surprising that the 10-times softer pile cushion would significantly reduce compression and tension stresses even though the drop height was doubled to 4 m. Such a soft cushion almost completely suppresses tension stresses.

The penetration per blow is also important during pile driving for greater economy and during testing for sufficient capacity activation (if capacity is not activated during the test it cannot be calculated from measurements). The results in Fig. 1 correspond to activated capacities, Ru-a, which achieve a permanent penetration, e, of at least 1 mm under one impact. With a permanent penetration of less than 1 mm only a lower bound capacity can be determined by the pile test.

Fig. 2 shows Ru-a values as a function of ram weight for larger permanent sets, e of 3 to 4 m) and for smaller ones (less than 1.5 mm). The results suggest that the activated capacities fall into a range of roughly 50 to 100 times ram weight and, therefore, support the contention that the ram weight should be between 1 and 2% of the required test load. However, the relationship is not linear and if it is necessary to load the pile to a very high capacity then it may be necessary to mobilize a greater ram weight. This would also apply to unusually long piles, very softly cushioned ram impacts, or when it is necessary to achieved penetrations greater than 1.5 mm. Also activation of a high end bearing in a granular soil would require much more energy than a pile socketed in rock.

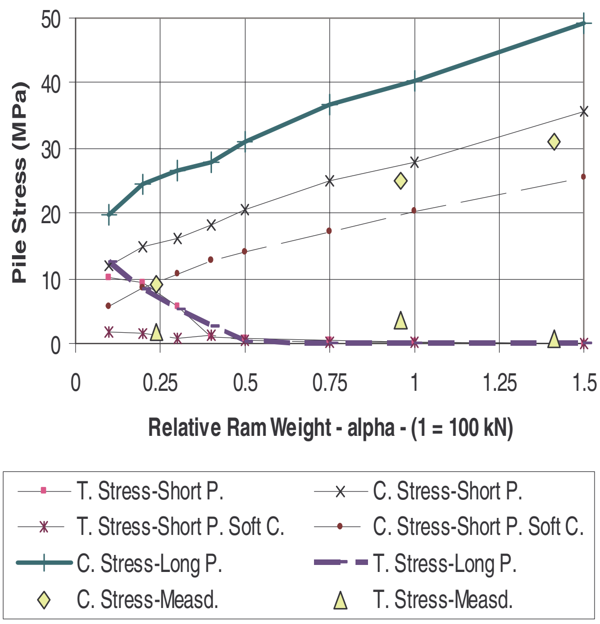

Figure 1. Tension and compression stresses as a function of the relative ram weight.

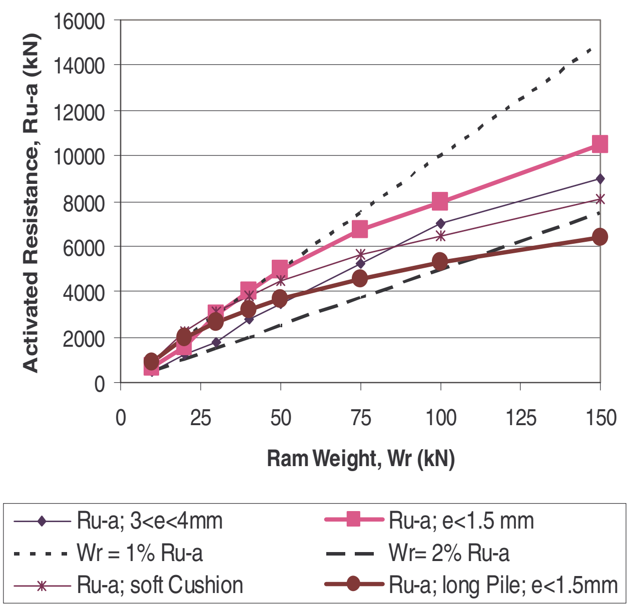

Figure 2. Activated capacity relative to ram weight.

