SWEDISH DEFENCE
RESEARCH AGENCY

FOI-R--0968--SE
November 2003
ISSN 1650-1942

Technical report

Håkan Hansson

A note on empirical formulas for the prediction of concrete penetration

Weapons and Protection
SE-147 25 Tumba

SWEDISH DEFENCE RESEARCH AGENCY

Weapons and Protection
SE-147 25 Tumba

FOI-R--0968--SE

November 2003

ISSN 1650-1942

Technical report

Håkan Hansson

A note on empirical formulas for the prediction of concrete penetration

<table>
<tr><td rowspan="6">Issuing organization
FOI – Swedish Defence Research Agency
Weapons and Protection
SE-147 25 Tumba</td><td>Report number, ISRN
FOI-R--0968--SE</td><td>Report type
Technical report</td></tr>
<tr><td colspan="2">Research area code
5. Combat</td></tr>
<tr><td>Month year
November 2003</td><td>Project no.
E2358</td></tr>
<tr><td colspan="2">Customers code
5. Commissioned Research</td></tr>
<tr><td colspan="2">Sub area code
53 Protection and Fortification</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td rowspan="4">Author/s (editor/s)
Håkan Hansson</td><td colspan="2">Project manager
Håkan Hansson</td></tr>
<tr><td colspan="2">Approved by</td></tr>
<tr><td colspan="2">Sponsoring agency
Swedish Armed Forces</td></tr>
<tr><td colspan="2">Scientifically and technically responsible</td></tr>
<tr><td colspan="3">Report title
A note on empirical formulas for the prediction of concrete penetration</td></tr>
<tr><td colspan="3">Abstract (not more than 200 words)
The use of empirical formulas to predict penetration depths of projectiles in concrete is discussed in the report. An existing empirical equation is compared with experimental data from the literature, and the limitations of the empirical equation are discussed. Further, modifications and limitations for the used formula are given to consider projectiles with a length to diameter ratio between 6 and 10, and with a calibre head radius between 2 and 6. The modified model gives a fair agreement with the existing penetration data from the literature.</td></tr>
<tr><td colspan="3">Keywords
Concrete, penetration, empirical formula.</td></tr>
<tr><td>Further bibliographic information</td><td colspan="2">Language English</td></tr>
<tr><td>ISSN 1650-1942</td><td colspan="2">Pages 18 p.</td></tr>
<tr><td></td><td colspan="2">Price acc. to pricelist</td></tr>
</table>

Utgivare Totalförsvarets Forskningsinstitut - FOI Vapen och skydd 147 25 Tumba	**Rapportnummer, ISRN** FOI-R--0968--SE	**Klassificering** Teknisk rapport
	Forskningsområde 5. Bekämpning	
	Månad, år November 2003	**Projektnummer** E2358
	Verksamhetsgren 5. Uppdragsfinansierad verksamhet	
	Delområde 53 Skydd och anläggningteknik	
Författare/redaktör Håkan Hansson	**Projektledare** Håkan Hansson	
	Godkänd av	
	Uppdragsgivare/kundbeteckning Försvarsmakten	
	Tekniskt och/eller vetenskapligt ansvarig	

Rapportens titel (i översättning)

Användande av empiriska formler för att bedömma penetration i betong

Sammanfattning (högst 200 ord)

Användandet av empiriska former för att bedöma projektilers penetrationsdjup i betong diskuteras i rapporten. En existerande empirisk formel jämförs med data från existerande penetrationsförsök i tillgänglig litteratur och begränsningarna för den empiriska ekvationen diskuteras. Dessutom ges förslag på modifieringar och avgränsningar för att med hjälp av den aktuella formeln beakta penetration i betong av projektiler med ett förhållande mellan längd och projektildiameter på mellan 6 och 10, samt med ett förhållande mellan ogiveradie för nosen och projektildiameter på mellan 2 och 6. Den modifierade modellen överensstämmer relativt bra med tillgängliga penetrationsdata data från litteraturen.

Nyckelord

Betong, penetration, empirisk modell.

Övriga bibliografiska uppgifter	**Språk** Engelska
ISSN 1650-1942	**Antal sidor:** 18 s.
Distribution enligt missiv	**Pris: Enligt prislista**

Content

Introduction

Several empirical formulas, and formulas based on cavity expansion, are available for estimations of penetration performance of steel projectiles in concrete. In general, these formulas are intended for use within strict limitations. However, it seems that the use of extrapolation outside the validated data range is common. In some cases it's even necessary to obtain the original reference to be able to confirm if a specific formula can be used for a penetration case. There are also examples of penetration formulas were it's necessary to back calculate material parameters from similar penetration experiments. This makes the use of these types of formulas limited for prediction purposes, when experimental data isn't available. It's not likely that a penetration formula that can predict penetration performance for all types of cases will ever be developed. However, to get a first approximation of penetration performance or to use for specific penetration cases, an empirical formula can be useful. In this study, an existing penetration formula is compared with available experimental data regarding concrete penetration, and the limitations for empirical equations are discussed.

Penetration formulas

In general penetration formulas consider concrete strength, impact energy, CRH (Calibre Radius Head) and projectile cross section. Minor influences from other factors are also considered for some formulas, e.g. amount of reinforcement, aggregate type and ratio between projectile length and diameter. The formula used in ConWep (1992) is shown below in equation 1, which is an updated version from the one used in TM 5-855-1. This formula is used in this study for comparison with penetration data from available literature. The unconfined compressive strength of the concrete should be determined on cylinder samples with a length to diameter ratio of two. Diameters of the concrete samples or cores are normally between 75 to 100 mm. If cube strength is used as a quality measurement of the concrete it is necessary to reduce this value with approximately 10% to an unconfined compressive strength. However, the ratio between concrete strength measured on cubes and cylinders varies depending on the used concrete type. The unconfined compressive strength for cored cylinders is reduced compared with poured cylinders, and the strength also varies according to sample size. Both these phenomena need to be accounted for when a representative unconfined compressive strength is determined.

$$X = \frac{222 \times N \times W \times V^{1.8}}{D^{1.8} \times f'c^{0.5}} + D \quad for\ X > 2D\ (inch) \qquad \text{(eq. 1.)}$$

where

X = Penetration depth, inch
f'_c = Compressive strength of concrete, psi
N = Nose shape factor or nose performance coefficient (see eq. 2)
W = Projectile weight, lb
D = Projectile diameter, inch
V = $\frac{\text{Impact velocity in fps}}{1000}$

with
1 inch ≈ 25.4 mm
1 psi ≈ 6.89 kPa
1 lb ≈ 0.454 kg
1 fps ≈ 0.304 m/s

The nose performance coefficient N is given by:

$$N = 0.72 + 0.25(CRH - 0.25)^{0.5} \qquad \text{(eq. 2.)}$$

where

CRH = Calibre Radius Head, i.e. ratio between the tangent ogive radius and the projectile diameter.

