IMPACT ON BARRIERS:
SINGLE ROCK FALL VS. ROCK MASS FALL

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Problem statement

The difficulty is defining the quantity of material that interacts with the barrier!

$$p_{d,max} = a \cdot \rho_{wg} \cdot v^2, \text{ dynamic coefficient } a = 1.5\ldots5$$

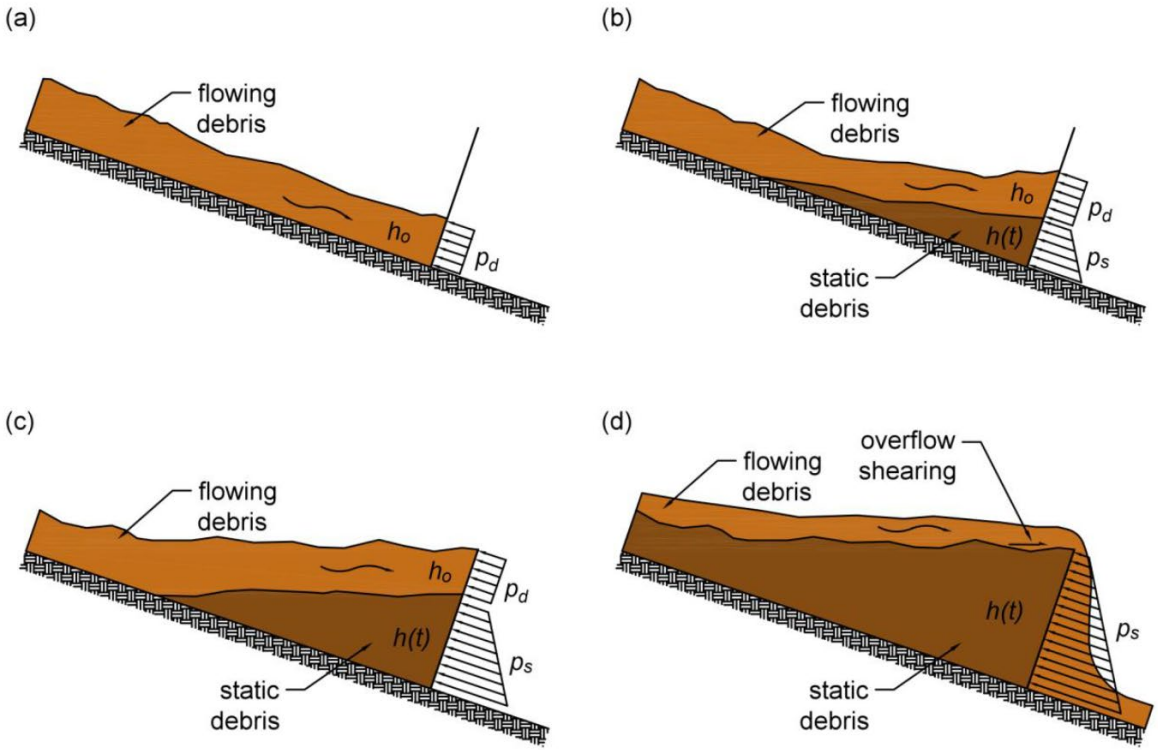
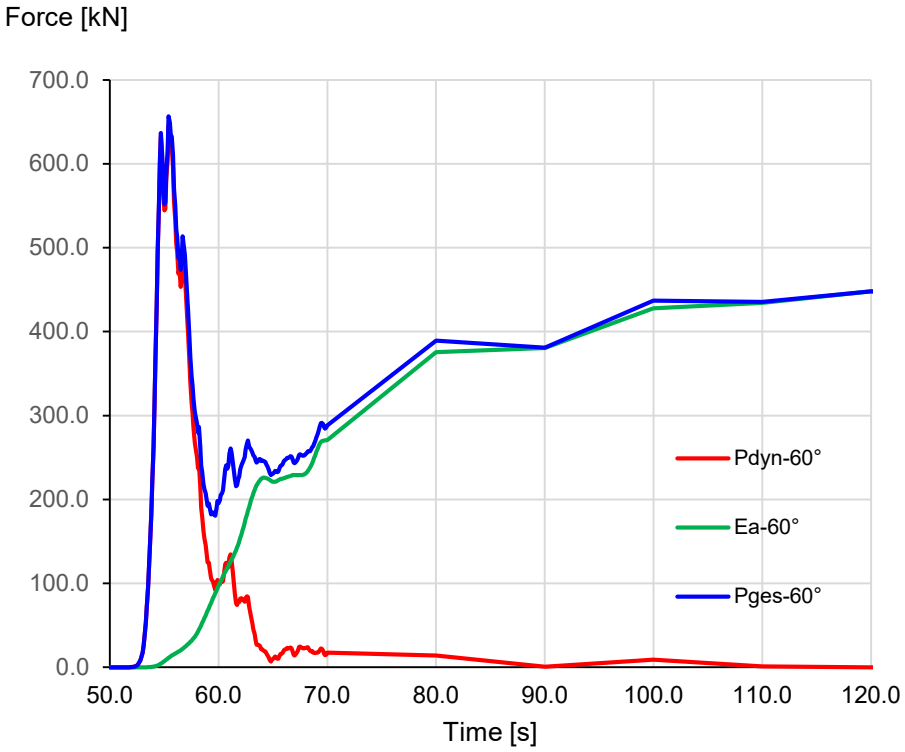


Figure 5. Assumed filling process for the calculation of dynamic and static loads on a barrier. Initial impact (a) imparts a dynamic load only followed by progressively larger static loads, (b) and (c), ending in overtopping where static and shear forces dominate.

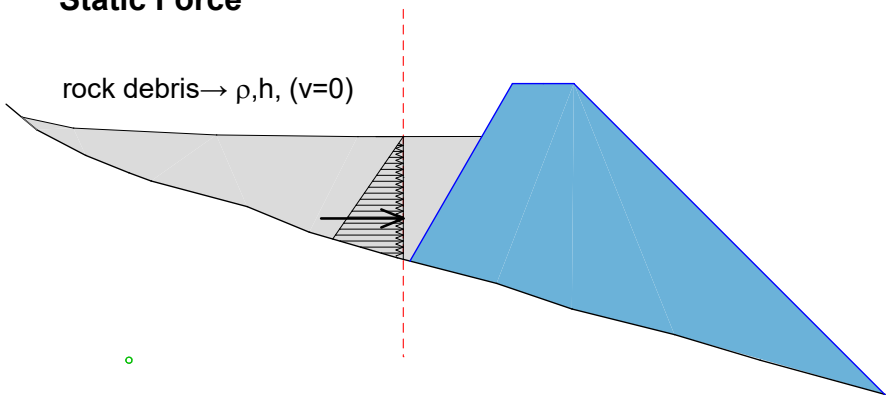
(W. Ashwood, 2014)