5 MEASUREMENTS

In the following, five examples showing results from piles of different properties and tested with a variety of loading devices will demonstrate that the theoretical considerations are in agreement with actual results. Table 1 summarizes the properties of the test piles which include a Continuous Flight Auger (CFA) pile, a square precast, prestressed concrete pile (PPCP), a long steel pipe pile, a large drilled shaft, and a concrete cylinder pile. Pile lengths ranged between 20 and 56 m, pile weights between 64 and 1549 kN and the ratio of ram to pile weight, α, varied between 0.23 and 6.4.

The tests on the piles of the first four examples were conducted with plywood cushions 50 to 100 mm thick. The loading device was a relatively simple drop weight system manufactured in the U.S., the ''APPLE'', which has variable mass components ranging between 98 and 356 kN. Fig. 3 shows the 356-kN ram for this system on the large, rock-socketed drilled shaft with the lowest ram-pile weight ratio of 0.23.

The fifth example shows results which were obtained with a cushion drop-mass RLT device. This latter system satisfies the conditions of a rapid load test, because it works with a relatively large ram weight and soft cushion. Fig. 4 is a photo of the guide system and 432-kN ram, which can be increased to 864 kN by adding additional ram segments. The massive frame accommodates both a hydraulic lifting device and a guide for the freely falling ram. The patented, soft cushion limits the force peak and stretches the force pulse over nearly 100 ms. It consists of a man-made material contained in a large steel box. Measurements taken on the pile and their evaluation are identical to those performed during dynamic testing. In addition, the pile penetration is also optically measured.

Figs. 5 through 8 show, for Cases 1 through 4 respectively, the measured force and velocity as a function of time. These measurements were evaluated by signal-matching, which provides the compressive and tensile stresses listed in Table 2.

Table 1. Pile and loading system data

	Pile type	Pile length	Pile weight Wp	Ram weight Wr	α= Wr/Wp
		m	kN	kN	
1	380 mm dia. CFA pile	24	59	98	1.7
2	500 mm square PPCP	27	159	169	0.94
3	610x12 mm steel pipe	56	109	356	3.3
4	1830mm dia. drilled shaft	25	1550	356	0.23
5	600x90 mm cylinder pile	20	68	432	6.4

Figure 3. Dynamic load test of a drilled shaft using a 356 kN drop weight.

Figure 4. Rapid load test of cylinder pile using a 432 kN cushioned drop-mass system.

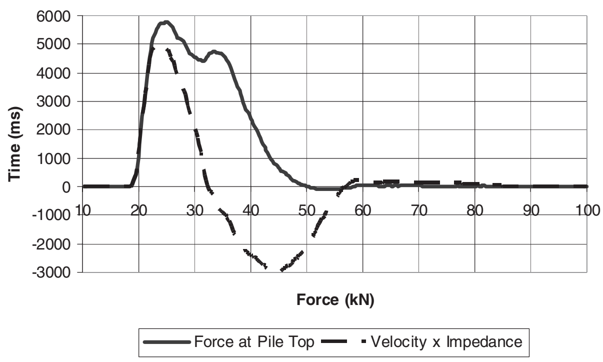

Figure 5. Pile top force and velocity for the CFA pile tested with a 98 kN drop-weight (Case 1; α = 1.7).

Table 2. Measurement results

Case No.	Pile Type	Tension Stress	Comp. Stress	Permanent Penetration	Ru-a	W r/ Ru-a	Tfr = Tfp/(2L/c)
		MPa	MP a	mm	MN	%	
1	380 mm dia. CFA pile	0.9	31	4.8	2.4	4.0	2.2
2	500 mm square PPCP	3.6	25	0.6	5.7	2.9	2.3
3	610x12 mm Steel Pipe	0.9	343	1.8	7.1	5.0	2.5
4	1830mm dia. Drilled Shaft	1.7	9.1	1.5	27.7	1.3	2.1
5	600x90 mm Cylinder Pile	1.7	43	22	5.8	7.7	7.8

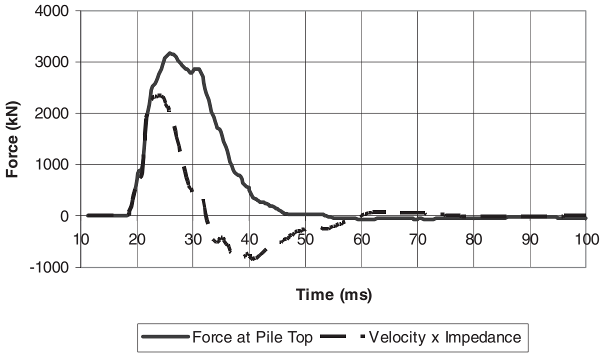

Figure 6. Pile top force and velocity for the PPC pile tested with a 169 kN drop-weight (Case 2; α = 0.94).