A conversion of the units gives the formula

$$X = \frac{11.76 \times N \times M \times V^{1.8}}{D^{1.8} \times f'c^{0.5}} + D \quad for\ X > 2D\ (mm) \qquad \text{(eq. 3.)}$$

where

X = Penetration depth, mm
f'_c = Compressive strength of concrete, MPa
N = Nose shape factor or nose performance coefficient (see eq. 2. above)
M = Projectile mass, kg
D = Projectile diameter, mm
V = Impact velocity, m/s

A closer examination of the formula (eq. 1 and 3) shows that a scale effect is included, i.e. the ratio between penetration depth and projectile dimension changes with the size of the projectile. This is also seen in other empirical formulas for concrete penetration. This is further discussed in the "Discussion and summary" chapter later in the report.

Comparison with experimental data

The predictions from equation 3 were compared with experimental penetration data from the literature. References for these penetration tests are given in a separate part of the reference list at the end of the report, and the used penetration data are given in the appendix. The limitations of the used data range are given in table 1 below. The used concrete types contained different aggregate type, i.e. limestone or granite/gneiss, and both unreinforced, reinforced and fibre reinforced concrete targets are represented in the data. The confinement of the concrete target varies among the used data, and also the relative thickness and diameter of the target. Therefore, it's likely that the data are subjected to influence of boundary effects. The determined value for the concretes unconfined compressive strength varies with age and cylinder size, also testing of cast and cored cylinders gives different strength. If the cube strength is determined, this value is approximate 10% higher than the cylinder strength for a normal strength concrete due to the stress state in a cube at failure conditions. This will induce uncertainties for the value that should be used for unconfined concrete strength. The yaw of the projectile at impact is also likely to influence the penetration depth, and also adds further uncertainty to the experimental results.

The major part of the data refers to projectiles with 20 to 76 mm diameter, with a few data series with smaller or larger projectiles. The major part of the tests was also conducted with normal strength concretes, with uni-axial compressive strength varying between 35 and 60 MPa. A few of the tests were performed with concretes with greater strengths.

Table 1. The used data range for comparison with equation 3 in figures 1 and 2.

Parameter	**Minimum value**	**Maximum value**
Projectile diameter (mm)	12.9	365
Projectile length (mm)	88.9	1200
Projectile length to diameter ratio, L/D	3.0	15.0
Projectile ogive radius to diameter ratio, CRH	1.5	6.0
Projectile mass (kg)	0.064	485
Impact velocity (m/s)	132	1050
Uni-axial compressive strength, f´c (MPa)	21.6	140
Penetration depth (mm)	55	1960
Penetration depth/projectile length, X/L	0.36	8.55

From the comparison between equation 3 and the experimental data in figure 3 it's noticed that the penetration performance for a warhead is not likely to be under predicted, i.e. the penetration depth is likely to be greater than predicted. According to this the formula (eq. 3) can be used as an approximation of the lower limit of the performance of a penetrating warhead.

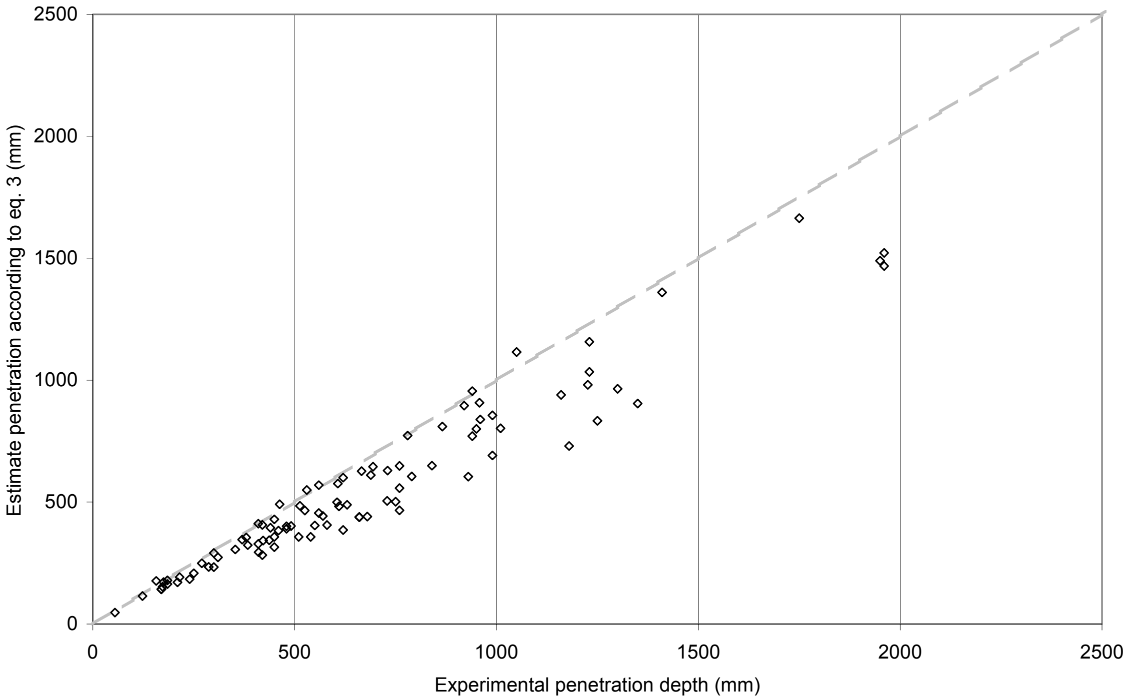

Figure 1. Estimated penetration depth according to equation 3 compared with experimental data.