Process and impact model according to ONR 24801

Forces P_{dyn}, $P_{stat} = E_a$, P_{ges}

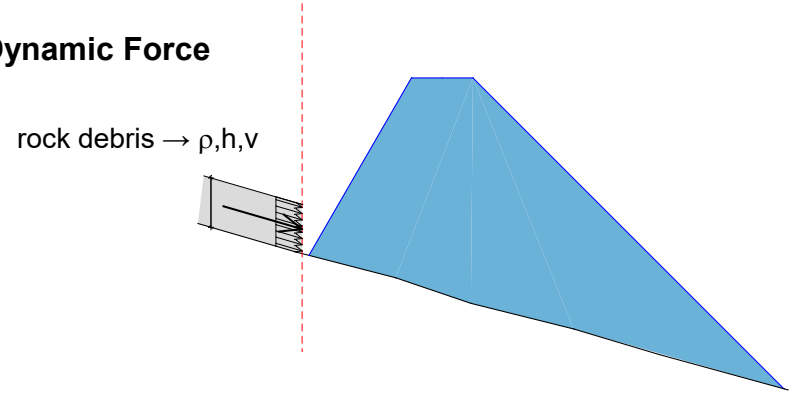


Static Force



$$P_{st} = E_a = \frac{1}{2} \cdot K_a \cdot (\rho_M \cdot g \cdot h_{st}{}^2)$$

Dynamic Force



$$P_{dyn} = (\rho_M \cdot h_{dyn} \cdot v^2)$$

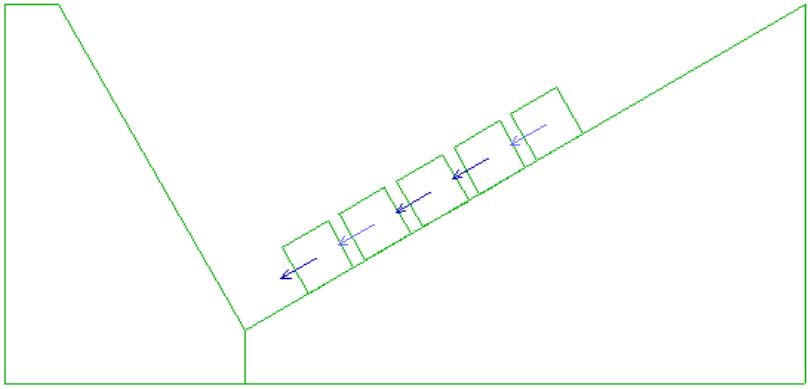
Two DEM-codes

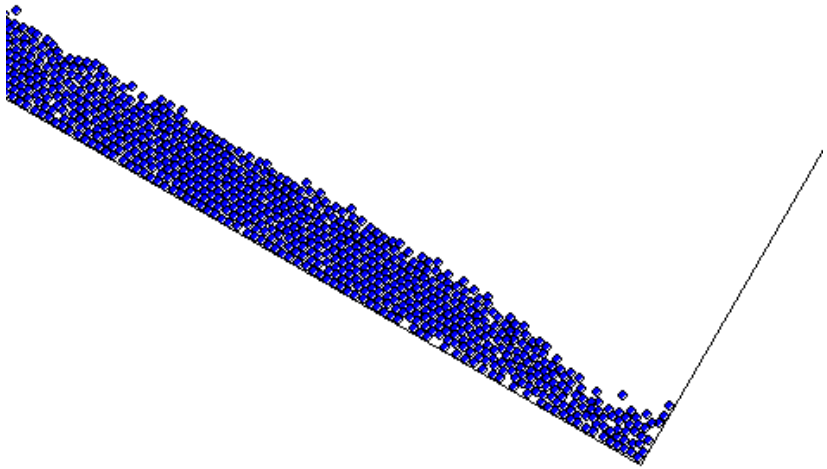
UDEC

***U**niversal **D**istinct **E**lement **C**ode*

PFC2D

***P**article **F**low **C**ode in **2 D**imensions*





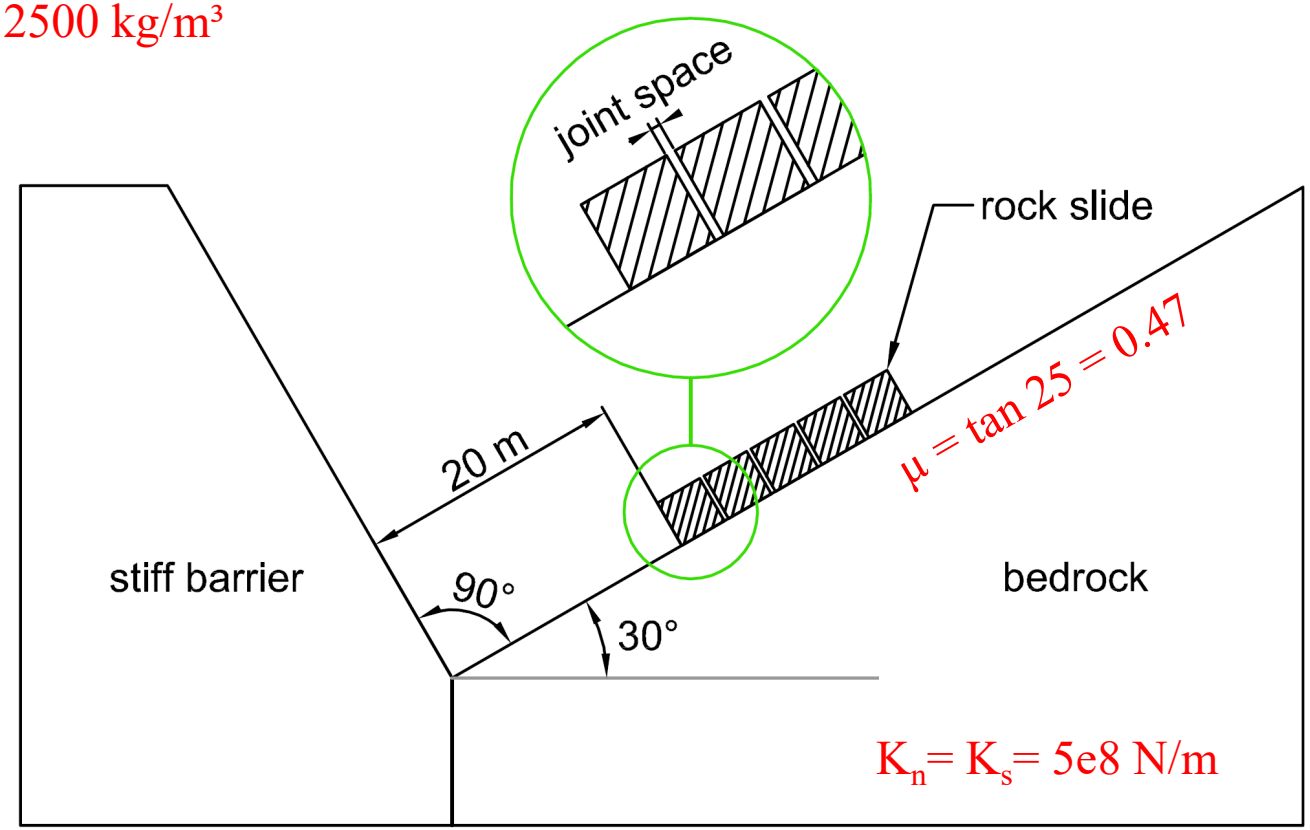
Both codes are capable to model the movement and the interaction of stressed assemblies of particles.

Sliding block vs. Rock slide

Rigid block model

Block volume 1 m³

$\rho = 2500$ kg/m³



PFC & UDEC: Free falling

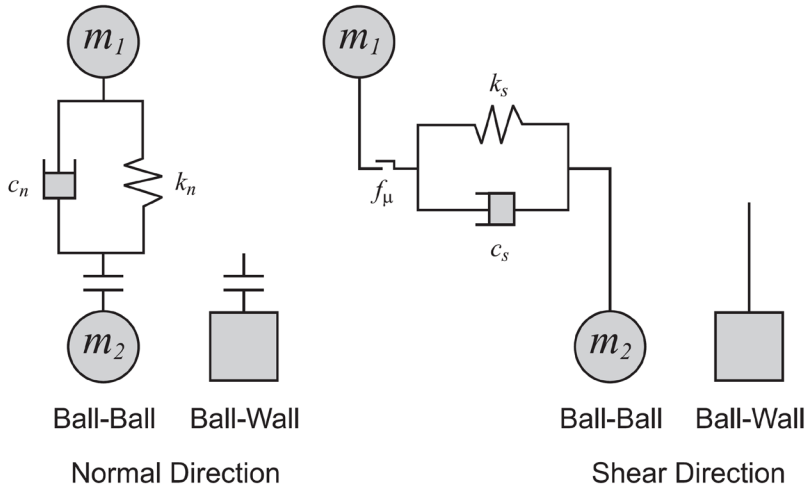
In order to model the free falling of blocks, neither the acceleration nor the velocity is to be reduced during fall as a consequence of mechanical damping.

$$F_{(i)} + F^{d}_{(i)} = M_{(i)} A_{(i)}; \quad i = 1 \ldots 6$$

$$F^{d}_{(i)} = -\alpha \left| F_{(i)} \right| \mathrm{sign}(v_{(i)}) \quad i = 1 \ldots 6$$

$$\mathrm{sign}(y) = \begin{cases} +1 & \text{wenn } y > 0 \\ -1 & \text{wenn } y < 0 \\ 0 & \text{wenn } y = 0 \end{cases}$$

The reduction of the velocity caused by the impact is modelled with the help of a viscous damping model integrated in PFC.



