FFI Norwegian Defence
Research Establishment

23/01670

FFI-RAPPORT

Penetration into rock-rubble overlays

Jan Arild Teland

Penetration into rock-rubble overlays

Jan Arild Teland

Norwegian Defence Research Establishment (FFI) 15 January 2024

Keywords
Penetrasjon
Stein
Penetrasjon
IMPETUS

FFI report
23/01670

Project number
1581

Electronic ISBN
978-82-464-3489-6

Approvers
Morten Huseby, *forskningsleder*
Halvor Ajer, *forskningssjef*

The document is electronically approved and therefore has no handwritten signature.

Copyright
© Norwegian Defence Research Establishment (FFI). The publication may be freely cited where the source is acknowledged.

Summary

Rock-rubble overlays can be used for protection against projectiles. Due to the asymmetric and stochastic properties of a rock-rubble overlay, incoming projectiles can be deflected or may even ricochet. In this report we investigate penetration into rock-rubble overlays using the numerical code IMPETUS. The numerical results were seen to be in surprisingly good agreement with the only known empirical formula for penetration depth.

Sammendrag

Steinfyllinger kan brukes som beskyttelse mot prosjektiler. På grunn av de usymmetriske og stokastiske egenskapene til en steinfylling kan innkommende prosjektiler avbøyes eller rikosjettere. I denne rapporten undersøker vi penetrasjon i steinfylling med den numeriske koden IMPETUS. Det viste seg at de numeriske resultatene var i overraskende god overensstemmelse med den eneste kjente empiriske formelen for penetrasjonsdybde.

Contents

1 Introduction

A rock-rubble overlay is a collection of randomly distributed rocks in close proximity. Such a construction is often used as an alternative to (mostly) homogenous concrete slabs for protection of underground facilities against penetration. Rock-rubble overlays have the advantage of being much cheaper (if rocks are available nearby, they just need to be moved) and easier to repair than concrete slabs. For extra protection, sometimes rock-rubble overlays are used in combination with concrete slabs.

Rock-rubble overlays have stochastic properties and are asymmetric in nature. As a consequence, they have a tendency to deflect incoming projectiles or possibly even cause ricochet (Figure 1.1). It follows that the exact penetration tunnel in rock-rubble will be much more sensitive to initial conditions than in a homogenous material. This, in turn, implies that it is very difficult to develop analytical or empirical formulas for their protection capability, in particular the penetration depth. As far as we are aware, the only formula for this situation is given in the American manual UFC 3-340-1.

Neither has much work been done on rock-rubble overlay using numerical simulations. The statistical nature of the situation may seem to imply that while simulations are possible in principle, a huge number of them may be necessary to obtain statistically valid results. The most advanced approach so far (1) used LS-DYNA to study the sensitivity to various parameters. In this report we will study penetration into rock-rubble overlays using numerical simulations with the code IMPETUS. Our focus will be mainly on seeing whether some useful information can be derived from numerical simulations, in particular whether IMPETUS is capable of reproducing the main features of the UFC-formula.

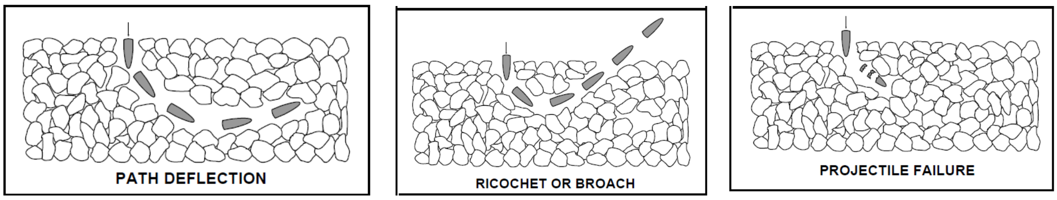


Figure 1.1 Projectile penetration into rock-rubble overlays (from UFC 3-340-1).

2 Numerical code

IMPETUS (2) is a Finite Element code, mostly used for describing non-linear mechanical problems where extreme loadings can lead to large deformations. The code was initially developed to model detonation of buried charges under vehicles, but has later grown to include many other uses.

IMPETUS has much in common with AUTODYN (3), but is better suited for certain problems, while at the same time lacking some of the opportunities in AUTODYN (no Euler solver for instance, though one is currently being developed). One of the advantages of IMPETUS is that it has been explicitly written to run on GPUs. In many cases GPUs are able to calculate very much faster than CPUs. Additionally, IMPETUS has a unique particle model that can be used to model sand and air, and which is not affected by technical problems of the standard methods (interaction between Euler and Lagrangian grids) in AUTODYN and similar codes. At FFI the calculation part of IMPETUS is run on a dedicated server with a number of GPUs. This gives considerably larger computing power and speed than AUTODYN on a normal PC.

Pre- and post processing of the IMPETUS simulations are done on a normal PC. During the covid-19 pandemic, another server was added enabling the possibility of running unclassified simulations on the internet from home.