An average value of the penetration performance is obtained if the results from equation 3 are multiplied by a factor of 1.25, see figure 2. The error bars in the figure indicate ±20% for the estimated penetration depth, from this it is seen that it is unlikely that a warhead will have a penetration performance better than 1.5 times the value determined by equation 3.

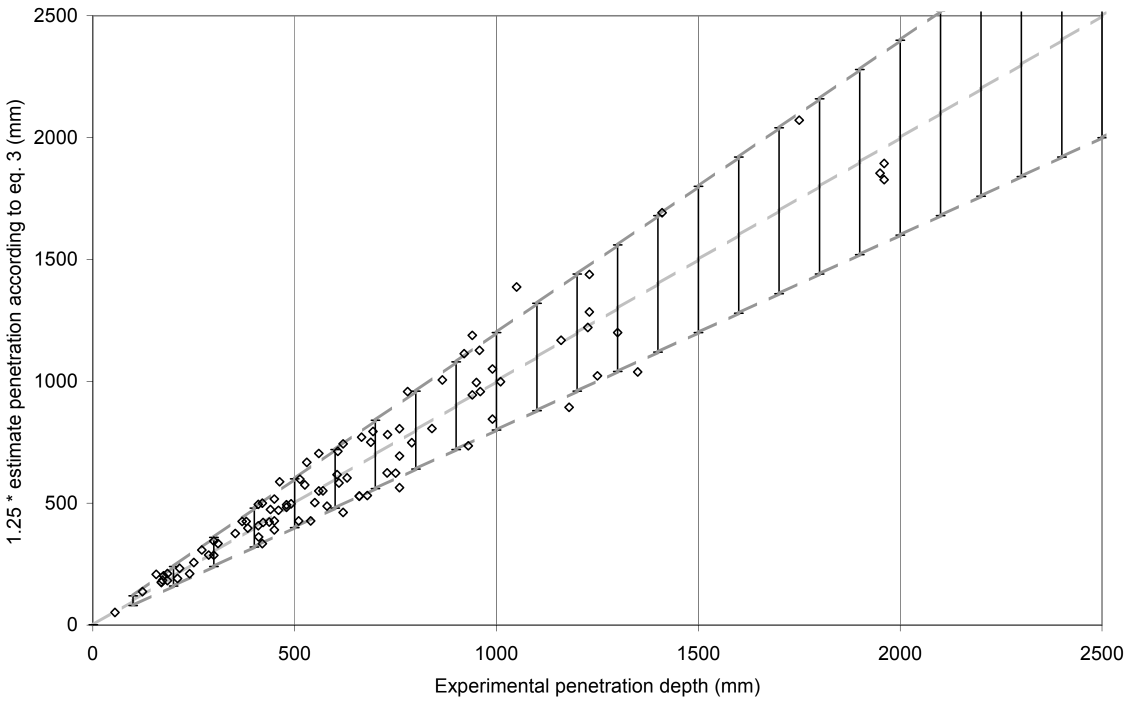

Figure 2. Estimated penetration depth according equation 3 multiplied with a factor of 1.25 and compared with experimental data. The error bars indicate ±20% of the predicted penetration depth.

Data for the penetration tests performed with a length to diameter ratio for the projectiles between 6 and 10 are plotted in figure 3 below, see also table 2. From the figure it's shown that equation 3 is likely to underestimate the penetration depths in a concrete with a high uni-axial compressive strength to a larger degree than for a normal strength concrete. Therefore, the maximum value for the uni-axial concrete strength in equation 3 should be limited to 65 MPa. To obtain a good correlation to an empirical equation it would be necessary to use experimental data from experiments with similar types of projectiles, impact conditions and concretes as the case that needs to be predicted. Otherwise, the uncertainties for the predictions are likely to be substantial. Data referring to concrete with limestone aggregate aren't used in the diagram. The reason for this is that concrete containing limestone aggregate normally offers less penetration resistance than concretes with granite aggregate.

Table 2. The used data range for comparison with equation 3 in figure 3.

Parameter	**Minimum value**	**Maximum value**
Projectile diameter (mm)	20.3	105
Projectile length (mm)	151	632
Projectile length to diameter ratio, L/D	6.0	10.0
Projectile ogive radius to diameter ratio, CRH	2.0	6.0
Projectile mass (kg)	0.48	30.4
Impact velocity (m/s)	132	1024
Uni-axial compressive strength, f´c (MPa)	32.4	108
Penetration depth (mm)	55	1750
Penetration depth/projectile length, X/L	0.36	6.43

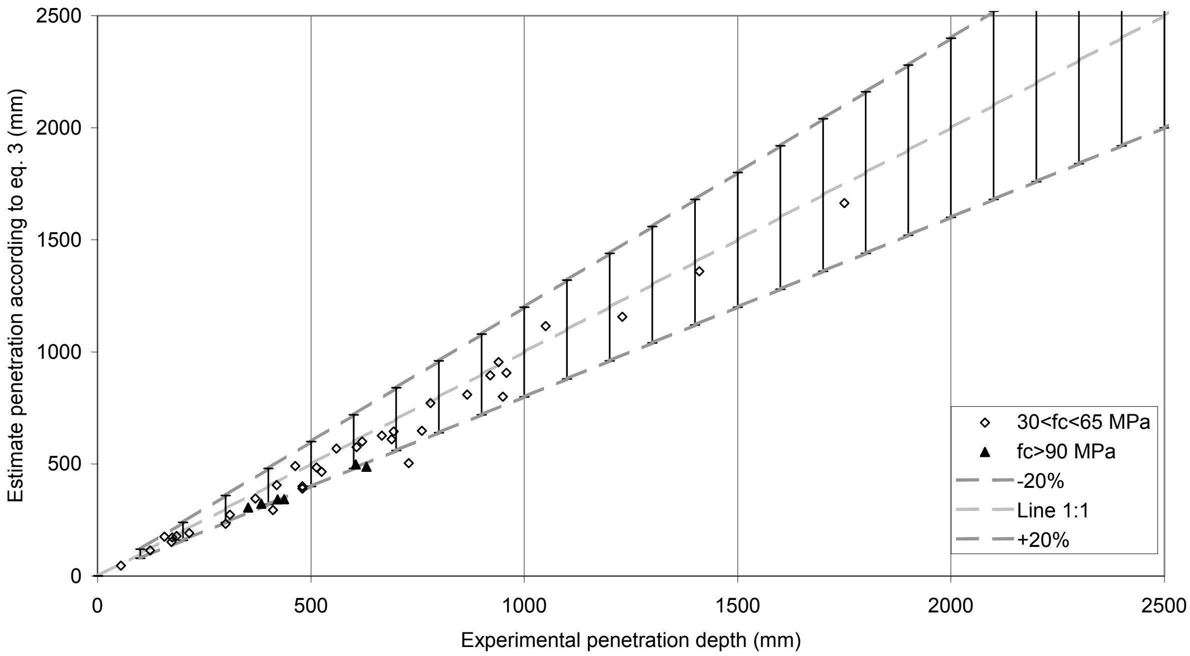

Figure 3. Estimated penetration depth according to equation 3 compared with experimental data for steel projectiles with a length to diameter ratio between 6 and 10. Penetration tests with concrete containing limestone aggregate are excluded from the data sets.

