19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

NUMERICAL RICOCHET CALCULATIONS OF FIELD ARTILLERY ROUNDS

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When considering firing safety, the possible range of projectiles that ricochet off ground may be a critical parameter. This paper wil focus on the a way to determine the possibilities of ricochet by numerical calculation.
A 155 mm field artillery round projectile was used as a test vehicle in all cases. However a mechanical system of this kind in geometrically scalable. Thus the calculations will be valid for smaller calibers also, providing that the shape of the projectile is roughly the same.
The results are compared to another published theoretical and experimental work. The correspondance between the calculations and the external results are quite good provided that the projectile does not deform too much. When the deformation is significant, ricochet seems to become more likely.

INTRODUCTION

In range safety considerations the possible range for a projectile after ricochet must be addressed. To avoid expensive trials theoretical models of the ricochet process can be developed from experiments, or the process can be simulated on a computer. In addition to presenting and interpreting the results from the computer simulations, we will compare the results to a previously published theoretical model. The theoretical model has a few simplifications that in some cases give different results from the simulations, and we will address these differences.

The values needed to characterize the post-impact trajectory of the ricochet are the velocity, the direction and the spin. Using these values, we will in principle be able to calculate the maximum range a projectile can travel. However, this actual range is hard to estimate because of the difficulties in calculating the effective aerodynamic coefficient due to the spinning and tumbling of the projectile. We have therefore added the rate of tumbling that can be of help in an aerodynamical description.

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To simulate the ricochet process, different pre-impact values for the velocity and spin, the angle of impact and the yield strength of the surface, were used. The values for the velocity ranged from 300 m/s to 500 m/s, the spin from 400 rad/s to 1000 rad/s, the angle of impact from 5° to 60° and the target yield strength from 30 MPa to 100 MPa. The theoretical model that was used, will only tell whether or not there is a ricochet, and not calculate any post-impact trajectory.

THE SIMULATIONS

The simulations were carried out using Autodyn™ 3D [1] from Century Dynamics. The projectile and the target are made up of a grid of brick shaped zones (cells), where several differential equations can be used to calculate the conservation of mass, momentum and energy for each of these zones. We used Autodyn's Lagrange processor that converts these differential equations into finite difference equations. A user defined subroutine was added to Autodyn in order to facilitate the implementation of a spinning projectile.

In the table below, we have listed the values we used for both the projectile and the surface except for the yield stress, which we have varied in the different simulations.

	Surface	Projectile
Initial density:	1.6 kg/m^3	4.02 kg/m^3 (average)
Bulk modulus:	10 GPa	197.5 GPa
Shear modulus:	500 MPa	90 GPa
Yield stress:	varies	varies
Erosion strain:	1.0	1.0

The linear equation of state was chosen, and the von Mises criterion was used to describe the yield surface. To remove distorted cells we included an erosion model (instantaneous geometric strain) rather than a failure model. This means that the erosion of the material starts when the strain reaches a certain limit, and if the cells are very distorted, they are removed from the calculations. We have also set the friction coefficient between the projectile and the surface to zero.

To model the projectile, we have used a 155 mm shell with a right cylindrical main body and an ogival nose section. For simplicity, the fuse was removed.

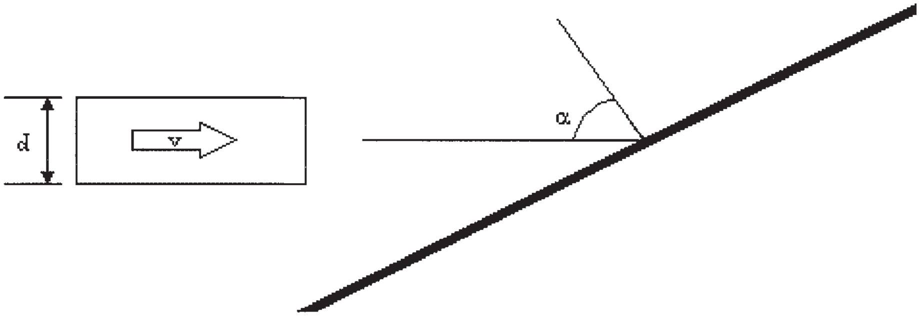
We assumed that the target surface was smooth and planar. It is of course very difficult to create a surface that resembles a real ground. The soil surface can change from hard rock to soft sand and even water within a small area. However, it is highly likely that the ricochet will vary as the surface varies, so we have changed the yield strength of both the surface and the projectile to see what kind of effect this may have on the ricochet process.