3 Simplifications

The penetration process into homogenous materials have been studied extensively both at FFI and in the weapons effects community as a whole (4). In this case the penetration process typically depends on the following parameters:

- Impact angle
- Impact velocity
- Material properties

However, the penetration process in a stochastic and unsymmetric material such as rock-rubble overlays means that more factors are relevant:

- Point of impact
- Rock shapes

- Rock sizes
- Rock distribution
- etc…

It should be clear that a small change in any of these parameters may lead to the projectile experiencing different forces and possibly take a completely different path through the rock-rubble overlay. This seems to suggest that an enormous amount of simulations are necessary to obtain statistically valid results. For the moment we avoid this problem by simplifying the problem somewhat.

More precisely, the following simplifications are made:

- All rocks are spherical
- All rocks have the same diameter
- The rocks are packed as densely as possible

We will later discuss the potential impact of these simplifications on the results.

4 Empirical data

The only empirical data we are aware of has been summarized in the manual UFC 3-340-1. This manual links to internal American reports that we have not found on online. We do therefore not have the original data, but only the empirical formula developed based on this data.

The empirical formula for penetration depth in a semi-infinite rock-rubble target from UFC 3-340-1 is given by Equation (1):

$$\begin{aligned} x &= av \\ a &= 6.925\frac{m}{D^2\sqrt{C}}B^{-0.075}f_5 f_6 f_7 \end{aligned} \tag{4.1}$$

We see that the penetration depth is linear in velocity, with a relatively complicated proportional constant *a* depending on several parameters. The formula is valid for the projectile length/diameter ranges *L/D* = [2.75, 7] and *v*=[150, 370] m/s.

Let us first explain the parameters involved in the formula.

x: Penetration depth (m)

m: Projectile mass (kg)

D: Projectile diameter (mm)

B: Boulder size (mm). Note that in the equation this enters through $B^{-0.075}$. Since the exponent is so close to zero, this factor will be nearly constant.

C: Ratio between rock diameter and projectile diameter, $C=B/D$. Only valid in range $C=[1,3]$. For $C=1$, rocks and projectile are the same size. For $C=3$, the rocks are bigger than the projectile. (The formula has not been extended to $C > 3$ as these boulders would be so large, that they would in any case be difficult to handle in building a rock-rubble overlay without heavy machinery).

f_5: Function of L/D and C are given by the graphs in Figure 4.1.

f_6: Function of filling material between the rocks (Table 4.1).

f_7: Function of rock type (Table 4.1). The only distinction is between hard rock ($f_7=1.0$) and soft rock ($f_7=1.4$).

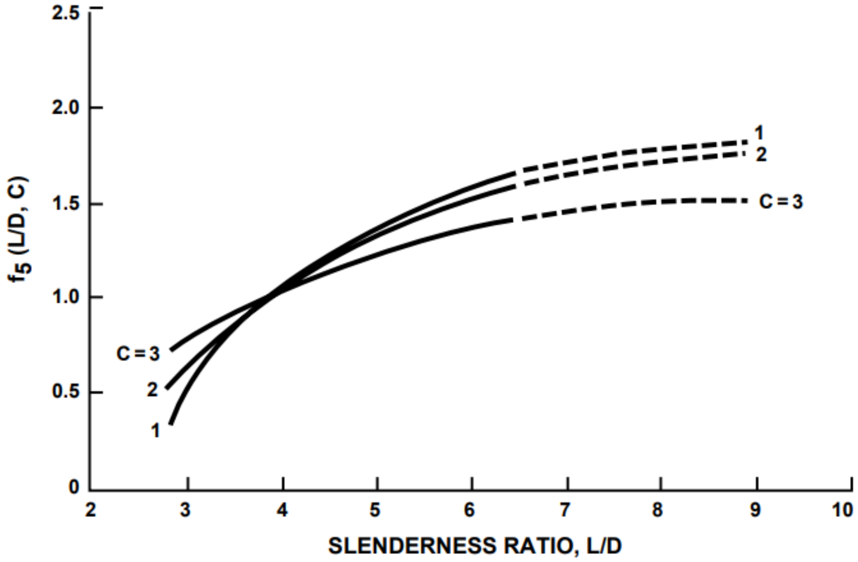


Figure 4.1 Definition of f_5. (From UFC 3-340-1).

Rock Caliber	Filler Material		
	Air	Fine Sand	Grout[1]
1	1.0	0.6	0.185
2	1.0	0.6	0.225
3	1.0	0.6	0.250

Rock Caliber	Hard Rock Compressive Strength 200 MPa To 300 MPa	Soft Rock Compressive Strength 30 MPa
1	1.0	1.0
2	1.0	1.4
3	1.0	1.4

Table 4.1 Definitions of f_6 (left) and f_7 (right).

Equation (4.1) becomes a lot easier to interpret if we insert values for the projectile parameters we will use in our simulations (see Chapter 5), assuming hard rock. This gives us:

$$x = av$$

$$a = 0.0288\frac{1}{\sqrt{C}}B^{-0.075}$$

Now the formula basically only depends on B and C. Further, B will vary from 200 mm to 600 mm, which means that $B^{-0.075}$ varies from 0.672 to 0.619, i.e. a difference of less than 10%. Thus, for a given impact velocity the dependency on rock size is almost exclusively given by the $C^{-1/2}$ factor. Further, for a given rock size, the penetration depth is proportional to the impact velocity.