$$D^n = c_n \cdot \left| V^n \right|$$

$$D^s = c_s \cdot \left| V^s \right|,$$

Critical Damping Ratio

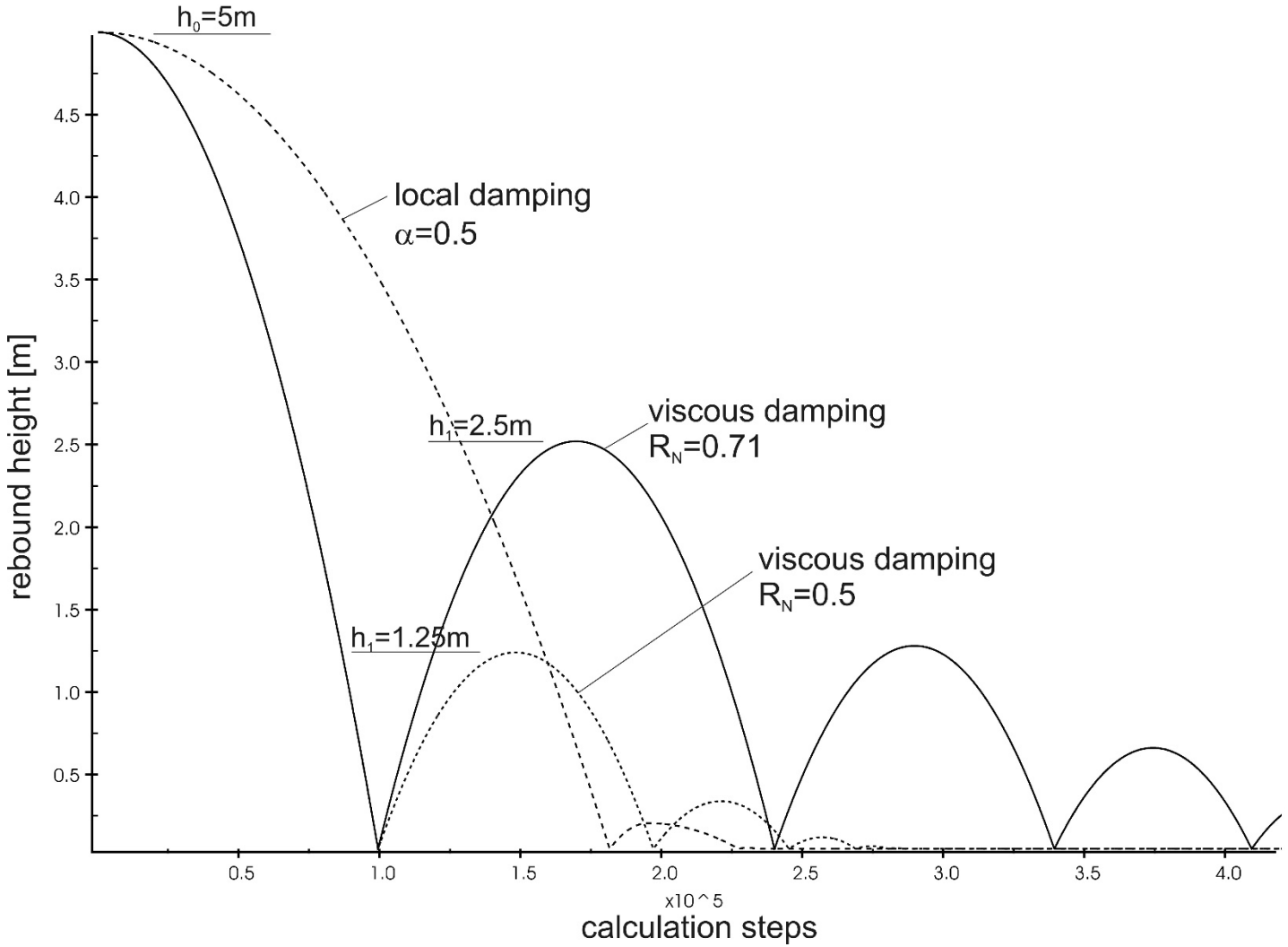
$$c_n = \beta_n \cdot c_n^{crit}$$

$$c_s = \beta_s \cdot c_s^{crit}.$$

$$c_n^{crit} = 2mw_n = 2\sqrt{mk_n}$$

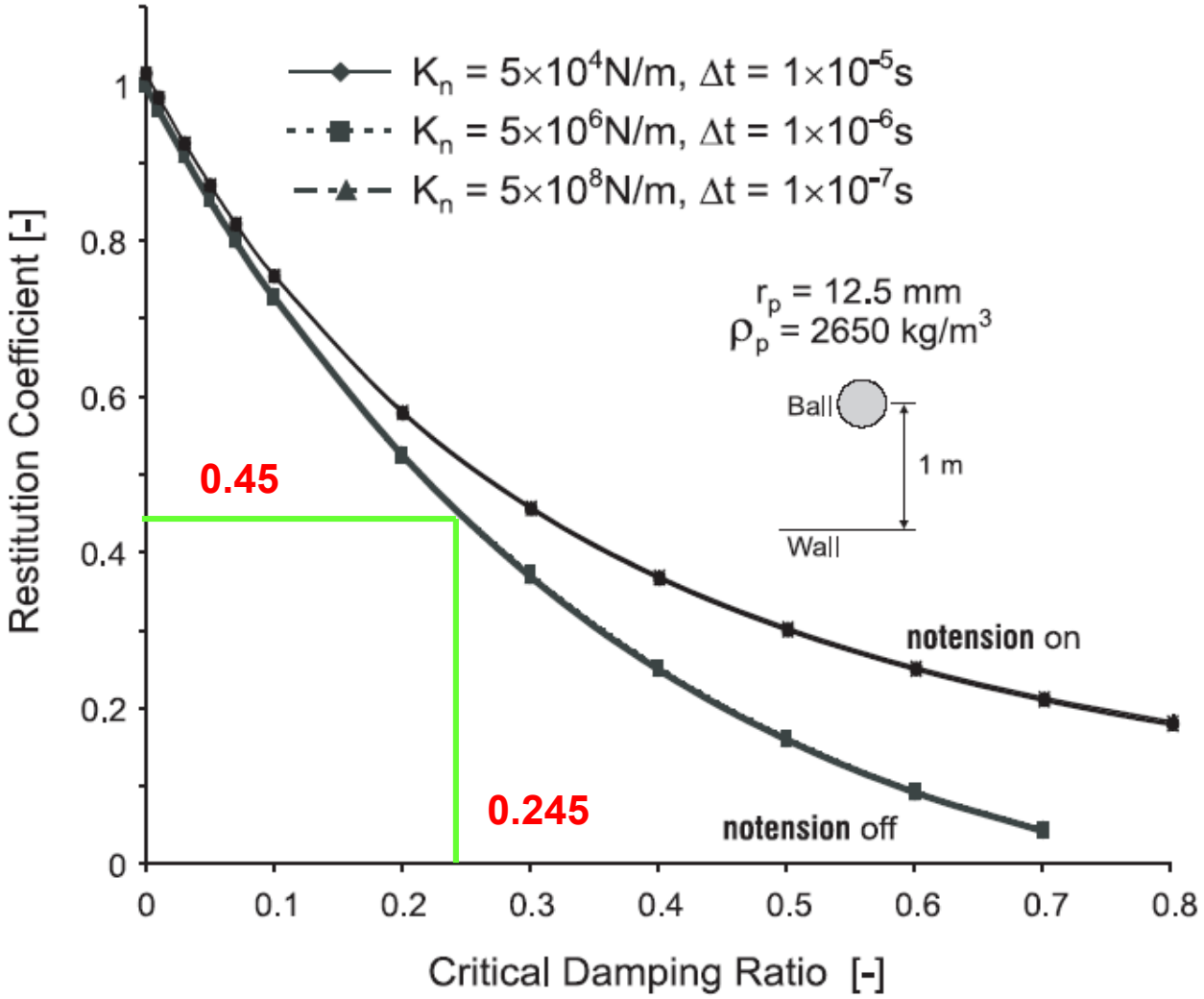
$$c_s^{crit} = 2mw_s = 2\sqrt{mk_s}$$

Drop tests, rebound height

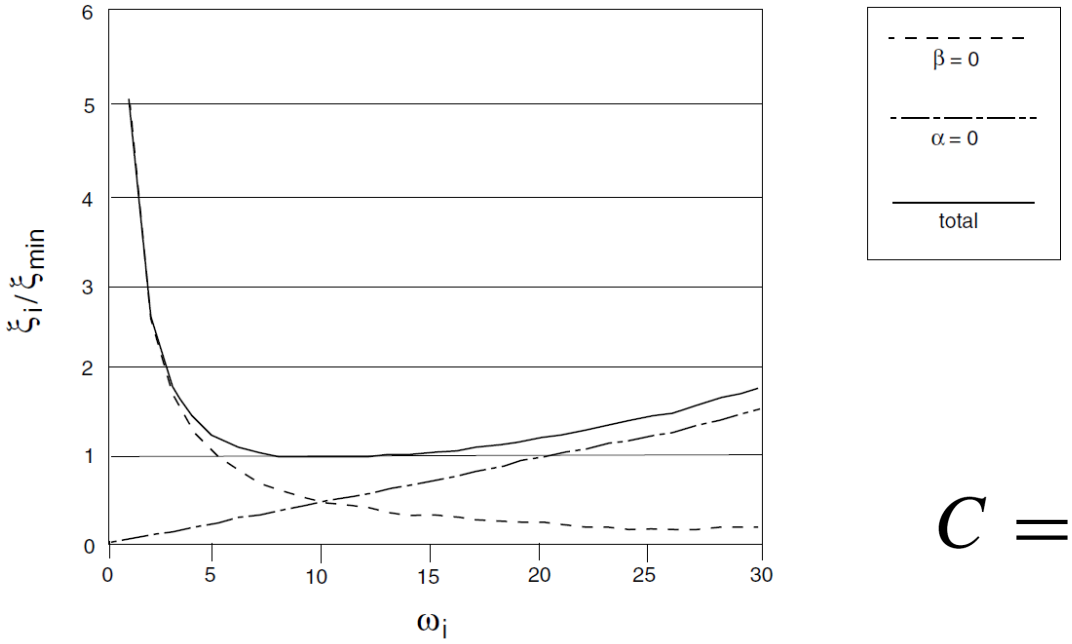


Calbration by Drop Test

Relation between restitution coefficient and critical damping ratio (Itasca 1999)



UDEC: Rayleigh damping

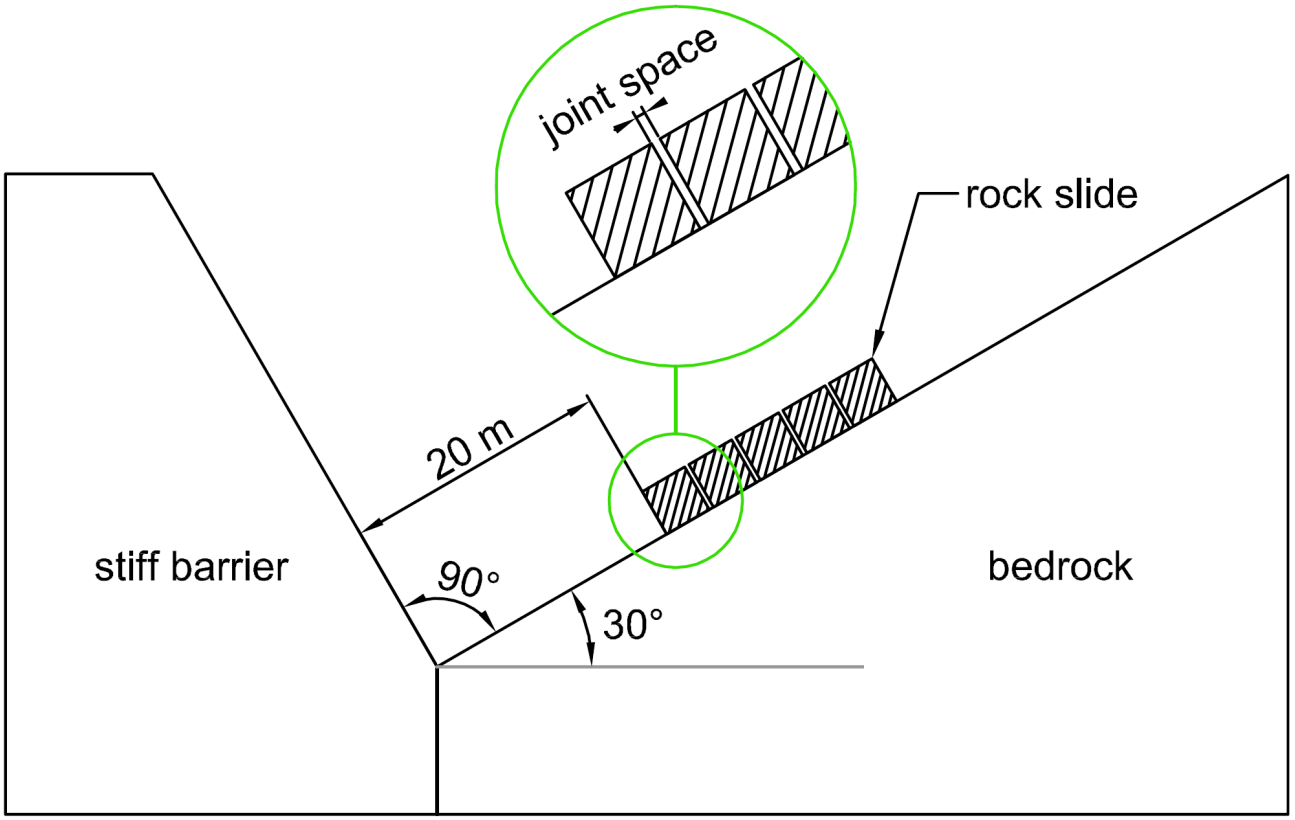


$$C = \alpha M + \beta K$$

where α = the mass-proportional damping constant; and
β = the stiffness-proportional damping constant.

UDEC Rayleigh damping (for a block volume of 1 m³):
- natural frequency f_{min}= 71.17 Hz
- fraction of critical damping ξ_{min}= 0.16

Analysis 1: Sliding block vs. Rock slide

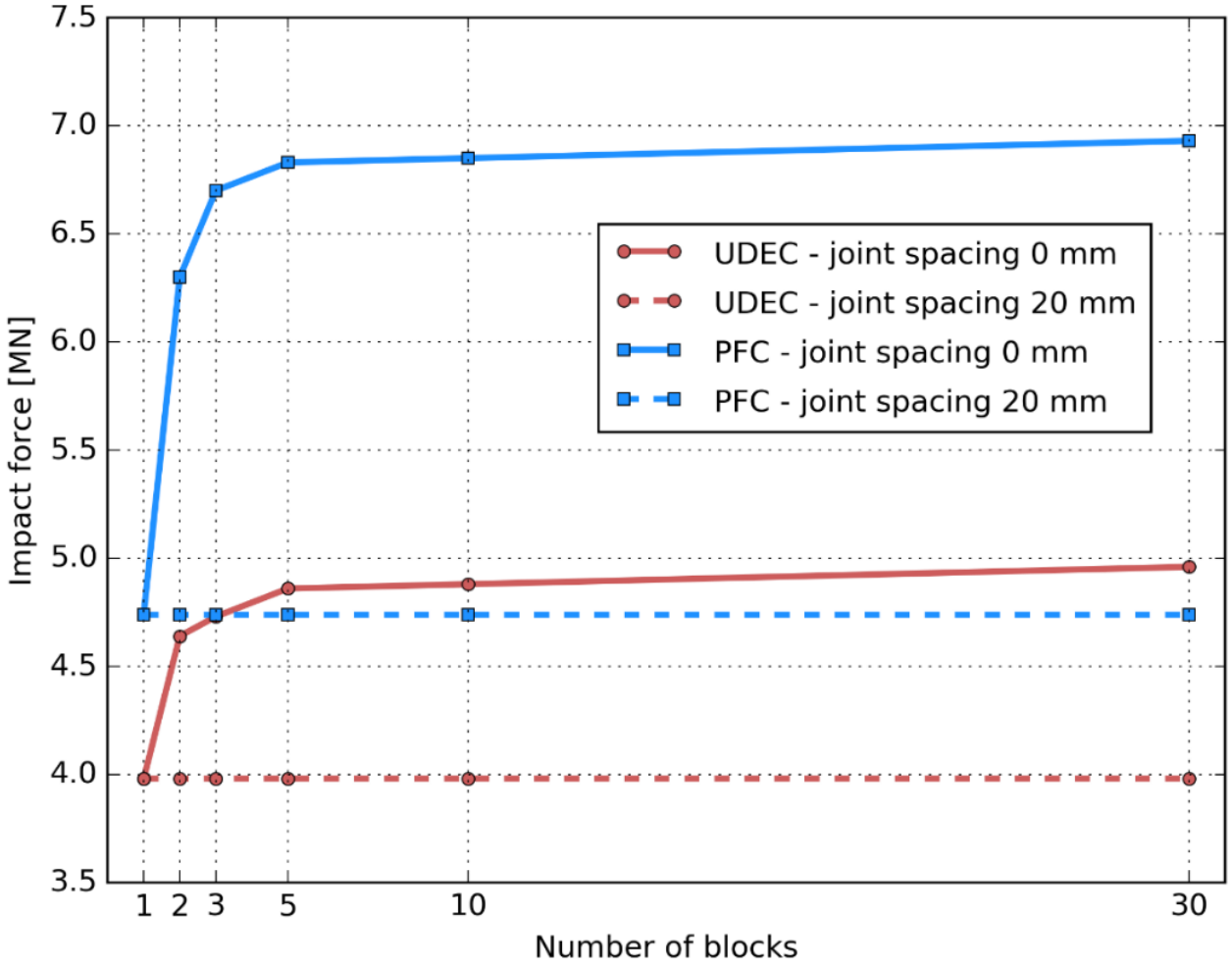


The number of modeled blocks was varied between 1 and 30 and the joint spacing between the adjoining blocks was varied between 0 and 20 mm.

Movie 1: joint spacing 0.00 m

Movie 2: joint spacing 0.20 m

Maximum impact force vs number of blocks

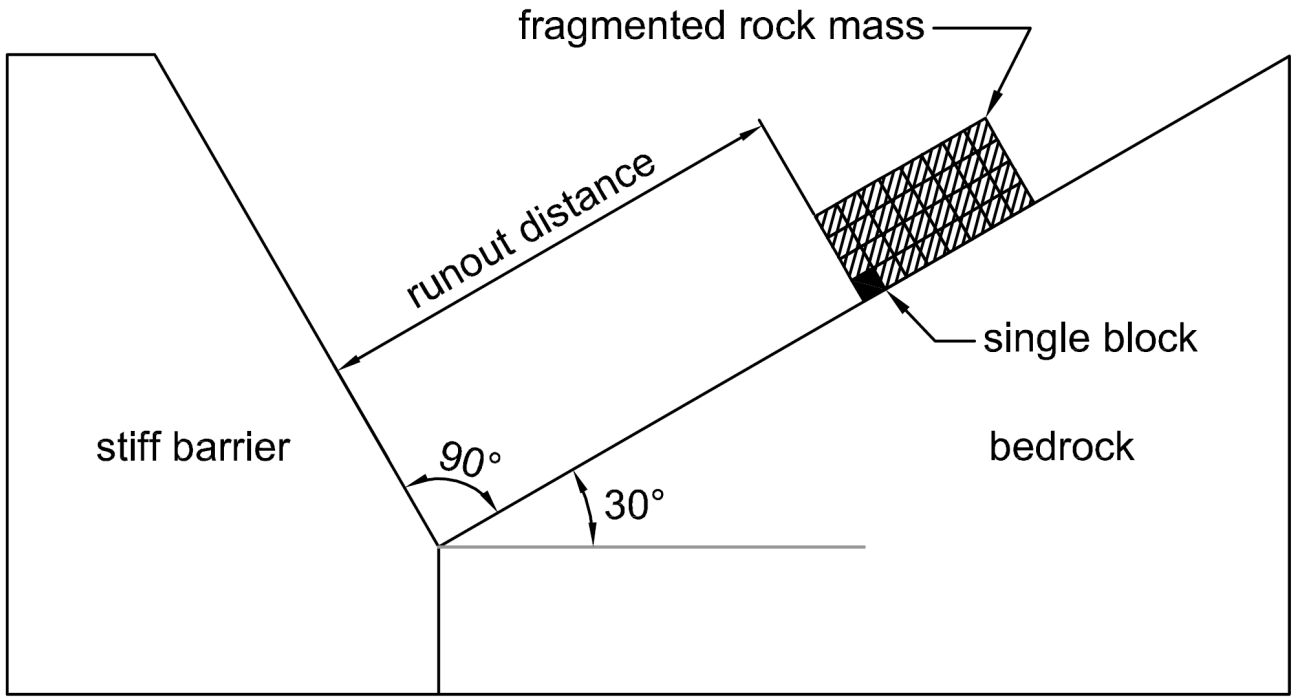


PFC and UDEC show an increase in the maximum impact force as the number of blocks increases. From a number of blocks greater than or equal to five, the increase in impact force is insignificant.