THE THEORETICAL MODEL

We have used the model developed by Wijk in [2] to compare with the results from the computer simulations. This model assumes a blunt projectile that may either penetrate or slide off the surface. The maximum angle at which penetration will take place is given by

$$\tan^3(\alpha_{max}) + \tan(\alpha_{max}) = 8mv^2/(3\sigma\pi d^3)$$

Here α_{max} is the critical angle between the projectile and the normal direction of the surface, m is the mass of the projectile, v is the velocity, d is the diameter and σ is the yield strength of the target surface. See the figure below.



We will refer to the angle $90° - \alpha$ as the impact angle. $90° - \alpha_{max}$ is thus the smallest angle between the surface and the direction of the projectile for which penetration will occur.

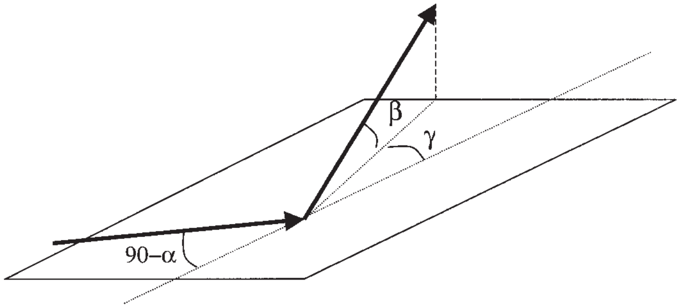
RESULTS AND DISCUSSIONS

Since the computer simulations give more information than just whether there is a ricochet or not, we will look at some of these results before we compare them to Wijk's model. First we define the vertical ricochet angle (β) as the angle between the direction of the projectile and the surface at the outgoing branch of the trajectory.

Since the projectile is spinning the impact angle and β will generally be in two different planes. The angle between these planes will be referred to as the horizontal ricochet angle (γ).

The impact angle is larger than the vertical ricochet angle for nearly all of the simulations we have performed. In the simulations, there was only one exception, and in that case the projectile was deformed.

The spin of the projectile has very little effect on the vertical ricochet angle. In the simulations we varied the spin velocities with values between 400 rad/s and 1000 rad/s,



and there were only minor differences in the vertical ricochet angles. However, if we look at the results for the cases where the velocity is 500 m/s and the yield strength of the surface and the projectile is 30 Mpa and 200 Mpa respectively, we get very different results for different values of the spin. The simulations for an impact angle of 20° gives no ricochet when the spin is 400 rad/s, while there is a ricochet when the spin is increased to 1000 rad/s. This may indicate that the spin may have an effect on whether we get a ricochet or not.

There are a few differences between Wijk's model and the simulations. The two methods use different projectiles. In the simulations we have modelled a 155 mm shell, while the model uses a blunt cylindrical projectile with a fixed diameter. But since Wijk assumes that the entire front penetrates the surface before there is any change in the direction of the projectile, this is assumed to have very little effect.

There is no mention of the yield strength of the projectile in Wijk's model, but it is assumed that it has no deformation. It is therefore natural to avoid deformation in the simulations as well, and we have tried to simulate this by creating a projectile that has a much higher yield strength than the target.

Finally, Wijk's model does not include the spin of the projectile.

To compare the results from the simulations to the results of the theoretical model, we have four different cases. In the first two cases only the velocity of the projectile varies, in the third case we decrease the yield strength of the target and in the fourth case we increase the yield strength of the projectile.

Case 1

We have used the following values:

target yield strength	= 100 MPa
projectile yield strength	= 200 MPa
spin	= 800 rad/s
velocity	= 300 m/s
projectile mass	= 42 kg

The results of the simulations are given in the tables below. There was no ricochet for impact angles larger than 55°. The last value in the table is the rotation around the center of mass (RACM) and around an axis perpendicular to the spin.

Impact angle	89 mils (5°)	178 mils (10°)	356 mils (20°)	533 mils (30°) (Deformed)
β	69 mils (3.89°)	123 mil s(6.91°)	233 mils (13.08°)	344 mils (19.33°)
γ	22 mils (1.26°)	45 mils (2.55°)	68 mils (3.85°)	60 mils (3.35°)
Ricochet velocity	297.17 m/s	288.71 m/s	275.46 m/s	255.12 m/s
Ricochet spin	424.31 rad/s	324.55 rad/s	137.16 rad/s	87.45 rad/s
RACM	52.57 rad/s	55.32 rad/s	54.18 rad/s	94.77 rad/s
622 mil (35°) (Deformed)	711 mils (40°) (Deformed)	800 mils (45°) (Deformed)	889 mils (50°) (Deformed)	978 mils (55°) (Deformed)
411 mil (23.1°)	479 mils (26.93°)	574 mils (32.29°)	680 mils (38.25°)	942 mils (52.96°)
74 mil (4.16°)	67 mils (3.79°)	78 mils (4.4°)	144 mils (8.07°)	95 mils (5.34°)
226.57 m/s	211.16 m/s	182.5 m/s	124.93 m/s	85.4 m/s
81.59 rad/s	75.59 rad/s	49.74 rad/s	23.95 rad/s	20.72 rad/s
129.29 rad/s	135.83 rad/s	148.19 rad/s	157.16 rad/s	150.21 rad/s

The result from the theoretical model with the values above is using a diameter d= 0.155 m we get α_{max} = 62.7°, and the impact angle = 27.3° compared to 55° in the simulations. Thus in this case there is a rather large difference between the two methods.