Thus, we can test the following functional dependence in the simulations, even if the exact penetration depth does not turn out correctly:

- Dependence of penetration depth on $C^{-1/2}$.
- Dependence of penetration depth on v.

5 Numerical simulation set-up

5.1 Generating rock-rubble in IMPETUS

One potentially challenging problem in setting up simulations is to generate a rock-rubble overlay in IMPETUS. Even with the given simplifications, this may not have been trivial. It is easy enough to generate one rock by using *COMPONENT_SPHERE. However, this method is not feasible for overlays that contain thousands of rocks. A copy-paste method will be very boring and time consuming, especially if it is necessary to change some parameters of the overlay.

Fortunately, from correspondence with the IMPETUS developer, we learned that IMPETUS already had an undocumented(!) way of generating rock-rubble overlays. The undocumented command is very simple and the only required user input is:

- Geometric dimensions of the rock-rubble overlay
- Number of rocks

The syntax is shown in the Appendix A.1.

Using this feature, it was very easy to generate the required rock-rubble overlays. Since there will be air (vacuum) between the rocks, this corresponds to a parameter value of f_6=1.0 in Equation (4.1).

5.2 Projectile

In this first approach a generic projectile was used. The geometry was chosen to be roughly similar to an actual warhead. The projectile had a length of 800 mm and a diameter of 200 mm (Figure 5.1). Assuming the density to be similar to steel, the projectile mass becomes 166.4 kg. We note that for our chosen projectile we have *L/D*=4, in which case f_5 is roughly equal to 1.0 for all values of *C*.

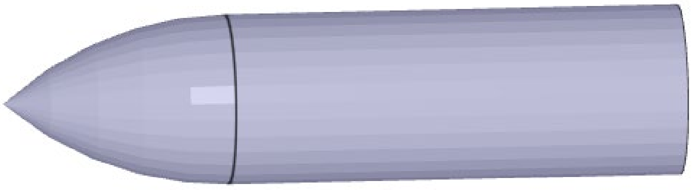


Figure 5.1 Generic projectile for the simulations.

For further simplification the projectile was modelled as rigid with density of steel. This was not expected to make any difference for relatively low impact velocities, where the empirical formula is valid.

5.3 Granite model

There are not a great deal of available material models for granite in the literature. In our simulations we used a model developed by Ai and Ahrens (5). This granite model is based on

Johnson-Holmquist model (JH-2). The parameters are reproduced in Table 5.1 and the IMPETUS material file is shown in Appendix A.3.

If the empirical formula is correct, the penetration depth is not very sensitive to the type of rock. Since our model is chosen almost at random, it is however unlikely to match exactly the rocks used in the experiments. However, this should not be a major concern, since we are mostly interested in the trend when varying the rock size and the impact velocity.

Density	2657 kg/m^3
Shear modulus	30.0 GPa
A	1.01
B	0.68
C	0.005
m	0.76
n	0.83
epsilon_0	1
Hugoniot Elastic limit	4.5 GPa
HEL pressure	2.73 GPa
Tensile strength	0.15 GPa
Beta	1
D_1	0.005
D_2	0.7
K_1	55.6 GPa
K_2	-23 GPa
K_3	2980 GPa

Table 5.1 Material parameters for the granite model used in the simulations.

We used numerical erosion instead of node splitting to decrease simulation time. A geometric strain = 2.0 was chosen as erosion criterion.

5.4 Target

The size of the target was initially chosen to be rectangular of 4 m x 4 m x 6 m. However, it was seen that in *C=1.0* case the penetration depth was very close to 6 meters leading to suspected boundary effects. For *C=1.0* therefore the dimensions were expanded to 4 m x 4 m x 8 m. This was extremely time consuming in the *C=1.0* case. Also, this case used a lot of memory and could only be run in parallell on multiple GPUs. This meant that while the simulation was running, all other users were prevented from running their own simulations due to all computer memory being used. For this reason, no study of the effect of different impact points was performed for C=1.0, except for at impact velocity of 350 m/s.

It turned out that the target side dimensions of 4 meters was too small to avoid the projectile exiting the target side in a few cases. Unfortunately, it was difficult to avoid this without creating a bigger target (which would have caused further memory problems). A potential future solution could be to enclose everything in a box. Still, this did probably not affect the results too much since the residual velocity was very low for the projectiles that exited the target.

An example of the IMPETUS simulation file is shown in Appendix A.

6 Numerical simulations

To test the *C* (rock/projectile diameter) and velocity dependence of the empirical formula, we performed a range of simulations with different values of these parameters. More precisely, simulations were run for the following cases:

- *C*=1.0, 1.5, 2.0, 2.5 and 3.0
- Impact velocities = 150 m/s, 250 m/s and 350 m/s.

Further, to get statistically relevant data, the simulations were performed with varying impact points (+/- 10 cm in x- and y-directions), except, as explained earlier for *C*=1.0.