Analysis 2: Rock fall vs. Rock mass fall

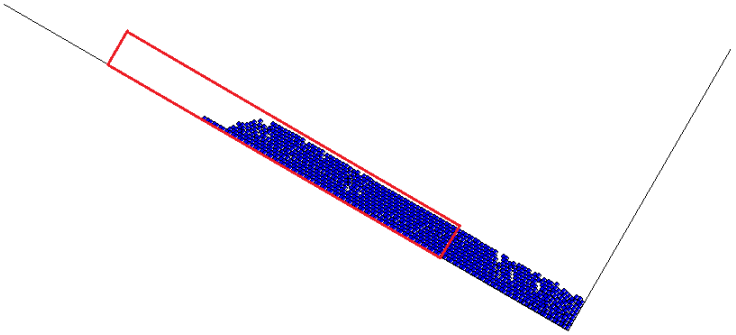
Version 1: const. number of 1000 Blocks,
Version 2: const. Volume of 1000 m³

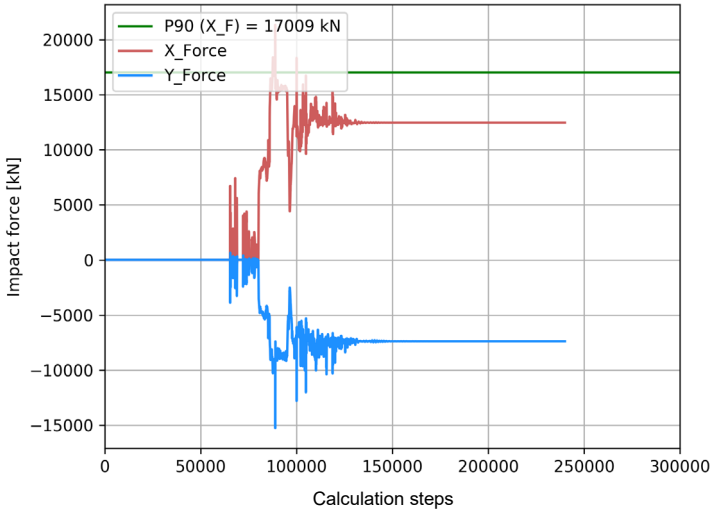
The volume of the modeled equally sized blocks was varied between 0.1 and 10 m³.



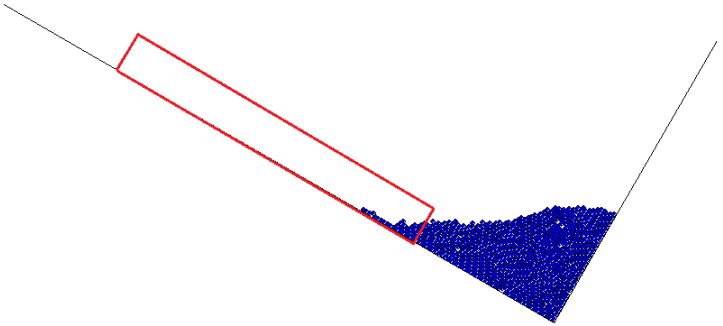
Test arrangement

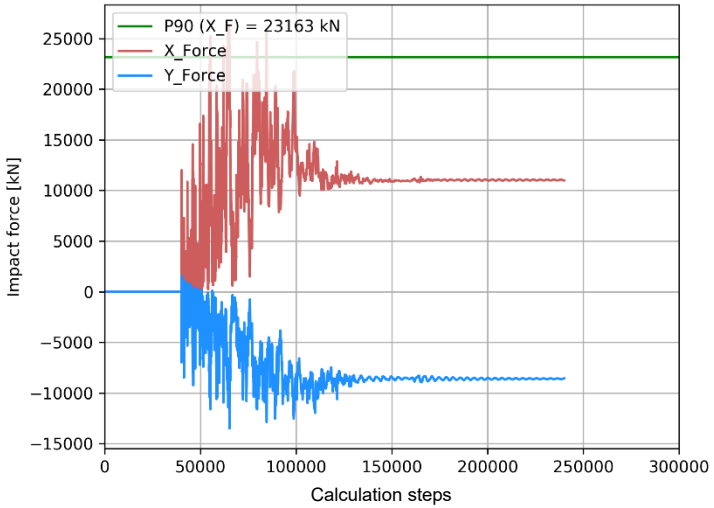
Fixed rotational velocity





Free rotational velocity

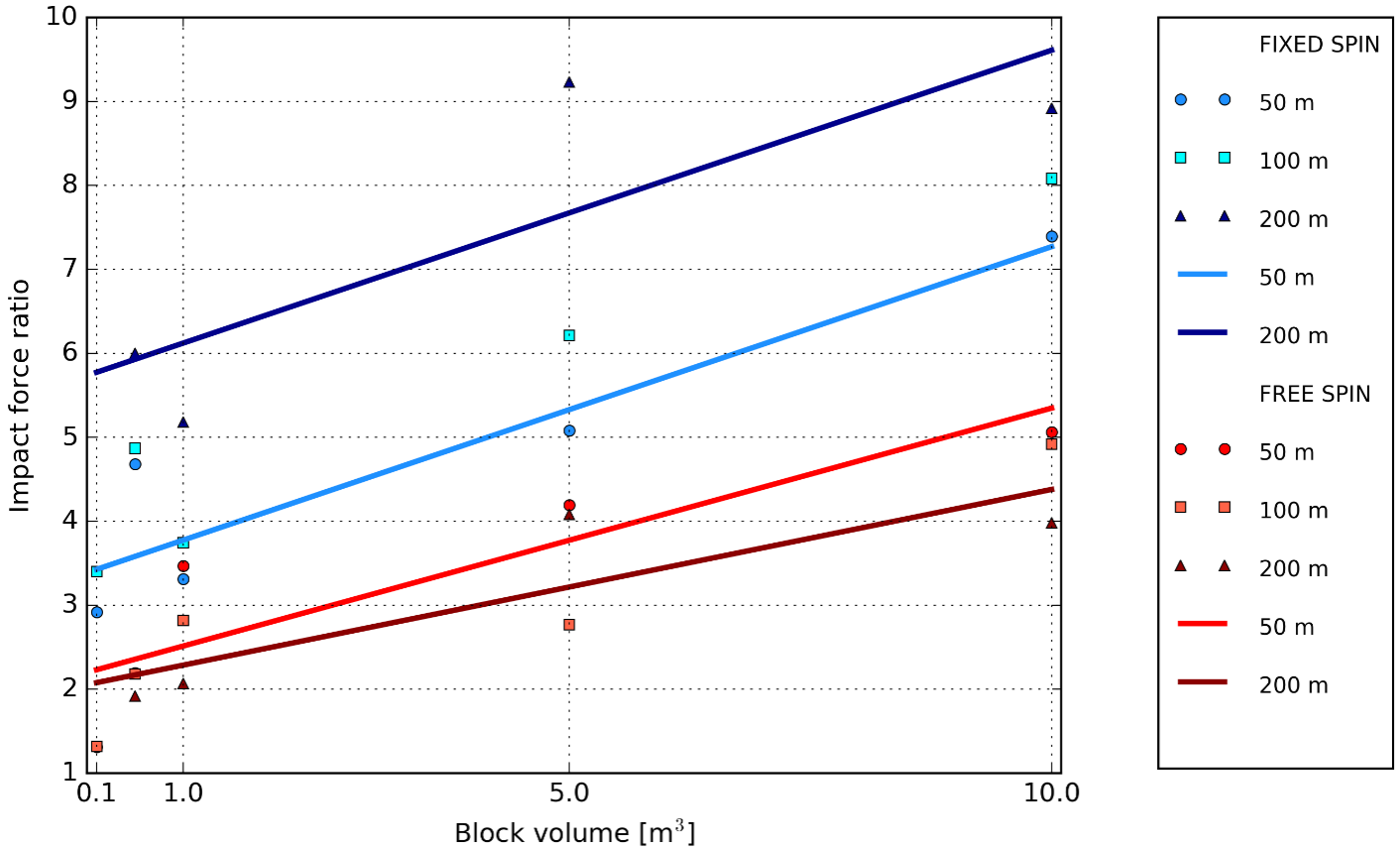




runout distance of 50 m, block volume of 1 m³, 1000 blocks

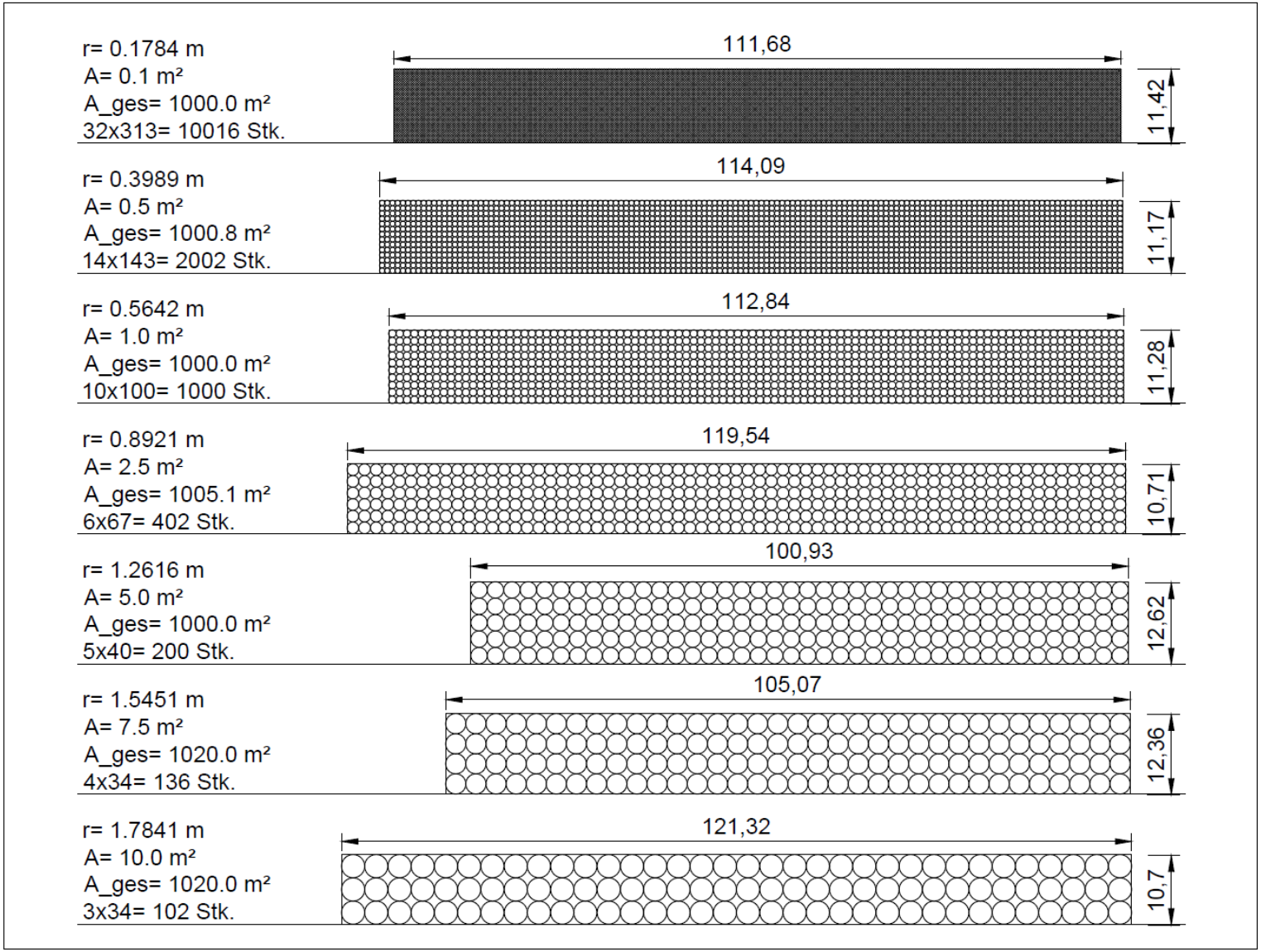
Version 1: Block number was kept constant