Case 2

In this case we have increased the velocity of the projectile to 500 m/s, while the other values are the same as they were in Case 1. The results from the simulations are as follows:

Impact angle	89 mil (5°)	178 mil (10°)	356 mil (20°)	533 mil (30°) (Deformed)
β	67 mil (3.77°)	129 mil (7.24°)	289 mil (16.23°)	440 mil (24.76°)
γ	20 mil (1.13°)	37 mil (2.08°)	41 mil (2.31°)	84 mil (4.73°)
Ricochet velocity	496.01 m/s	489.12 m/s	455.91 m/s	271.75 m/s
Ricochet spin	319.24 rad/s	214.59 rad/s	127.95 rad/s	64.51 rad/s
RACM	47.15 rad/s	55.96 rad/s	109.51 rad/s	51.29 rad/s

Impact angle	622 mil (35°) (Deformed)	711 mil (40°) (Deformed)	800 mil (45°)	
β	601 mil (33.79°)	1127 mil (63.39°)	(No Ricochet)	
γ	63 mil (3.54°)	446 mil (25.1°)		
Ricochet velocity	205.17 m/s	49.7 m/s		
Ricochet spin	33.7 rad/s	42.5 rad/s		
RACM	83.8 rad/s	59.67 rad/s		

Thus the critical angle is around 40°–45°. From Wijk's model with diameter d= 0.155 m we and the impact angle = 19.9°. There is still a fairly large difference between the two models.

Case 3

To avoid large deformations of the projectile, we have reduced the yield strength of the surface to 30 MPa. The first table shows the results of the simulations with a spin of 400 rad/s and the second with a spin of 1000 rad/s. The velocity is 500 m/s for both simulations.

Impact angle	89 mil (5°)	178 mil (10°)	356 mil (20°)	533 mil (30°)
β	76 mil (4.3°)	153 mil (8.63°)	(No ricochet)	(No ricochet)
γ	25 mil (1.43°)	23 mil (1.27°)		
Ricochet velocity	496.1 m/s	485 m/s		
Ricochet spin	131.56 rad/s	83.7 rad/s		
RACM	28.61 rad/s	23.53 rad/s		
Impact angle	89 mil (5°)	178 mil (10°)	356 mil (20°) (Deformed)	533 mil (30°)
β	76 mil (4.3°)	154 mil (8.67°)	345 mil (19.41°)	(No ricochet)
γ	30 mil (1.7°)	43 mil (2.44°)	64 mil (3.62°)	
Ricochet velocity	493.84 m/s	482.69 m/s	305.11 m/s	
Ricochet spin	447.29 rad/s	367.89 rad/s	96.37 rad/s	
RACM	25.6 rad/s	38.25 rad/s	64.35 rad/s	

The only difference between these two simulations is the spin of the projectiles. So for the computer calculations, we see that the spin may have an effect on whether there is a ricochet or not.

Spin is not considered in the theoretical model, so there will of course be different results in this case as well. Wijk's model with the same values gives $\alpha_{max} = 77°$, and the impact angle becomes 13°.

Disregarding the fact that the two simulations have different ricochet angles, this is the best match we have had so far, and it is most likely due to the large difference between the yield strength of the projectile and that of the surface. We will try to increase this difference even further in the next case.

Case 4

If the yield strength for the projectile is 2 GPa and 100 MPa for the surface, we get the results below. The projectile is modelled with a velocity of 500 m/s and a spin of 800 rad/s.

Impact angle	89 mil (5°)	178 mil (10°)	356 mil (20°)	444 mil (25°)
β	67 mil (3.76°)	122 mil (6.88°)	157 mil (8.83°)	(No ricochet)
γ	17 mil (0.93°)	41 mil (2.29°)	38 mil (2.15°)	
Ricochet velocity	496 m/s	485.79 m/s	349.99 m/s	
Ricochet spin	407.4 rad/s	369.09 rad/s	318.28 rad/s	
RACM	42.33 rad/s	35.33 rad/s	59.71 rad/s	

In this case the deformation of the projectile is minimal and the simulation should therefore be in agreement with the results of Wijk's model. As in Case 2, the critical impact angle will be 19.9°. This agrees fairly well with the simulations which have an impact angle between 20° and 25°.