Most simulations were run for 40 ms. At this time, usually the projectile had come to rest in the z-direction or had a very small residual velocity which would not result in much extra penetration. In some cases, for the *C*=1.0 simulations, the projectile was still moving at a considerable velocity, and those were extended to 60 ms.

The penetration depth was measured by integration of the the z-component of the velocity of the center of mass. This was much simpler than manual inspection since the penetration channel is not obvious in a target with cavities and a large number of rocks being pushed around.

6.1 Rock size dependency

The setup for C=1.0, 2.0 and 3.0 is shown in Figure 6.1.

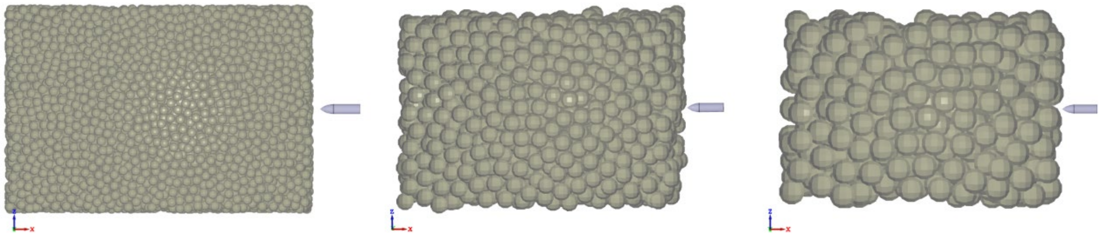


Figure 6.1 Simulation setup for C=1 (left), C=2 (middle) and C=3 (right).

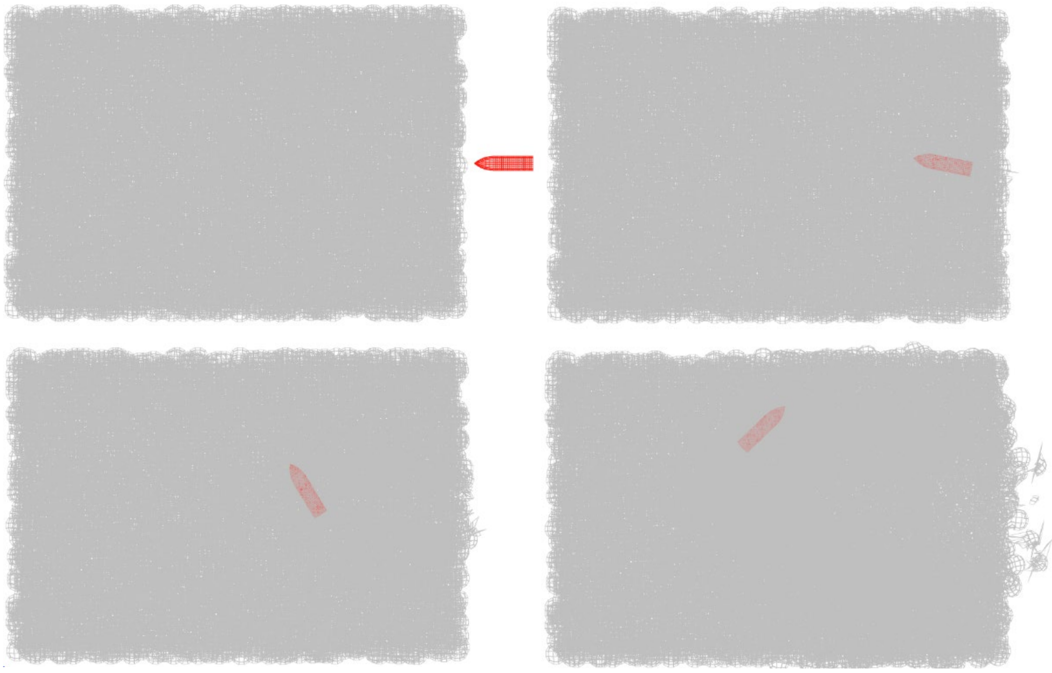


Figure 6.2 Center impact (0,0), C=1.5, 250 m/s at t=0 ms, t=6 ms, t=14 ms and t=40 ms (projectile at rest).

The penetration process is not so easy to visualize due to the 3D nature of the situation. However, in Figure 6.2 we have made an attempt. There we see the projectile penetrating a target with C=1.5, v=250 m/s and center impact. We note that the projectile tumbles before finally coming to rest having rotated about 135 degrees along the axis into the plane.

The tumbling is obviously a results of the target being non-homogenous. With a different impact point, the projectile will hit the surface of the first rock at a different angle, which may lead to a quite different penetration process. In Figure 6.3 we have shown the final state (t=40 ms) for three different cases where the impact point has been skewed 10 cm in three different directions. It is clearly seen that small changes to the impact point may lead to very different outcomes for the final projectile position.

Figure 6.3 Final state with impact point skewed from central impact. Left: (x,y) =(-10,0) cm, Middle: (x,y)= (0,10) cm, Right: (x,y)=(0, -10) cm. (x-axis is into the plane).