Ratio of the maximum impact force generated by single rock fall and rock mass



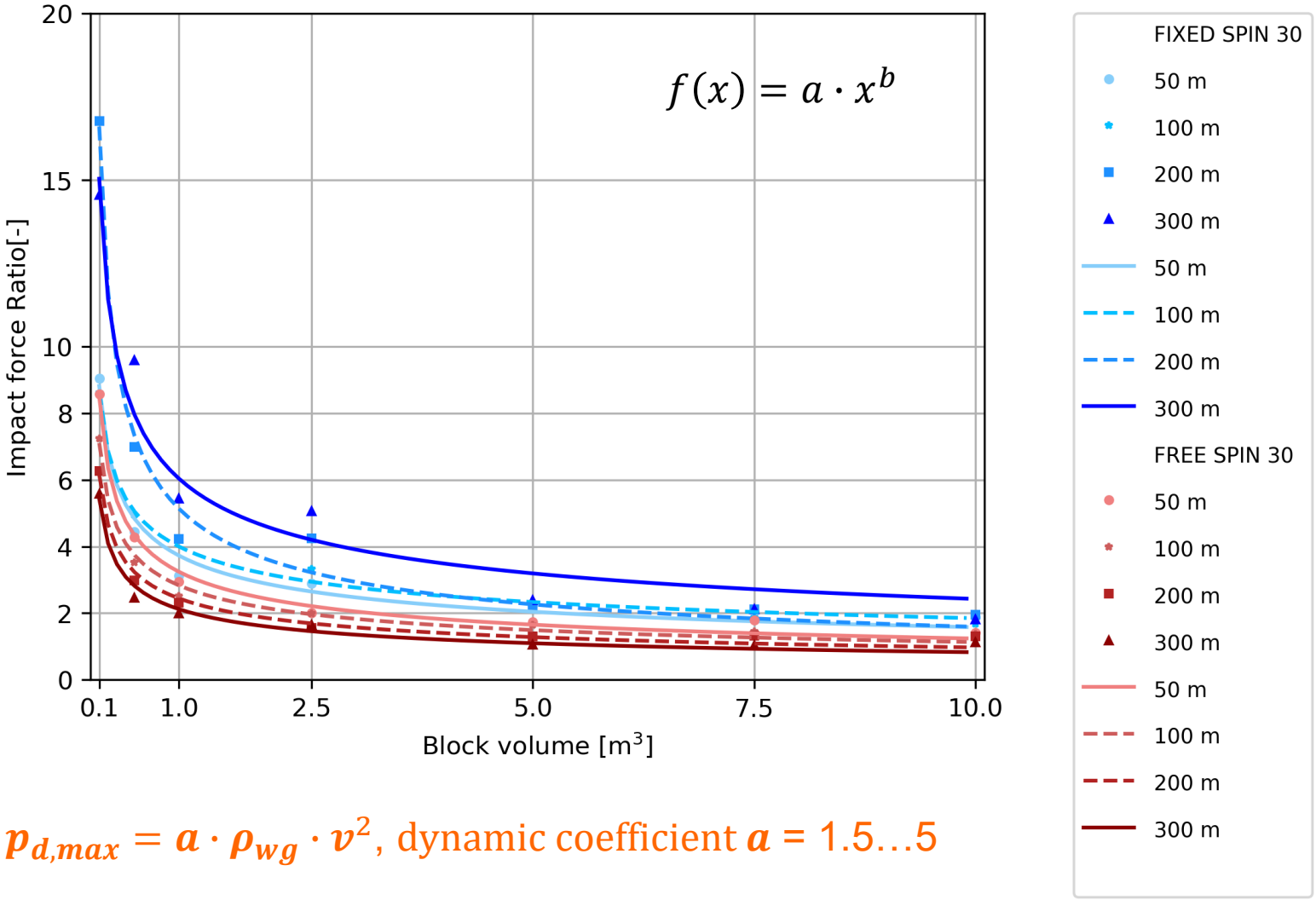
$p_{d,max} = a \cdot \rho_{wg} \cdot v^2$, dynamic coefficient a = 1.5…5

Version 2: Block volume was kept constant



Version 2: Block volume was kept constant

Ratio of the maximum impact force generated by single rock fall and rock mass



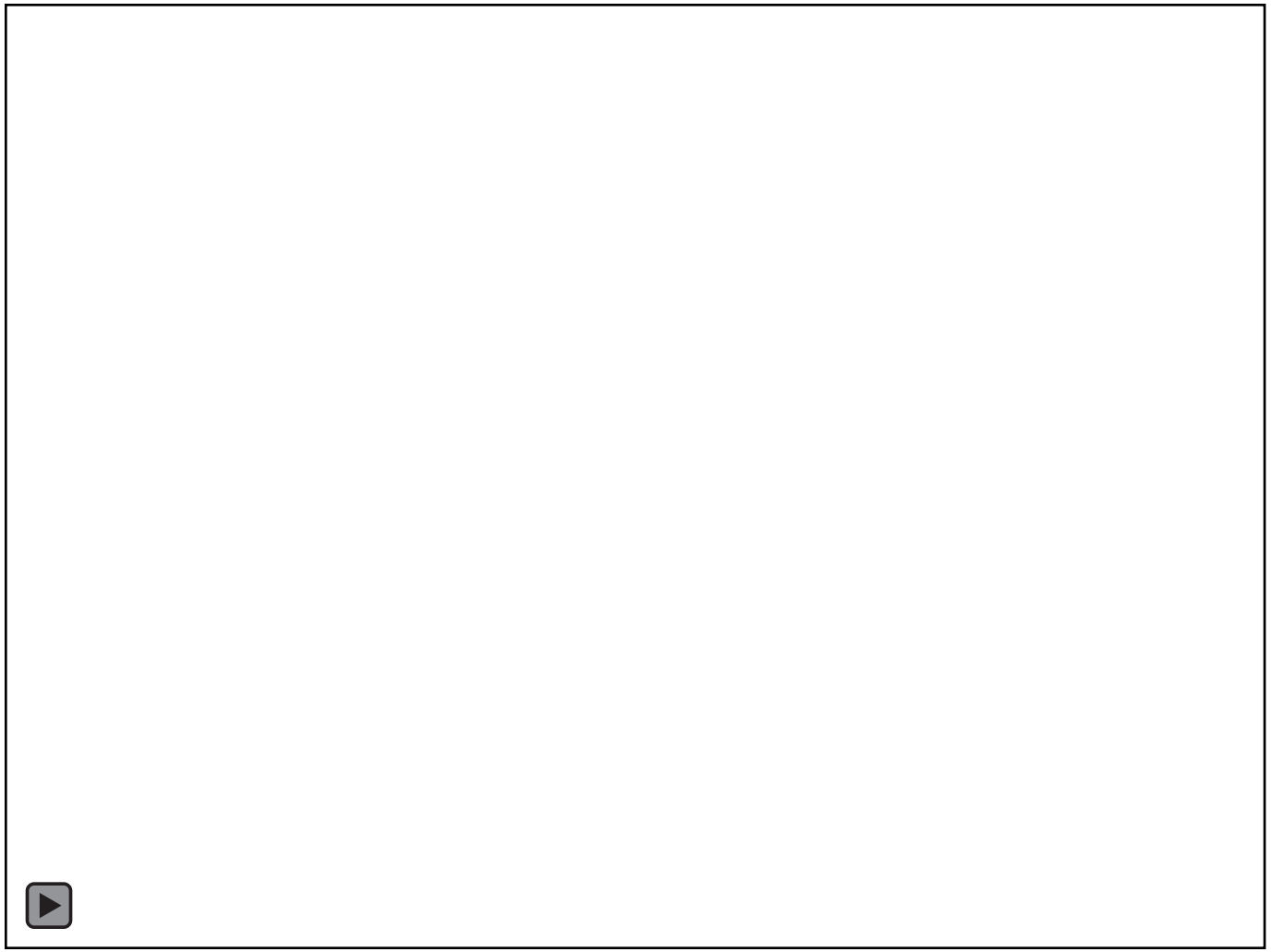
$p_{d,max} = a \cdot \rho_{wg} \cdot v^2$, dynamic coefficient a = 1.5…5

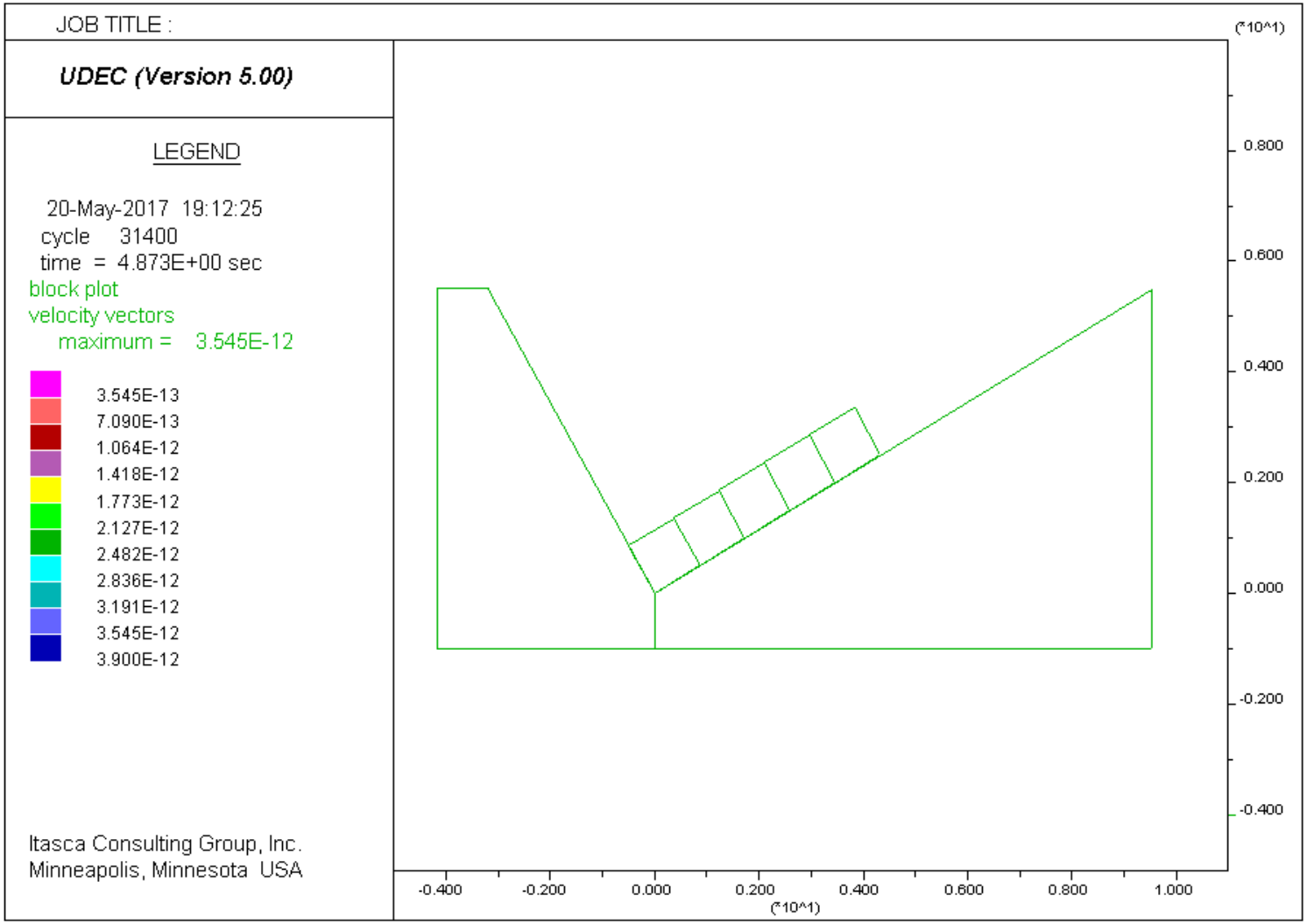
Conclusions

- The results of Analysis 1 indicate that the front part (i.e. the first five blocks) of a rock slide generates 90-98% of the maximum impact force. The effect of the following sliding blocks (beyond five) is negligible. An explanation could be that the first few blocks, after their impact, are acting as a barrier themselves, taking up most impact force of the following blocks.