Discussion and summary

The estimated penetration depths in concrete given by the used formula (eq. 1 or 3) can be considered to be a first approximation for the lower limit of a warheads performance, and by multiplying the obtained result with a factor of 1.5 it's possible to get an approximation of the upper limit of the performance. However, considering the uncertainties for the experimental data, and the large variations regarding the test set-up for the experiments, the obtained penetration depth is a fair approximation of the test results. However, it's wise to keep in mind the limitations for different models, especially regarding the use of the formula for modern types of geopenetrators and/or High Performance Concrete (HPC). To obtain a good approximation of the performance of these types of penetrators it's necessary to develop special formulas, or use numerical tools. Heidar and Günther (1998) showed that the existing penetration formulas in the literature were unable to predict the performance in concrete of a modern geopenetrator to an acceptable degree. The used formulas resulted in prediction errors between 30% and 100%, i.e. some formulas only estimated half the penetration depth. There are also large variations for predicted penetration depth between different formulas when penetration of flat nosed projectiles in concrete is considered (Teland and Sjøl, 1999).

Hanchak et al. (1992) compared the penetration resistance for concretes with unconfined compressive strengths of 40 and 140 MPa, showing only minor difference in protective performance for projectiles with L/D=5.66 and CRH=3. The existing penetration formulas are therefore likely to under estimate the penetration depths in HPC, due to the fact that they aren't validated for these concrete types. The uncertainty regarding the estimated penetration performance increases even more if modern types of geopenetrators and HPC with an unconfined compressive strength of 90 MPa, or higher, are combined in one penetration case. If the formula (eq. 1 or 3) is used for these types of predictions it is necessary to consider the increased uncertainty for the penetration depth.

Further limitations of the empirical formulas arise if different target geometries, layered structures, varying impact conditions, multiple impact or dual charge warheads are considered. The risk of perforation, or scabbing at the back face of the target, is also necessary to estimate for the used combination of penetrator and target. These types of penetration cases further enhance the complexity of the penetration problems, and also increase the uncertainties of the predicted penetration depths.

The recommendations to improve the predictions are to use 65 MPa as an upper limit for the uni-axial compressive strength in the equation (eq. 3), and the length to diameter ratio of a considered steel projectile should not exceed 10. The predicted penetration depth for projectiles with a length to diameter ratio ≥6 should be increased with 6.5% to improve the correlation with existing experimental data for this type of projectiles. Furthermore, the aggregate for the concrete should be of granite or gneiss of good quality. Equivalent material, or material with higher resistance to penetration, is also suitable as aggregate for the concrete (e.g. bauxite, porphyry granite or mylonite). The penetration depth of a penetrator is increased if limestone, weathered granite or other "weak" material is used as aggregate for the concrete. The Mohs hardness for quarts based aggregate is approximately 7, while the hardness value for limestone aggregate is approximately 3. These recommendations are used for the data plotted in figure 4, with the use of the same data sets as for figure 3 earlier in the report. This results in a relative good prediction of the penetration depth for the projectiles, given the variations that normally are obtained for penetration tests.