To compare the simulation results with the empirical formula, we need a value for the f_7 parameter. Since we are using a random granite material model, there is no obvious correspondence. From Table 4.1 we see that f_7 is usually 1.0, except for soft rocks with C equal to 2.0 or bigger. Initially we will assume that our granite model is hard and thus corresponds to a value of f_7=1.0.

We are now able to plot the simulation results for penetration depth and compare with the UFC-formula. This has been done in Figure 6.4 for an impact velocity of 250 m/s. The penetration depth is quite dependent on impact point for all values of C, but in general there seems to be very good agreement with the empirical formula. The exception is for $C=2.5$ where all simulations give too little penetration. Our guess is that this is a coincidence with the impact points, since there seems to be no obvious reason why C=2.5 should give less penetration than C=3.0.

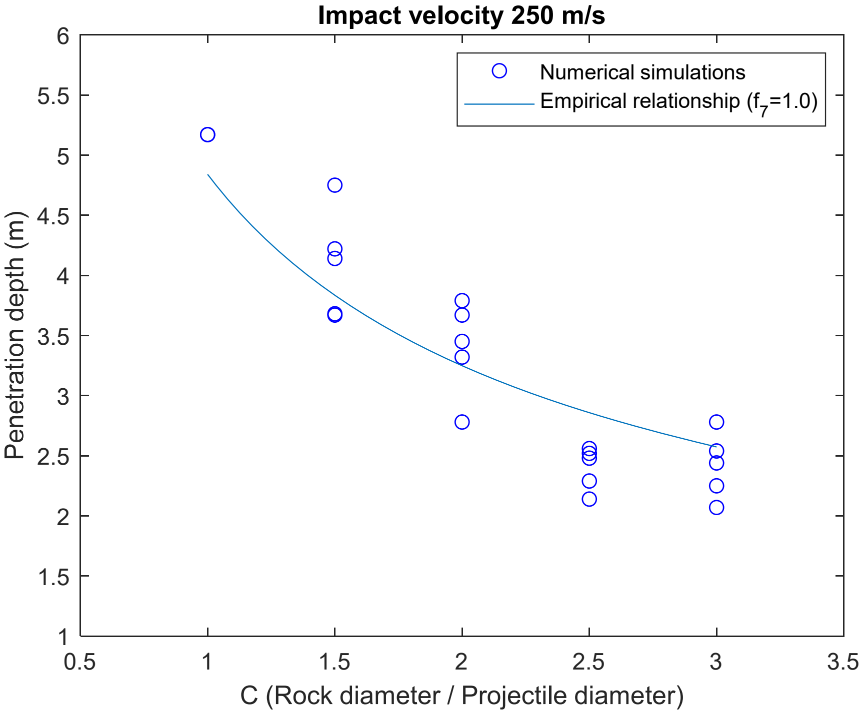


Figure 6.4 Penetration depth as a function of C for impact velocity of 250 m/s.

We note that the agreement between Equation (4.1) and the IMPETUS simulations looks excellent for an impact velocity of 250 m/s. However, for the two other velocities, Figure 6.5 shows that the fit is not equally good.

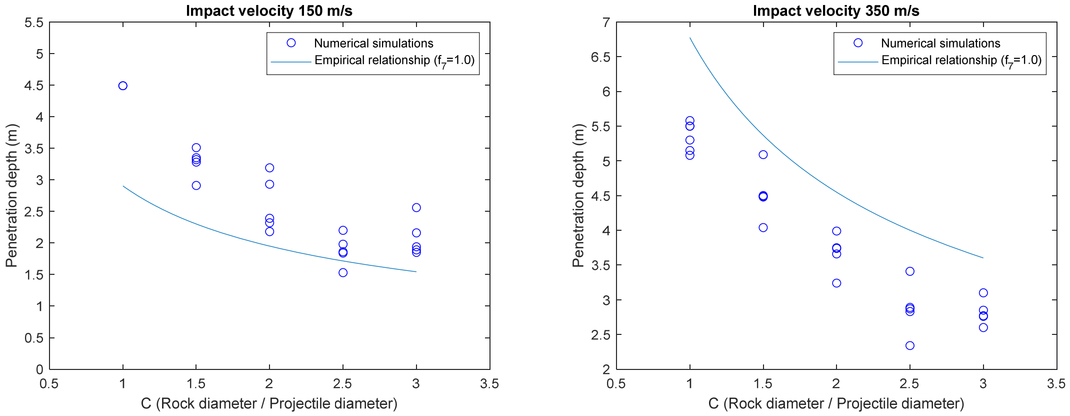


Figure 6.5 Penetration depth as a function of C for impact velocity of 150 m/s and 350 m/s.

We note that the slope is roughly correct, but it is slightly skewed in comparison with the data points. Thus, it looks like with different values for f_7 we might get better results. In Figure 6.6

we have plotted the curve and the data for values of f_7=1.2 and f_7=0.8 respectively, and we see that the empirical formula now matches the data quite well.