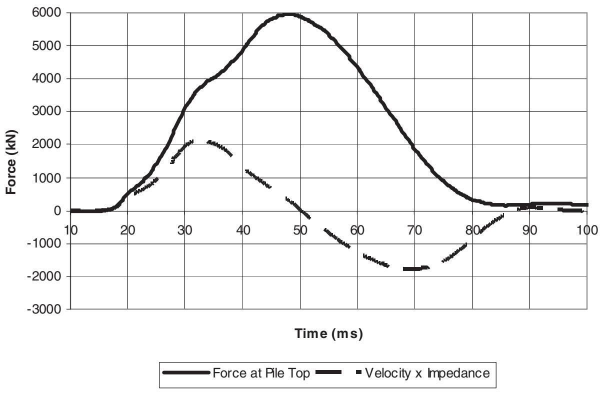

Figure 7. Pile top force and velocity for the steel pipe tested with a 356 kN drop-weight (Case 3; α = 3.3).

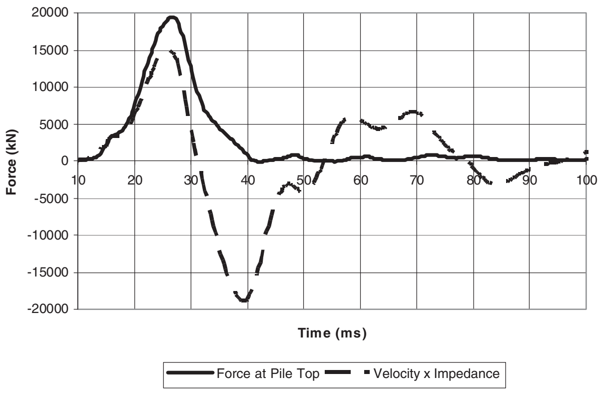

Figure 8. Pile top force and velocity for the large drilled shaft tested with a 356 kN drop-weight (Case 4; α = 0.23).

Relative to the activated capacities, the ram weights ranged between 1.3% and 7.7%. The lowest value of 1.3% pertained to the large drilled shaft which was socketed into rock and for which an ultimate capacity could not be activated (probably the rock was of the same or greater strength than the shaft's concrete). The

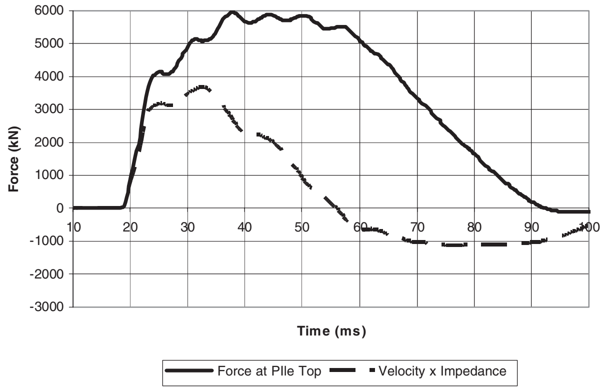

Figure 9. Pile top force and velocity for the cylinder pile tested with the 432 kN cushioned drop mass RLT (Case 5; α = 6.4).

measured signals from the RLT system in Fig. 9 show a relatively short (approximately 5 ms) rise time during the impact time and then a very flat force curve. Because of the relatively short rise time, it is possible to easily and reliably evaluate these records with the same signal-matching methods as used for dynamic load test results. (However, the relatively short rise time also results in a small tension stress.) The dynamic tests yielded longer rise times (e.g. Figs. 7 and 8) because of the insertion of soft plywood cushions and the particular characteristics of the drop-weight system. It should be noted that tension stresses may not only be induced by short rise times but also by a very rapid decrease of the force pulse.