CONCLUSIONS

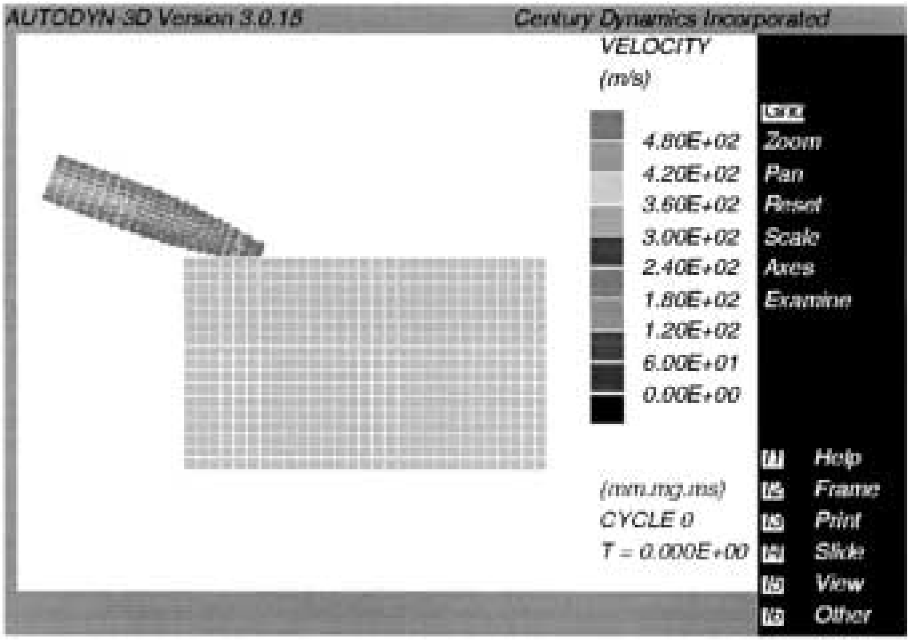
As long as the deformations of the projectile are small, the theoretical model gives similar results as the computer simulations. But if the projectile is significantly deformed, the results herein suggest that the critical impact angle in Wijk's model is too small.

In this paper only the critical impact angle has been discussed. However, the Autodyn simulations also give valuable information about other ballistic parameters like the velocity, direction, spin rate and tumbling rate after impact. It is left to the reader to consider these details.

The final page shows examples of graphical output from the simulations.

REFERENCES

1. AUTODYN Interactive Non-Linear Dynamic Analysis Software, Century Dynamics 1998
2. Wijk, Gunnar; A ricochet model, FOA-R-98-00892-310-SE, Försvarets Forskningsanstalt, Tumba, Sweden (1998)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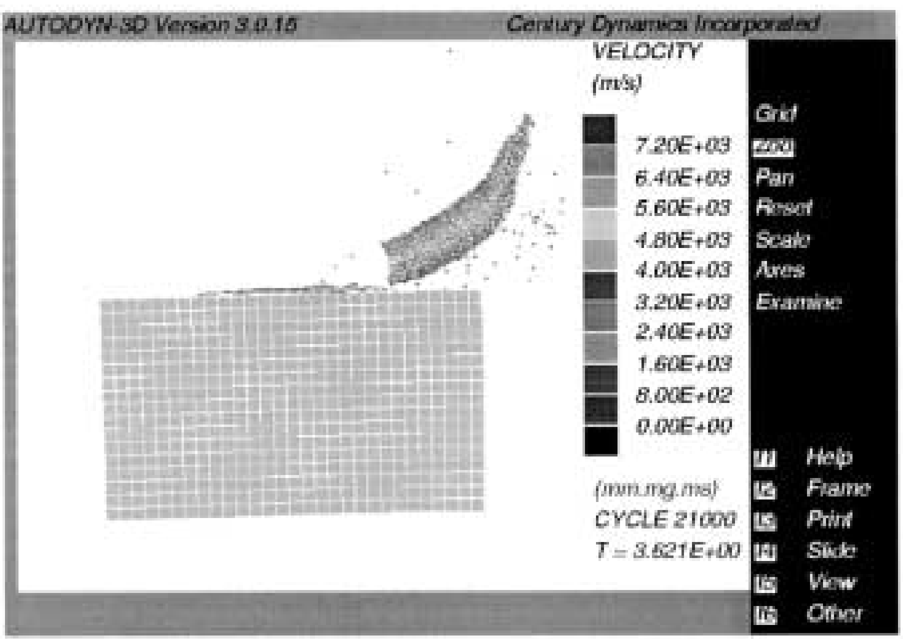
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