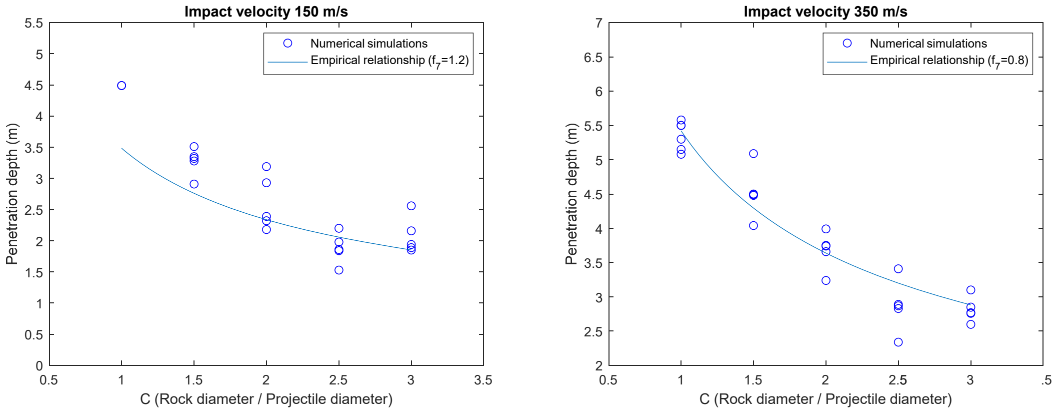


Figure 6.6 *Penetration depth as a function of C for impact velocity of 150 m/s and 350 m/s, with different values for* f_7*.*

6.2 Velocity dependence

However, since f_7 is a parameter describing the strength of the rocks, it makes no sense for it to depend on the impact velocity. Instead of a varying f_7, it probably means the linear velocity dependence in Equation (4.1) is not quite correct. To investigate this further, in Figure 6.7 we have plotted all the numerical datapoints as a function of velocity together with the empirical formula.

The C-values are not marked on the figure, but the C=1.0 points give most penetration and correspond to the upper most points in the plot. Correspondingly the C=3.0 points are the lower points. We see that Equation (4.1) fits the numerical datapoints reasonably well, although not perfect. However, given that v=0 m/s must give zero penetration, it is clear that a formula which is linear in velocity will not give the best possible fit to the numerical data.

By playing around with alternative velocity dependencies on the form av^n, it was found that the parameter values a=16.2 and n=0.48 produced a quite good fit for all velocities. This alternative relationship is also plotted in Figure 6.7 (dashed lines). Note that no attempt was made to find the absolutely best fit. It would not yet make sense to change the empirical formula just based on numerical simulations. This was mainly an attempt to show that such an empirical relationship might exist.

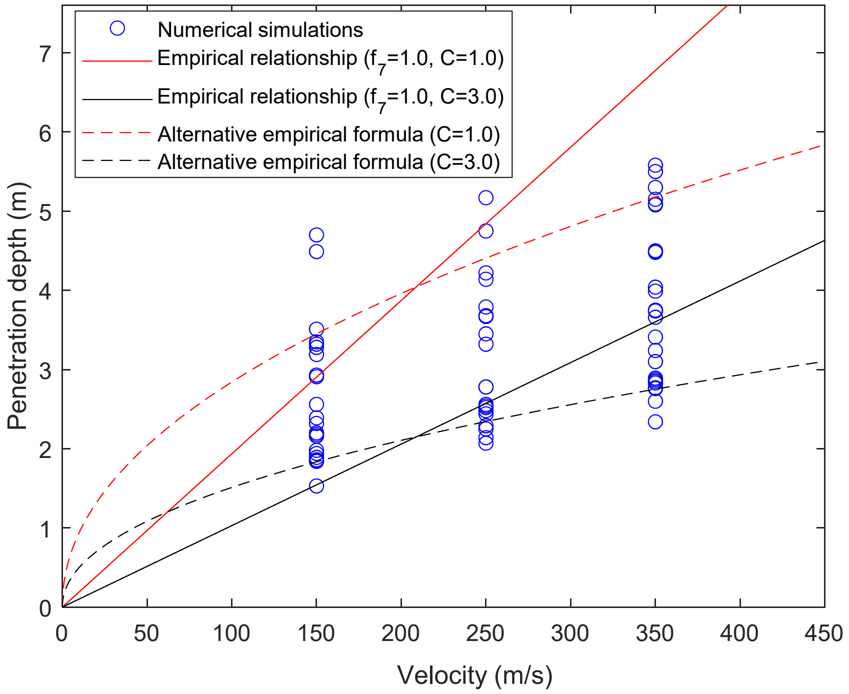


Figure 6.7 Penetration depth as a function of velocity.

6.3 Granite strength dependence

To investigate how the results depended on the granite strength, some simulations with scaled yield strength parameters A and B were performed. More precisely their values were scaled by the factors 1.5 and 2.0. The results for penetration depth as a function of this scaling are shown in Figure 6.8.