Table 2 also shows a relative force pulse duration, T_{fr}, defined as the ratio of the duration of the force pulse (T_{fp}) and the stress wave travel time.

$$T_{fr} = T_{fp}/(2L/c) \tag{5}$$

In Table 2, T_{fr} ranges within 2.1 and 2.5 and was only much greater (7.8) for the cushioned drop-mass case.

No clear tendency or relationship between stresses and T_{fr} can be discerned. In all cases, the stresses calculated by signal matching analysis were well below allowable limits, with the highest tension stresses of 3.6 MPa occurring in the PPCP where allowable values are typically twice this high.

Table 1 also lists the ram pile weight ratios, α, which had a minimum of less than 1/4 for the large bored pile. As a rule of thumb α > 1/4 has sometimes been suggested for stress control. The stress results of Table 2 support the contention that there is no direct relationship between the tension stresses and the relative ram weight. Cushioning, resistance distribution and soil stiffness obviously play an important role when it comes to stress magnitudes and can only be evaluated in a rational manner by a wave equation simulation.

6 SUMMARY

This paper presents calculated and measured results that support the following conclusions.

- Tension stresses in piles depend not only on the relative ram weight, which is responsible for the duration of the force pulse, but also on the length of the rise time relative to the stress wave travel time required to traverse the pile (2 L/c).
- The relative force duration lengthens with increased ram mass for a dynamic test, or increased reaction mass for an RLT.
- In a dynamic pile load test, to achieve sufficient penetration and thus activate the required test load, it is necessary to generate an impact load using a drop-mass having a weight of at least 2% of the test load. If the bearing layer is very stiff and therefore dissipates less energy (e.g. rock), this requirement can be reduced to 1%.
- While a rule-of-thumb minimum ram weight of 1/4 the pile weight may be reasonable, such assumptions should be checked by a wave equation simulation.
- For an impact load, the ram mass has little influence on the magnitude of tension stresses in the pile when this mass exceeds 50% of the pile mass.
- Compression stresses in the pile are clearly related to ram weight and cushion properties.
- The difference between dynamic and RLT methods is not clearly defined, particularly when large, permanent penetrations are demanded. Then higher ram weights are needed. In any event, the ultimate geomechanical capacity can only then be activated if the structural strength of the pile is sufficiently high.
- RLT measurements can be evaluated using proven signal-matching analysis methods from dynamic testing provided that the rise time of the force and velocity records is small compared with the stress wave travel time (2 L/c). The advantage of these methods is their ability to determine the dynamic resistance component in a rational manner.

REFERENCES

AASHTO, American Association of State Highway and Transportation Officials (1996). "Standard Specifications for Highway Bridges" (Sixteenth Edition).

Miyasaka, T. and Kuwabara, F. (2006). "Large Scale Pseudostatic Pile Load Test", Part.1-Ground Oscillation and Ultimate Soil Resistance, S. 1547–1548, Proceedings of 41st Annual Conference of Japanese Geotechnical Society, Kagoshima, July, 2006.

PDI (2005). "GRLWEAP Background Report", 4535 Renaissance Parkway, Cleveland, OH, 44128, USA. www.pile.com.

PDI (2006). "CAPWAP Background Report", 4535 Renaissance Parkway, Cleveland, OH, 44128, USA. www.pile.com.

Rausche, F., Morgano, M., Hannigan, P., Bixler, M. and Beim, J. (2006). "Experiences with heavy drop hammer testing of rock-socketed shafts", Deep Foundations Institute, Annual Conference, Washington, DC.

Rausche F., and Klingmueller, O. (2007). "Zur Beziehung zwischen Bärmasse, Futtersteifigkeit, dynamischen Spannungen und Pfahleindringung", Pfahlsymposium, University of Braunschweig, Department of Soil Mechanics and Foundations.

Timoshenko, S., and Goodier, J.N., (1951). "Theory of Elasticity", McGraw-Hill Book Company, Inc.

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