- The results of Analysis 2 indicate that there is a relationship between single rock fall and rock mass fall, which predominantly depends on block volume and rotational damping.

Thank you for attention

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Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
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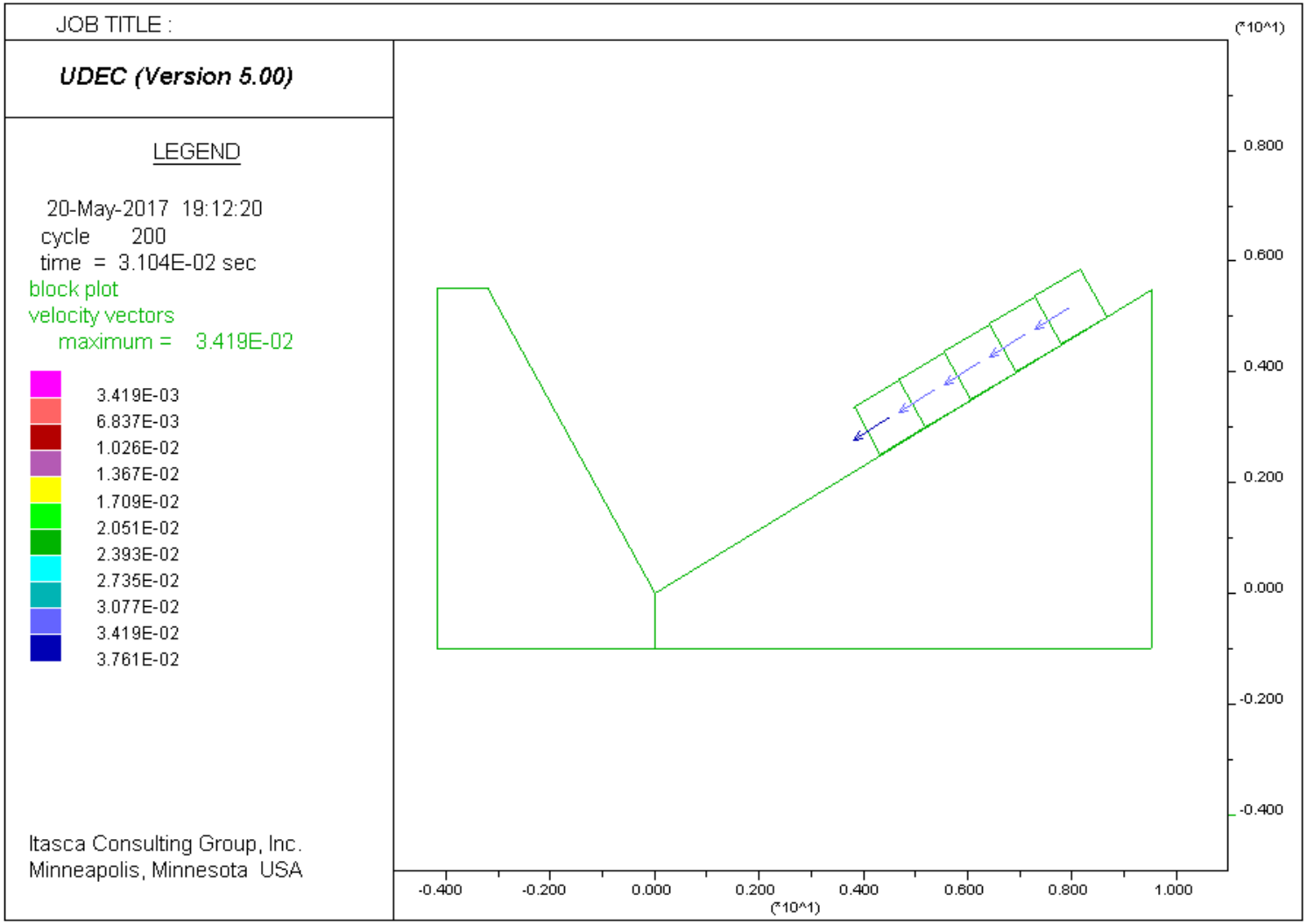