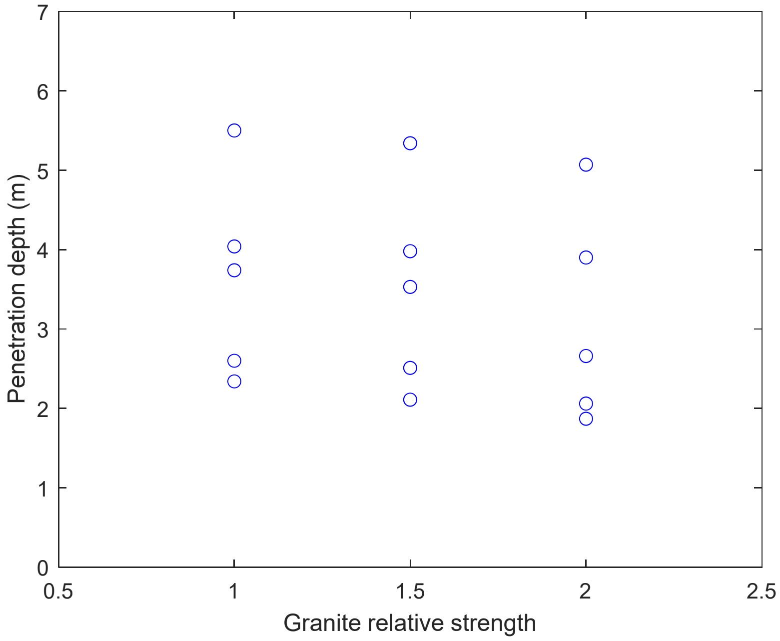


Figure 6.8 Penetration depth as a function of granite relative strength.

It is difficult to compare these numerical results with the empirical formula. The formula only distinguishes between "soft rock" and "hard rock" and we have no idea whether doubling the yield and failure parameter values of A and B correspond to going from "soft rock" to "hard rock". However, we note that the numerical results are not very sensitive to this parameter. This agrees very well with the formula for C=1, for which there should be no difference. However, for C=2 and C=3, the formula predicts an increase in penetration of 40% when going from hard rock to soft rock. It is hard to see any such increase in the numerical datapoints in Figure 6.8. This could be due to the formula not being accurate, or more likely that changing the value of A and B does not correspond to going from "soft rock" to "hard rock".

6.4 Effects of model simplifications

Initially we made various simplifications to the problem, for example assuming that all rocks are spherical, have the same diameter and are packed as densely as possible. How did this affect our results? This is obviously difficult to say, but our educated guess is that this has had relatively little impact. We saw that, with the simplifications, the results for penetration depth varies inside a relatively large range depending on the exact impact point. It seems likely that without the simplifying assumptions, that this range would have been extended somewhat, but the average penetration depth would have been roughly the same.

7 Conclusion

Numerical simulations of penetration into a granite rock-rubble overlay were performed. The results were compared with the only existing empirical formula. The agreement was surprisingly good, given that we used a "random" material model for granite. The dependence on the parameter *C* (rock diameter / projectile diameter) was reproduced almost exactly in the simulations. The velocity dependence was not equally perfect, but this can have a number of explanations. The same goes for the dependence on granite strength.

All in all, the simulations could not rule out that IMPETUS can be used for good predictions in simulations of this kind. Quite the opposite, in fact. Although more research is needed, the results look very promising so far.

Appendix

A.1 Generating rock-rubble in IMPETUS

```
*UNIT_SYSTEM
SI
*PARAMETER
R = 0.8
N = 1000
component = 3
*PARTICLE_DOMAIN
0, 0, [%N]
-2, -2, -2, 2,2,2
*PARTICLE_SOIL
3
DRY, 3, 0, 0, 0, 0, [%component]
*GEOMETRY_BOX
3
-0.5, -0.5, 0, 3.5,0.5,1.0
*END
```

A.2 Penetration into rock-rubble IMPETUS file

```
PARAMETER
tend = 0.04, "Termination time"
num_imp = 20 , "Number of .imp files"
num_ascii = 1000 , "Number of .out time steps"
%scale=1
%scale_rock=1
%initialVel=250
%skala_x = 1
%skala_r = 1
%vinkel=0
%vx=%initialVel*cos(%vinkel)
%vy=0
%vz=-%initialVel*sin(%vinkel)
R0 = 0.1 , "Projectile radius"
L = 0.8 , "Projectile length"
CRH = 4.0 , "Caliber radius head"
N1 = 20 , "Number of elements in length direction"
N2 = 30 , "Number of elements in circumferential direction"
N3 = 5 , "Number of elements in radial direction"
X = sqrt(%CRH^2 - (%CRH-1)^2)*%R0
*COMPONENT_PIPE
1,1,[%N1],[%N2],[%N3]
0,0,0,[%L],0,0,[%R0]
*TRANSFORM_MESH_CYLINDRICAL
1, P , 1, 100, 0 , 0 , 200
*TRANSFORM_MESH_CYLINDRICAL
2, P , 1, 100, 300, 300,
*COORDINATE_SYSTEM_CYLINDRICAL
```

```
100, 0,0,0
1,0,0, 0,1,0
*FUNCTION
200
R/%R0 * %X * (%L - Z)/%L
*FUNCTION
300
(R*%X)/(min(%X,max(z,0.0001))*%R0)*((1 - %CRH)*%R0 +
sqrt(max(0,(%CRH*%R0)^2 - (%X - min(%X,Z))^2))) - R
*UNIT_SYSTEM
SI
*TIME
[%tend]
*OUTPUT
[%tend/%num_imp], [%tend/%num_ascii]
*CONTACT
"Universal contact"
1
ALL, 0, ALL, 0
0, 0, 0, 0, 1.0e-4
*INCLUDE
../../run8/grains_1.k
[%scale_rock], [%scale_rock], [%scale_rock], 0, 0, 10
0,0,0,-0.21,0,0
*INCLUDE
../../modell3.k
*MAT_RIGID
1, 7850
*PART
1,1
*PART
11,100,,,,,2.0,1.5
*INITIAL_VELOCITY
P, 1, -[%initialVel],0,0
*end
```