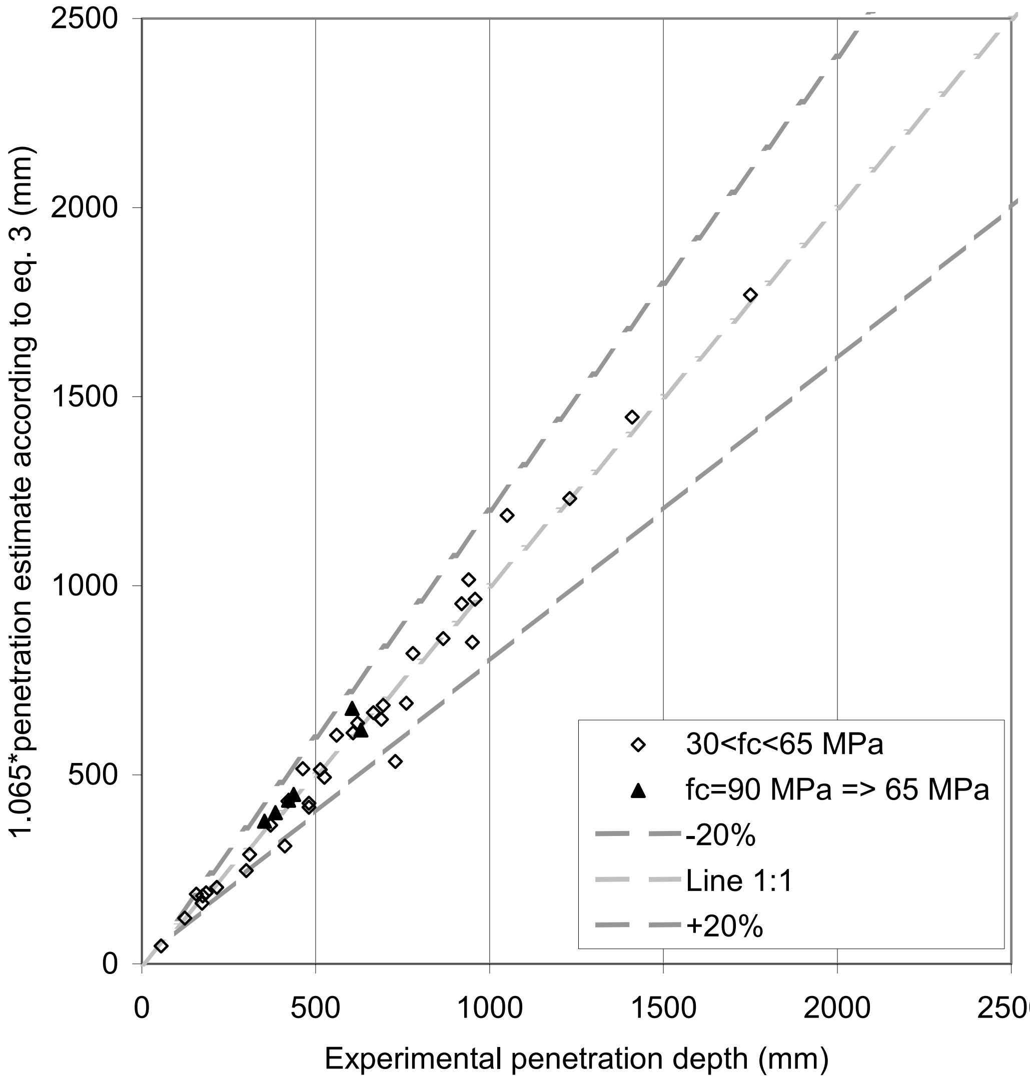

Figure 4. Estimated penetration depth according to equation 3 increased with 6.5% and compared with experimental data for steel projectiles with a length to diameter ratio between 6 and 10. Penetration tests with concrete containing limestone aggregate are excluded from the data sets. The uni-axial compressive strength are limited to 65 MPa in the formula for concretes with f'_c>65 MPa.

As discussed, the penetration depths for projectiles are increased for concretes with limestone aggregate compared with concrete with granite aggregates. To consider this it seems that the estimated penetration according to equation 1 or 3 should be increased with 26.5% for projectiles with a length to diameter ratio between 6 and 10. The results for a limestone data set using this recommendation are shown in figure 5 below. This recommendation might also give reasonable results for concrete with other relatively weak aggregate types.

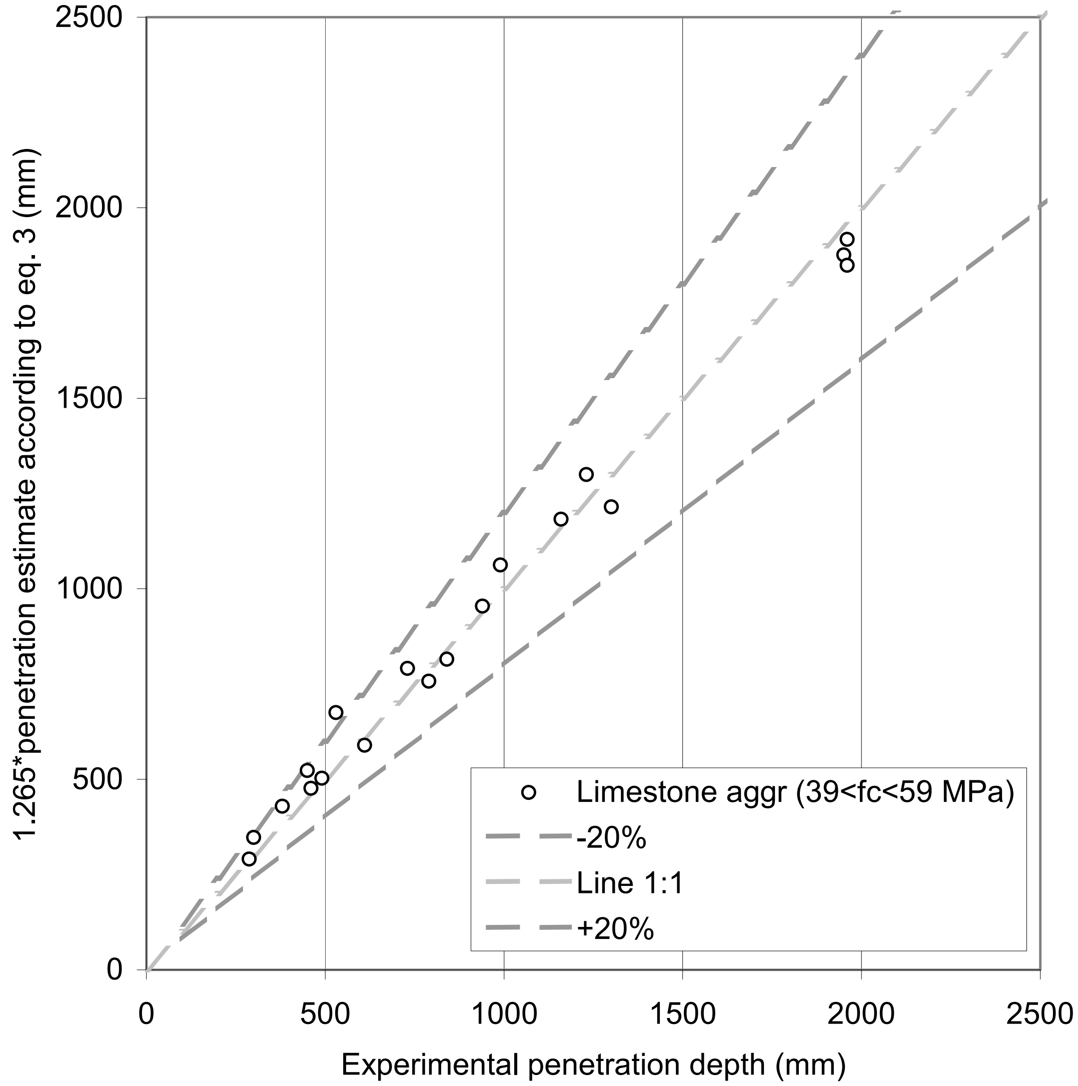

Figure 5. Estimated penetration depth according to equation 3 increased with 26.5% and compared with experimental data for steel projectiles with a length to diameter ratio between 6 and 10. The diagram is valid for concrete containing limestone aggregate.