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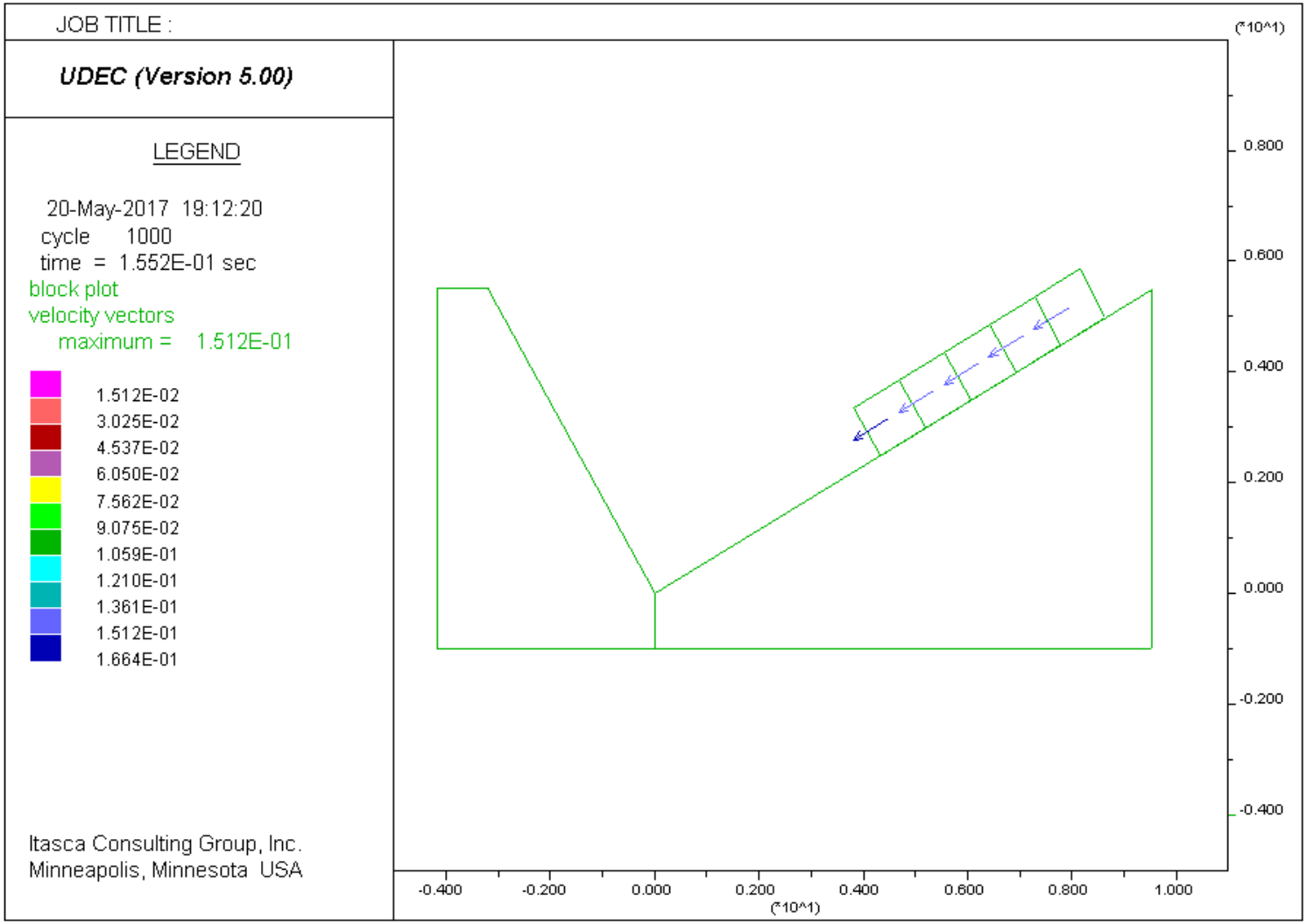
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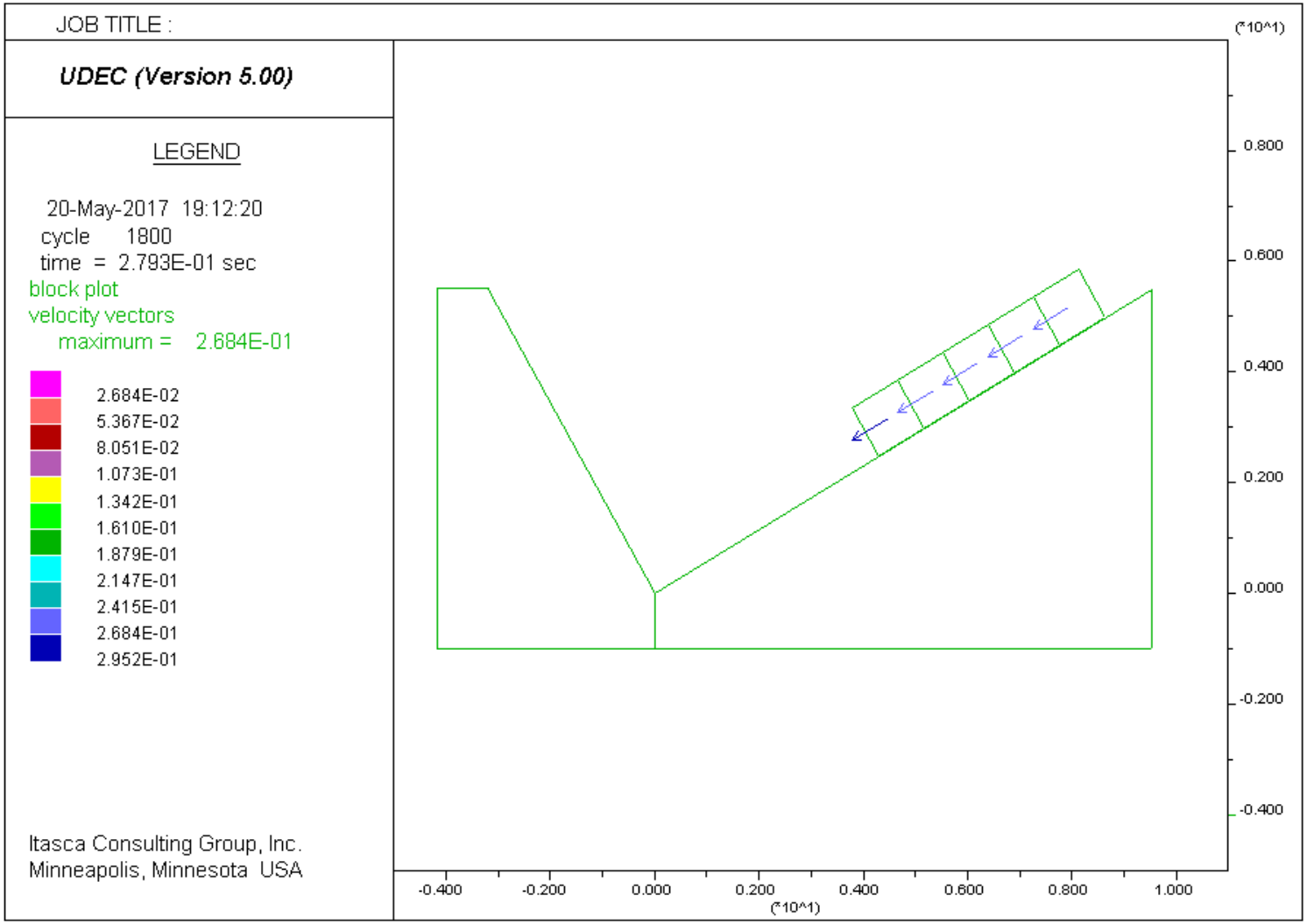
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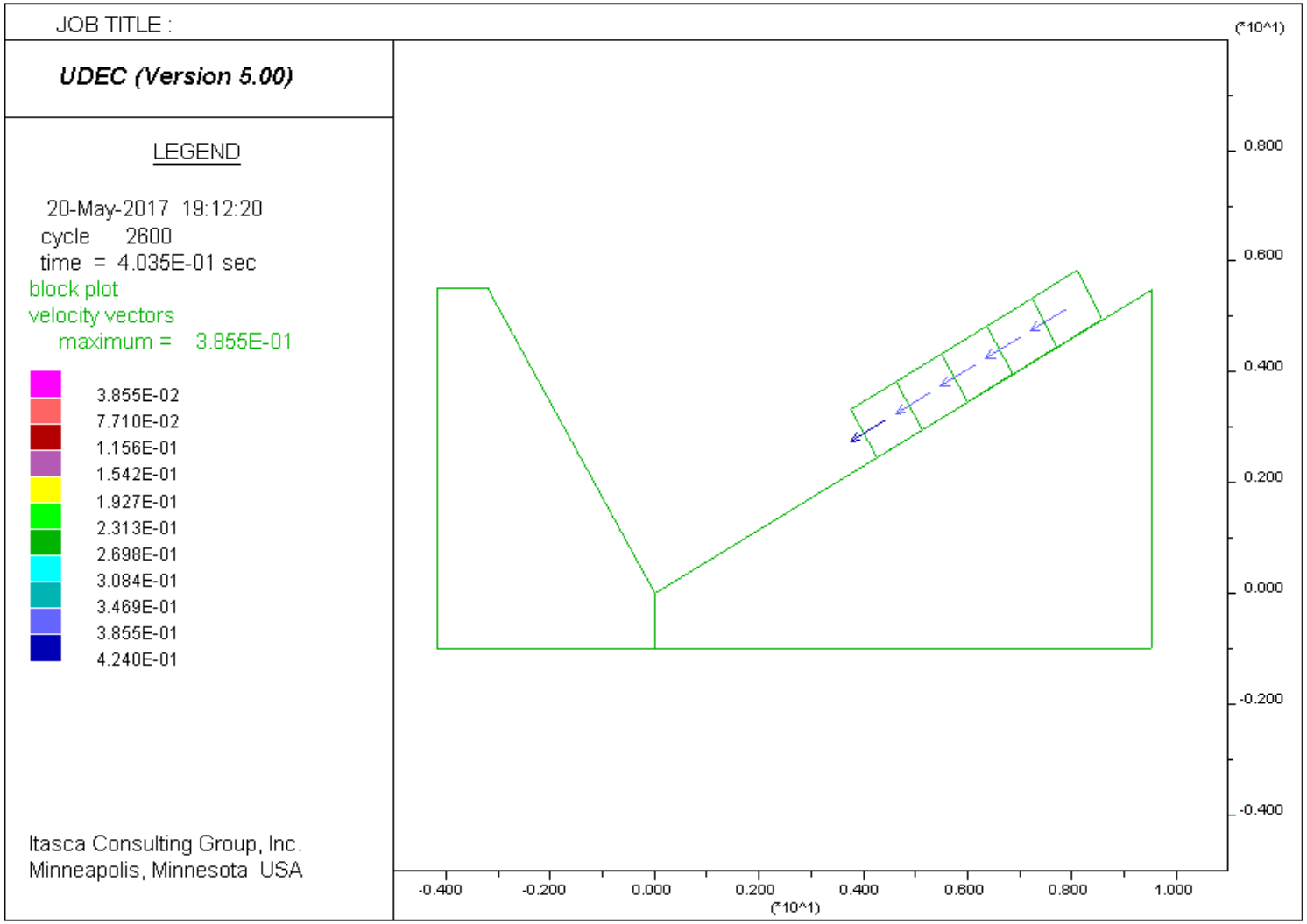
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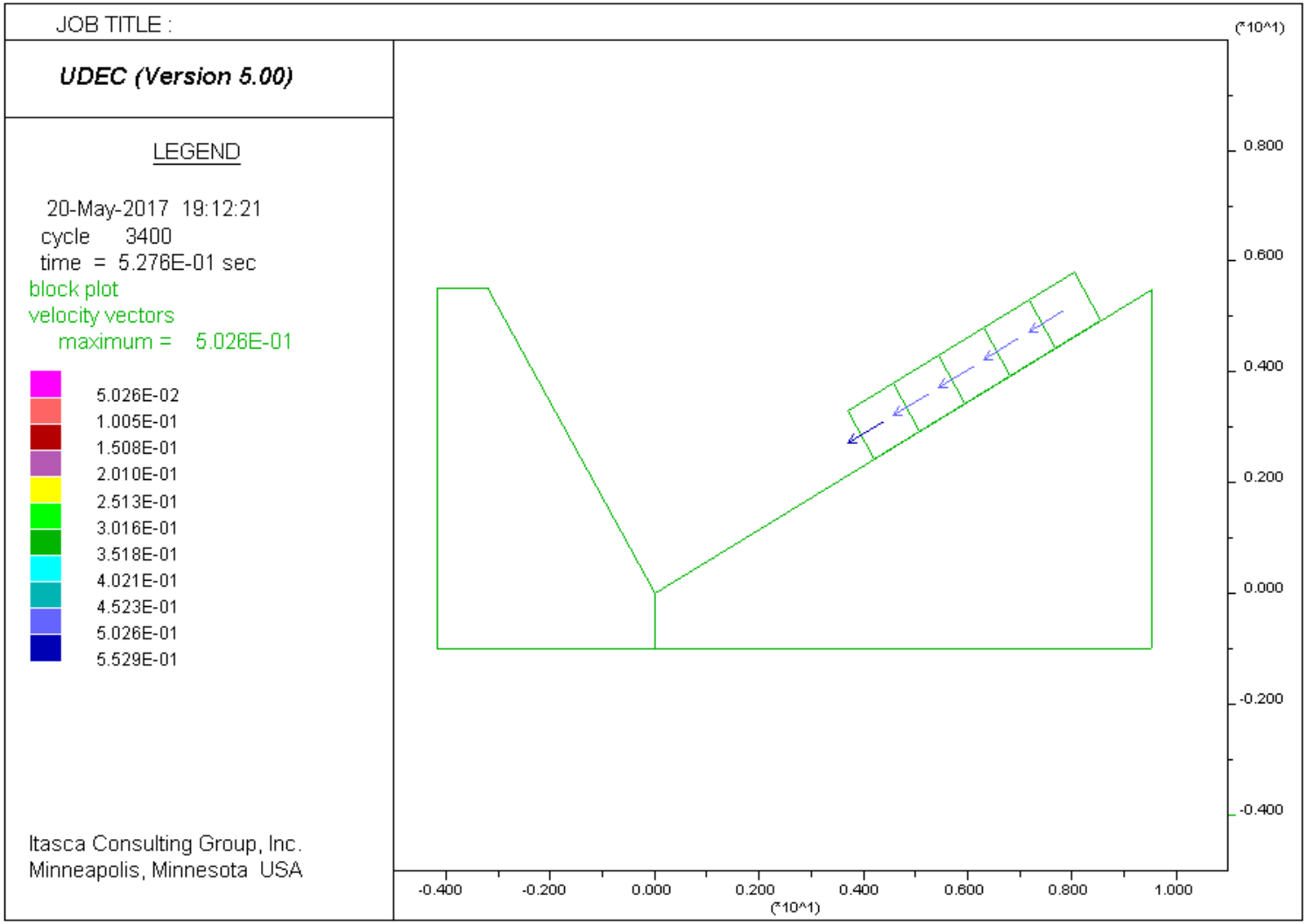