A.3 IMPETUS Granite model

```
*PARAMETER
# Materialparametere
# Modell 3
rho = 2657
G = 3e10
A = 1.01
B = 0.68
C = 0.005
m = 0.76
n = 0.83
eps_0 = 1
T = 1.5e8
HEL = 4.5e9
```

```
P_HEL = 2.73e9
beta = 1
D_1 = 0.005
D_2 = 0.7
K_1 = 5.59e10
K_2 = -2.3e10
K_3 = 2.98e12
erode = 0
*MAT_JH_CERAMIC
"Granite"
100, [%rho], [%G]
[%A], [%B], [%C], [%m], [%n], [%eps_0], [%T]
[%HEL], [%P_HEL], [%beta], [%D_1], [%D_2], [%K_1], [%K_2], [%K_3]
[%erode]
*END
```

References

(1) Fang, Q., Zhang, J, 3D Numerical modeling of projectile penetration into rock-rubble overlays accounting for random distribution of rock-rubble, Int. J. Impact Engng, Vol. 63, pp. 118-128, 2014

(2) www.impetus.no

(3) www.ansys.com

(4) Teland J. A., A review of analytical penetration mechanics, FFI/RAPPORT-99/01264

(5) Ai, H. A., Ahrens, T. J., Simulation of dynamic response of granite: A numerical approach of shock-induced damage beneath impact craters, Int. J. Impact Engng, Vol. 33, Issues 1-12, pp. 1-10, 2006

About FFI

The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's mission

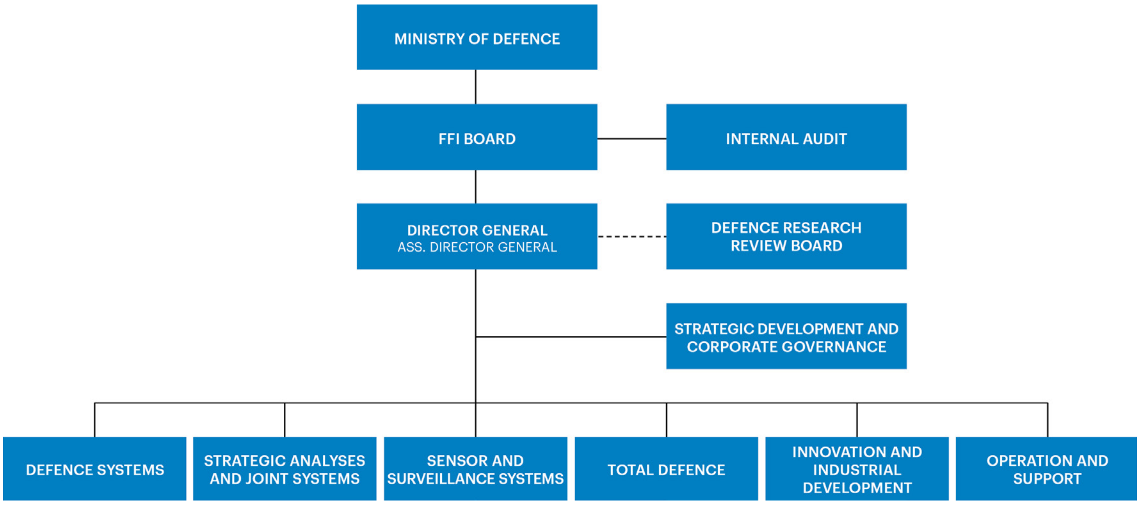
FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's vision

FFI turns knowledge and ideas into an efficient defence.

FFI's characteristics

Creative, daring, broad-minded and responsible.



Forsvarets forskningsinstitutt (FFI)
Postboks 25
2027 Kjeller

Besøksadresse:
Kjeller: Instituttveien 20, Kjeller
Horten: Nedre vei 16, Karljohansvern, Horten

Telefon: 91 50 30 03
E-post: post@ffi.no
ffi.no

Norwegian Defence Research Establishment (FFI)
PO box 25
NO-2027 Kjeller
NORWAY

Visitor address:
Kjeller: Instituttveien 20, Kjeller
Horten: Nedre vei 16, Karljohansvern, Horten

Telephone: +47 91 50 30 03
E-mail: post@ffi.no
ffi.no/en