It is quite usual that empirical equations for concrete penetration include a size effect or scale effect, as in the case for equations 1 and 3. The ratio between penetration depth and projectile dimension changes with the size of the projectile due to the scale effect. There are several phenomena that might result in a size effect for penetration of concrete, e.g. the variation of concrete strength by the considered volume. However, the greatest influence is likely to be caused by the increased strain rate in model scale tests. Replica scaling is only considered to hold if the strengths of the used materials are strain rate independent, otherwise a scaled down model/construction will appear stronger than the original design. It is also likely that models which incorporate materials that fracture on a global scale, e.g. due to cratering and scabbing, is likely to have size dependent penetration depths and exit velocities.

References

ConWep (Conventional weapons effects program), U.S. Army Engineer Waterways Experiment station, Vicksburg, 1992.

Hanchak, S. J., Forrestal, M. J., Young, E. R. and Ehrgott, J. Q., Perforation of Concrete slabs with 48 MPa (7 ksi) and 140 MPa (20 ksi) Unconfined Compressive Strengths, Int. J. Imp. Engng. Vol.12, No. 1, pp. 1-7, 1992.

Heidar, N. and Gűnther, U., Modern geopenetrators and relevant revision of concrete penetration models, Structures Under Shock and Impact V, 1998.

Teland, J. A. and Sjøl, H., An examination and reinterpretation of experimental data behind various empirical equations for penetration into concrete, 9th Int. Sym. Interaction of the Effects of Munitions with Structures, 1999.

References for penetration tests

Baty, R. S., Lundgren R. G. and Patterson W. J., On Pilot-Hole Assisted Penetration, 11th Int. Symposium Interaction of the Effects of Munitions with Structures, 2003.

Buzaud, E., Don, D., Chapelle, S., Gary, G. and Bailly, P., Perforation Studies into Mb50 Concrete Slabs, 9th Int. Sym. Interaction of the Effects of Munitions with Structures, 1999.

Buzaud, E., Laurensou, R., Darrigade, A., Belouet, P. and Lissayou, C., Hard Target Defeat: An Analysis of Reinforced Concrete Perforation Process, 9th Int. Sym. Interaction of the Effects of Munitions with Structures, 1999.

Dancygier, A.N. and Yankelevsky, D. Z., High stregth concrete response to hard projectile impact, Int. J Imp. Engng 18(6):583-599, 1996.

Gran, J. K. and Frew, D. J., In-target radial stress measurements from penetration experiments into concrete by ogive-nose steel projectiles, Int. J. Imp. Engng. Vol 19, No. 8, pp 715-726, 1997.

Gran, J. K., Moxley, R. E. and Adley, M. D., Measurement of Triaxial Stresses during Deep Penetration into Concrete, 9th Int. Sym. Interaction of the Effects of Munitions with Structures, 1999.

Forrestal M. J., Altman B. S., Cargile J. D. and Hanchak S. J., An empirical equation for penetration depth of ogive-nose projectiles into concrete targets, Int. J. Imp. Engng 15:395–405, 1994.

Forrestal, M.J., Frew, D.J., Hickerson, J.P. and Rohwer, T.A., Penetration of concrete targets with deceleration-time measurements, Int. J. Imp. Engng 28:479–497, 2003.

Forrestal M.J., Frew D.J., Hanchak S.J. and Brar N.S., Penetration of grout and concrete targets with ogive-nose steel projectiles, Int. J. Imp. Engng 18:465–76, 1996.

Frew D.J., Hanchak S.J., Green M.L. and Forrestal M.J., Penetration of concrete targets with ogive-nose steel rods, Int. J. Imp. Engng 21:489–97, 1998.

Hiermaier, S. and Thoma, K., Numerical Simulation of Penetration in Concrete Using Different Types of Code, 8th Int. Symposium Interaction of the Effects of Munitions with Structures, 1997.

Klughardt, G., Testing of Concrete-Penetrating Bombs from the Inventory of the Former GDR's Armed Forces, 9th Int. Sym. Interaction of the Effects of Munitions with Structures, 1999.

Magnusson, J., Unosson, M. and Carlberg, A., High performance concrete "HPC"-field experiments and production, FOI-R--0256--SE, ISSN 1650-1942, 2001.

Riedel, W., Thoma, K., Hiermaier, S. and Schmolinske,E., Penetration of Reinforced Concrete by BETA-B-500 Numerical Analysis using a New Macroscopic Concrete Model for Hydrocodes, 9th Int. Sym. Interaction of the Effects of Munitions with Structures, 1999.

Appendix: Used penetration data from literature.

Test id	M (kg)	D (mm)	Ogive (mm)	f´c (MPa)	V (m/s)	L (mm)	L/D	CRH	N	Pen. (mm)	X * (mm)	Reference
75 mm -97 Test no. 1	6.28	75.0	127	35 #	484	225	3.00	1.69	1.02	680	440	J. Magnusson et al. 2001
75 mm -97 Test no. 3	6.28	75.0	127	35 #	483	225	3.00	1.69	1.02	660	439	J. Magnusson et al. 2001
75 mm -97 Test no. 4	6.28	75.0	127	35 #	482	225	3.00	1.69	1.02	660	438	J. Magnusson et al. 2001
75 mm -98:2 Test no. 8	6.28	75.0	127	35 #	647	225	3.00	1.69	1.02	990	691	J. Magnusson et al. 2001
75 mm -98:2 Test no. 9	6.28	75.0	127	95 #	653	225	3.00	1.69	1.02	560	455	J. Magnusson et al. 2001
75 mm -98:2 Test no. 10	6.28	75.0	127	130 #	647	225	3.00	1.69	1.02	440	395	J. Magnusson et al. 2001
75 mm -98:2 Test no. 12	6.28	75.0	127	75 #	571	225	3.00	1.69	1.02	410	411	J. Magnusson et al. 2001
75 mm -99 Test 1	6.28	75	127	140 #	620	225	3.00	1.69	1.02	450	360	J. Magnusson et al. 2001
75 mm -99 Test 2	6.28	75	127	140 #	612	225	3.00	1.69	1.02	540	354	J. Magnusson et al. 2001
75 mm -99 Test 3	6.28	75	127	140 #	619	225	3.00	1.69	1.02	510	359	J. Magnusson et al. 2001
DA544	0.50	25.0	75	38.4	292	151	6.06	3.00	1.13	123	115	E. Buzaud et al., 1999
DA552	0.50	25.0	75	38.4	132	151	6.06	3.00	1.13	55	47	E. Buzaud et al., 1999
Test no. 1	2.30	50.8	152	43	320	356	7.00	3.00	1.13	185	179	J.K. Gran and D.J. Frew, 1997
Test no. 2	2.30	50.8	152	43	310	356	7.00	3.00	1.13	175	172	J.K. Gran and D.J. Frew, 1997
Test no. 3	2.30	50.8	152	43	316	356	7.00	3.00	1.13	157	176	J.K. Gran and D.J. Frew, 1997
SNL-00-06/2	13.0	76.2	229	23	139	531	6.96	3.00	1.13	240	184	M.J. Forrestal et al. 2003
SNL-00-03/1	13.0	76.2	229	23	200	531	6.96	3.00	1.13	420	282	M.J. Forrestal et al. 2003
SNL-00-02/2	13.1	76.2	229	23	250	531	6.96	3.00	1.13	620	385	M.J. Forrestal et al. 2003
SNL-00-01/1	13.2	76.2	229	23	284	531	6.96	3.00	1.13	760	466	M.J. Forrestal et al. 2003
SNL-00-05/3	13.1	76.2	229	23	337	531	6.96	3.00	1.13	930	604	M.J. Forrestal et al. 2003
SNL-00-04/4	13.1	76.2	229	23	379	531	6.96	3.00	1.13	1180	730	M.J. Forrestal et al. 2003
SNL-00-08/2	13.1	76.2	457	23	238	528	6.94	6.00	1.32	580	405	M.J. Forrestal et al. 2003
SNL-00-07/1	13.1	76.2	457	23	379	528	6.94	6.00	1.32	1250	833	M.J. Forrestal et al. 2003
SNL-00-11/3	12.9	76.2	229	39	238	531	6.96	3.00	1.13	300	291	M.J. Forrestal et al. 2003
SNL-00-12/4	12.9	76.2	229	39	276	531	6.96	3.00	1.13	380	355	M.J. Forrestal et al. 2003
SNL-00-09/1	12.9	76.2	229	39	314	531	6.96	3.00	1.13	450	429	M.J. Forrestal et al. 2003
SNL-00-10/2	12.9	76.2	229	39	370	531	6.96	3.00	1.13	530	549	M.J. Forrestal et al. 2003
SNL-00-14/5	13.0	76.2	229	39	456	531	6.96	3.00	1.13	940	770	M.J. Forrestal et al. 2003
SNL-00-15/2	12.9	76.2	457	39	313	528	6.94	6.00	1.32	610	482	M.J. Forrestal et al. 2003
SNL-00-16/3	12.9	76.2	457	39	449	528	6.94	6.00	1.32	990	856	M.J. Forrestal et al. 2003
WTD91 - 6	485	363	750	37	259	1200	3.31	2.07	1.06	1350	904	W. Riedel et al., 1999
WTD91 - 3	433	363	750	39	261	1200	3.31	2.07	1.06	960	839	W. Riedel et al., 1999
EMI - 1934	6.63	90.8	184	40.5	238	300	3.31	2.03	1.05	185	164	W. Riedel et al., 1999
EMI - 1935	6.64	90.8	184	42.4	254	300	3.31	2.03	1.05	210	171	W. Riedel et al., 1999
EMI	0.595	25.0	100	50	389			4.00	1.20	215	192	S. Hiermaier and K. Thoma, 1997

Note *: X refers to penetration calculated according equation 3 (ConWep, 1992). #: Estimated from measured cube strength.

Test id	M (kg)	D (mm)	Ogive (mm)	f´c (MPa)	V (m/s)	L (mm)	L/D	CRH	N	Pen. (mm)	X * (mm)	Reference
Test no. 4	4.37	50.8	152	40.5	516	387	7.62	3.00	1.13	694	646	J. K. Gran et al., 1999
Test no. 5	4.38	50.8	152	41.6	510	387	7.62	3.00	1.13	666	627	J. K. Gran et al., 1999
Test no. 6	4.38	50.8	152	42.4	505	387	7.62	3.00	1.13	689	610	J. K. Gran et al., 1999
Test #3	30.4	105	314	34.5	273	632	6.03	3.00	1.13	463	491	R. G. Baty et al, 2003
1-0354	0.478	20.3	60.9	58.4	442	203	10.0	3.00	1.13	287	234	D. J. Frew et al., 1998
1-0355	0.478	20.3	60.9	58.4	610	203	10.0	3.00	1.13	491	402	D. J. Frew et al., 1998
1-0356	0.478	20.3	60.9	58.4	805	203	10.0	3.00	1.13	840	649	D. J. Frew et al., 1998
1-0357	0.478	20.3	60.9	58.4	1009	203	10.0	3.00	1.13	1300	964	D. J. Frew et al., 1998
1-0390	0.478	20.3	60.9	58.4	791	203	10.0	3.00	1.13	730	629	D. J. Frew et al., 1998
1-0391	0.478	20.3	60.9	58.4	994	203	10.0	3.00	1.13	1160	939	D. J. Frew et al., 1998
1-0367	0.606	20.3	60.9	58.4	797	254	12.5	3.00	1.13	1010	803	D. J. Frew et al., 1998
1-0369	0.734	20.3	60.9	58.4	803	305	15.0	3.00	1.13	1226	981	D. J. Frew et al., 1998
LROD95-1	1.62	30.5	91.5	58.4	445	305	10.0	3.00	1.13	460	383	D. J. Frew et al., 1998
LROD95-2	1.62	30.5	91.5	58.4	584	305	10.0	3.00	1.13	790	605	D. J. Frew et al., 1998
LROD95-3	1.62	30.5	91.5	58.4	796	305	10.0	3.00	1.13	1230	1034	D. J. Frew et al., 1998
LROD96-0	1.62	30.5	91.5	58.4	980	305	10.0	3.00	1.13	1950	1489	D. J. Frew et al., 1998
LROD95-4	1.62	30.5	91.5	58.4	992	305	10.0	3.00	1.13	1960	1522	D. J. Frew et al., 1998
LROD96-1	1.62	30.5	91.5	58.4	972	305	10.0	3.00	1.13	1960	1468	D. J. Frew et al., 1998
fc=35 Test no. 14	0.906	26.9	53.8	35.2	277	242	9.01	2.00	1.05	173	152	M. J. Forrestal et al., 1994
fc=35 Test no. 13	0.910	26.9	53.8	37.8	410	242	9.01	2.00	1.05	310	273	M. J. Forrestal et al., 1994
fc=35 Test no. 15	0.907	26.9	53.8	38.1	431	242	9.01	2.00	1.05	411	295	M. J. Forrestal et al., 1994
fc=35 Test no. 11	0.912	26.9	53.8	33.5	499	242	9.01	2.00	1.05	480	400	M. J. Forrestal et al., 1994
fc=35 Test no. 12	0.910	26.9	53.8	38.4	567	242	9.01	2.00	1.05	525	465	M. J. Forrestal et al., 1994
fc=35 Test no. 2	0.905	26.9	53.8	36.9	590	242	9.01	2.00	1.05	729	504	M. J. Forrestal et al., 1994
fc=35 Test no. 1	0.901	26.9	53.8	40.1	591	242	9.01	2.00	1.05	513	484	M. J. Forrestal et al., 1994
fc=35 Test no. 3	0.903	26.9	53.8	35.4	631	242	9.01	2.00	1.05	607	576	M. J. Forrestal et al., 1994
fc=35 Test no. 4	0.905	26.9	53.8	34.7	642	242	9.01	2.00	1.05	620	600	M. J. Forrestal et al., 1994
fc=35 Test no. 5	0.901	26.9	53.8	36.0	773	242	9.01	2.00	1.05	866	810	M. J. Forrestal et al., 1994
fc=35 Test no. 6	0.904	26.9	53.8	32.4	800	242	9.01	2.00	1.05	958	908	M. J. Forrestal et al., 1994

Note *: X refers to penetration calculated according equation 3 (ConWep, 1992).

Test id	M (kg)	D (mm)	Ogive (mm)	f´c (MPa)	V (m/s)	L (mm)	L/D	CRH	N	Pen. (mm)	X * (mm)	Reference
fc=90 Test no. 2	0.907	26.9	53.8	90.5	561	242	9.01	2.00	1.05	353	306	M. J. Forrestal et al., 1994
fc=90 Test no. 1	0.898	26.9	53.8	91.0	584	242	9.01	2.00	1.05	384	323	M. J. Forrestal et al., 1994
fc=90 Test no. 3	0.908	26.9	53.8	95.0	608	242	9.01	2.00	1.05	422	342	M. J. Forrestal et al., 1994
fc=90 Test no. 4	0.905	26.9	53.8	101	622	242	9.01	2.00	1.05	437	344	M. J. Forrestal et al., 1994
fc=90 Test no. 6	0.907	26.9	53.8	94.0	750	242	9.01	2.00	1.05	630	489	M. J. Forrestal et al., 1994
fc=90 Test no. 5	0.900	26.9	53.8	108	793	242	9.01	2.00	1.05	605	499	M. J. Forrestal et al., 1994
6-2460	0.064	12.9	38.7	21.6	492	88.9	6.89	3.00	1.13	170	142	M. J. Forrestal et al., 1996
6-2467	0.064	12.9	38.7	21.6	618	88.9	6.89	3.00	1.13	250	208	M. J. Forrestal et al., 1996
6-2461	0.064	12.9	38.7	21.6	788	88.9	6.89	3.00	1.13	450	315	M. J. Forrestal et al., 1996
6-2469	0.064	12.9	38.7	21.6	910	88.9	6.89	3.00	1.13	550	404	M. J. Forrestal et al., 1996
6-2464	0.064	12.9	38.7	21.6	1029	88.9	6.89	3.00	1.13	750	501	M. J. Forrestal et al., 1996
6-2459	0.064	12.9	54.8	21.6	473	88.9	6.89	4.25	1.22	170	143	M. J. Forrestal et al., 1996
6-2468	0.064	12.9	54.8	21.6	660	88.9	6.89	4.25	1.22	270	249	M. J. Forrestal et al., 1996
6-2462	0.064	12.9	54.8	21.6	775	88.9	6.89	4.25	1.22	410	328	M. J. Forrestal et al., 1996
6-2470	0.064	12.9	54.8	21.6	921	88.9	6.89	4.25	1.22	570	443	M. J. Forrestal et al., 1996
6-2463	0.064	12.9	54.8	21.6	1050	88.9	6.89	4.25	1.22	760	558	M. J. Forrestal et al., 1996
1-0335	0.478	20.3	60.9	62.8	450	203	10.0	3.00	1.13	300	233	M. J. Forrestal et al., 1996
1-0336	0.478	20.3	60.9	62.8	612	203	10.0	3.00	1.13	480	390	M. J. Forrestal et al., 1996
1-0337	0.478	20.3	60.9	62.8	821	203	10.0	3.00	1.13	760	648	M. J. Forrestal et al., 1996
1-0341	0.478	20.3	60.9	62.8	926	203	10.0	3.00	1.13	950	800	M. J. Forrestal et al., 1996
1-0346	0.478	20.3	60.9	62.8	987	203	10.0	3.00	1.13	920	895	M. J. Forrestal et al., 1996
1-0338	0.478	20.3	60.9	62.8	1024	203	10.0	3.00	1.13	940	955	M. J. Forrestal et al., 1996
LROD-2	1.61	30.5	91.5	51	405	305	10.0	3.00	1.13	370	346	M. J. Forrestal et al., 1996
LROD-3	1.61	30.5	91.5	51	446	305	10.0	3.00	1.13	420	406	M. J. Forrestal et al., 1996
LROD-6	1.61	30.5	91.5	51	545	305	10.0	3.00	1.13	560	569	M. J. Forrestal et al., 1996
LROD-4	1.61	30.5	91.5	51	651	305	10.0	3.00	1.13	780	773	M. J. Forrestal et al., 1996
LROD-8	1.61	30.5	91.5	51	804	305	10.0	3.00	1.13	1050	1116	M. J. Forrestal et al., 1996
LROD-5	1.61	30.5	91.5	51	821	305	10.0	3.00	1.13	1230	1157	M. J. Forrestal et al., 1996
LROD-9	1.61	30.5	91.5	51	900	305	10.0	3.00	1.13	1410	1360	M. J. Forrestal et al., 1996
LROD-10	1.61	30.5	91.5	51	1009	305	10.0	3.00	1.13	1750	1664	M. J. Forrestal et al., 1996

Note *: X refers to penetration calculated according equation 3 (ConWep, 1992).