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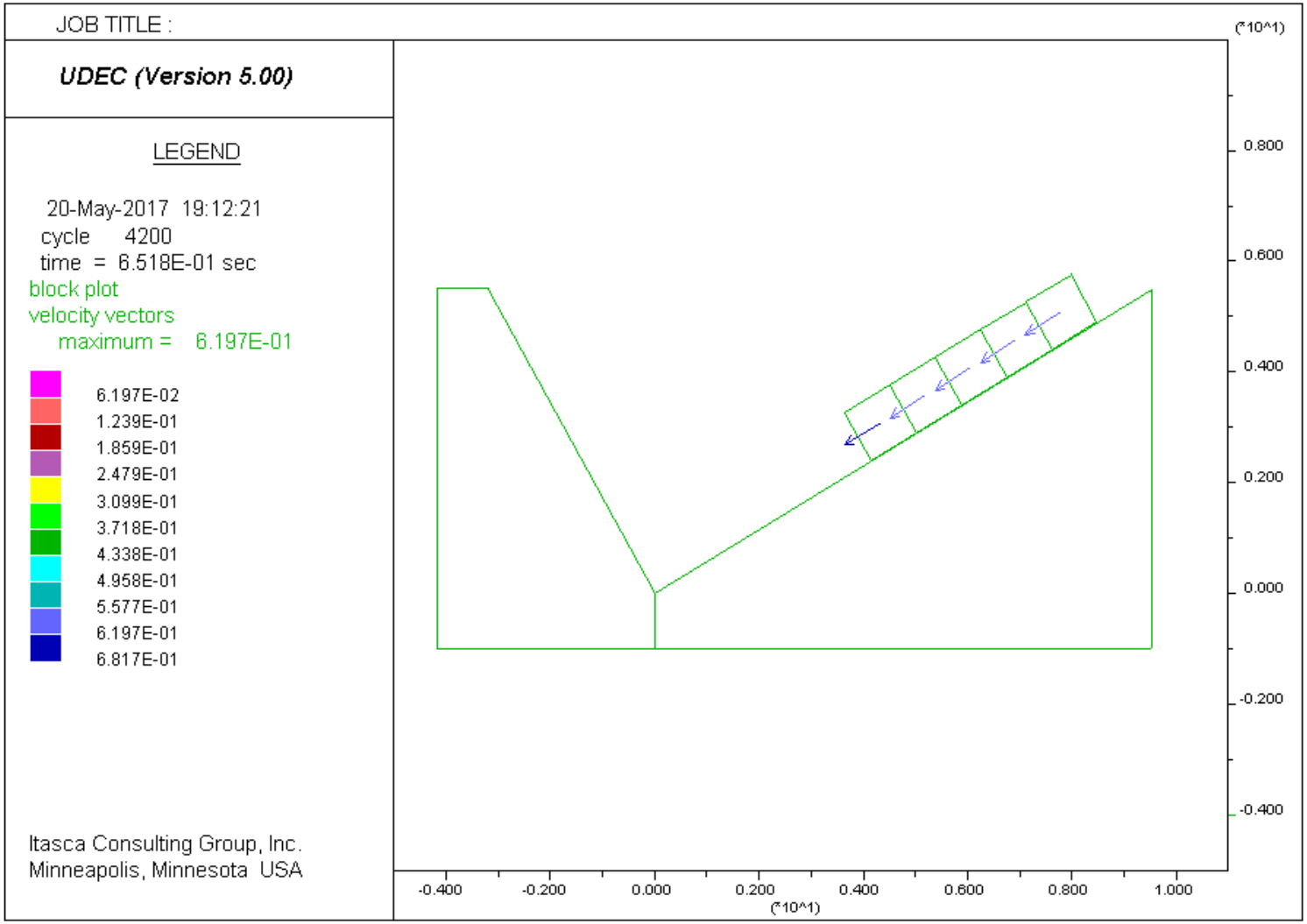
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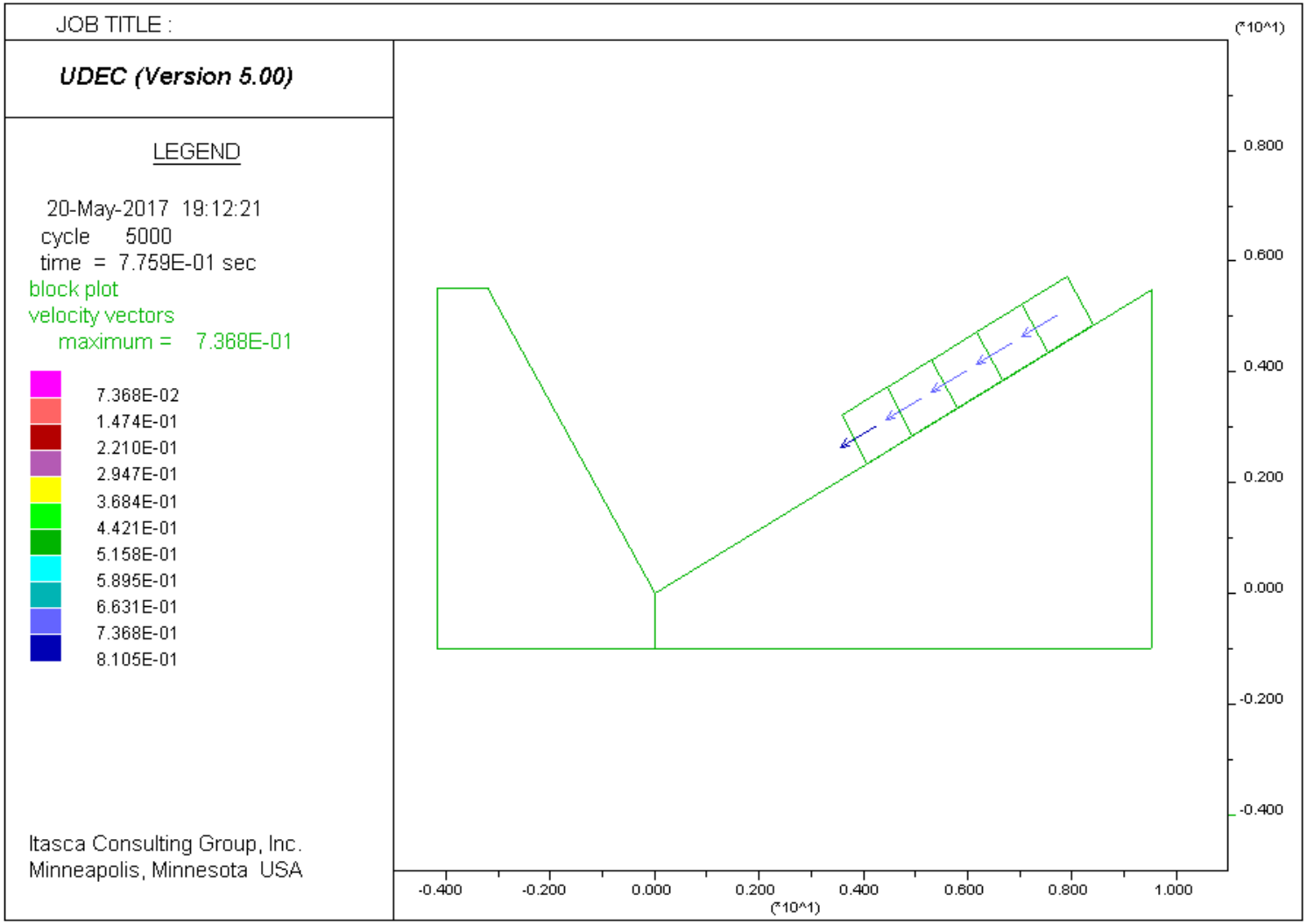
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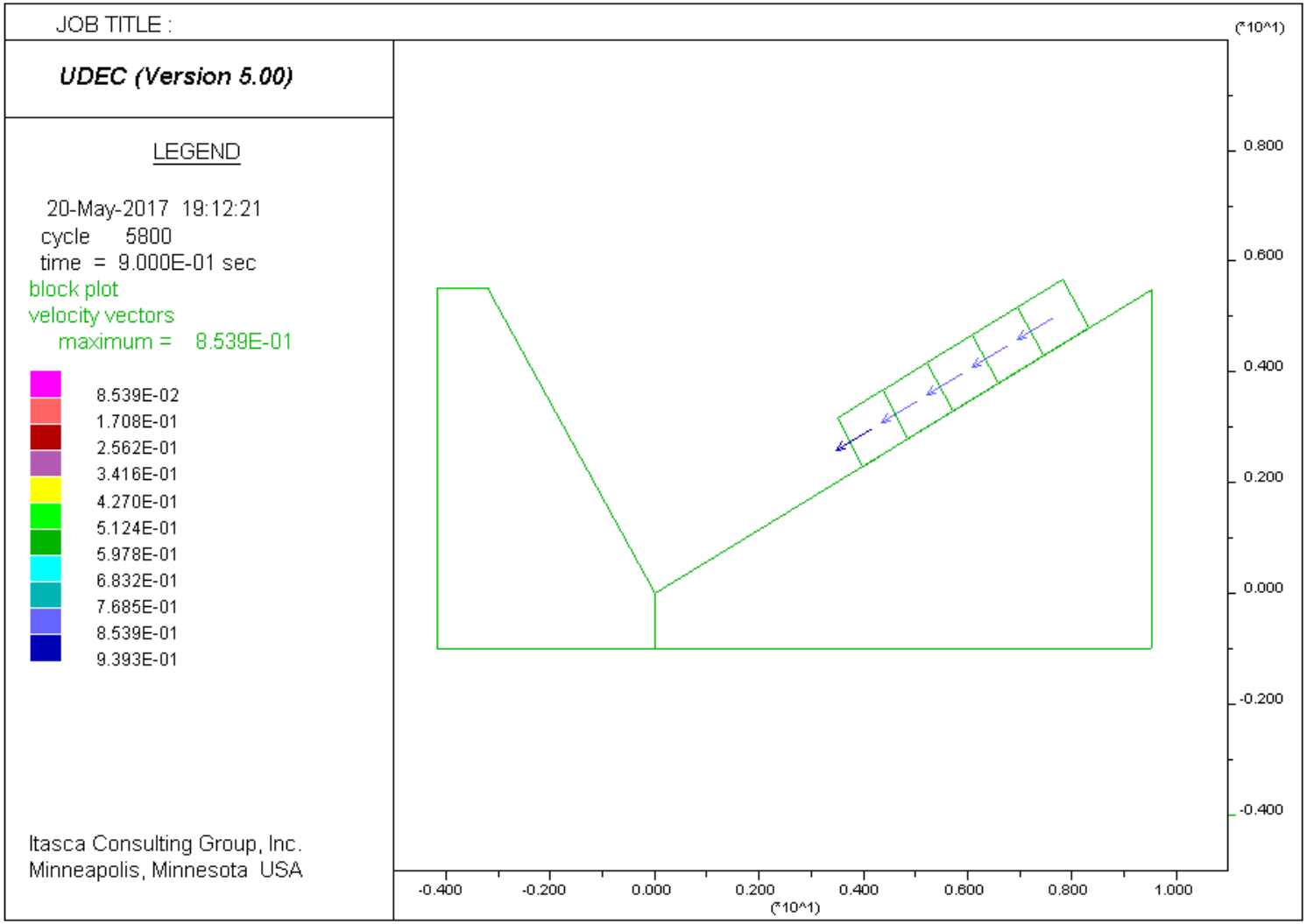
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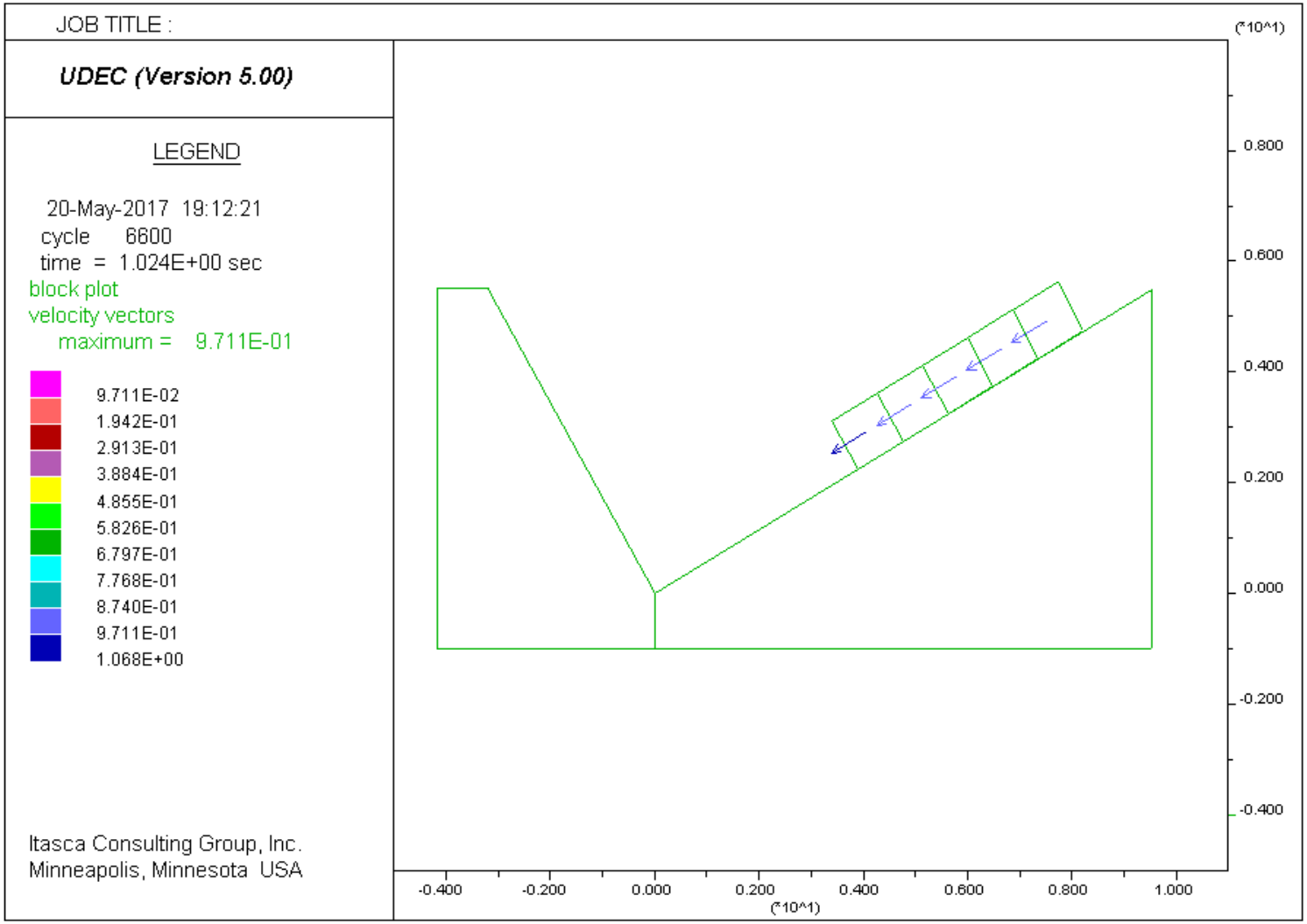
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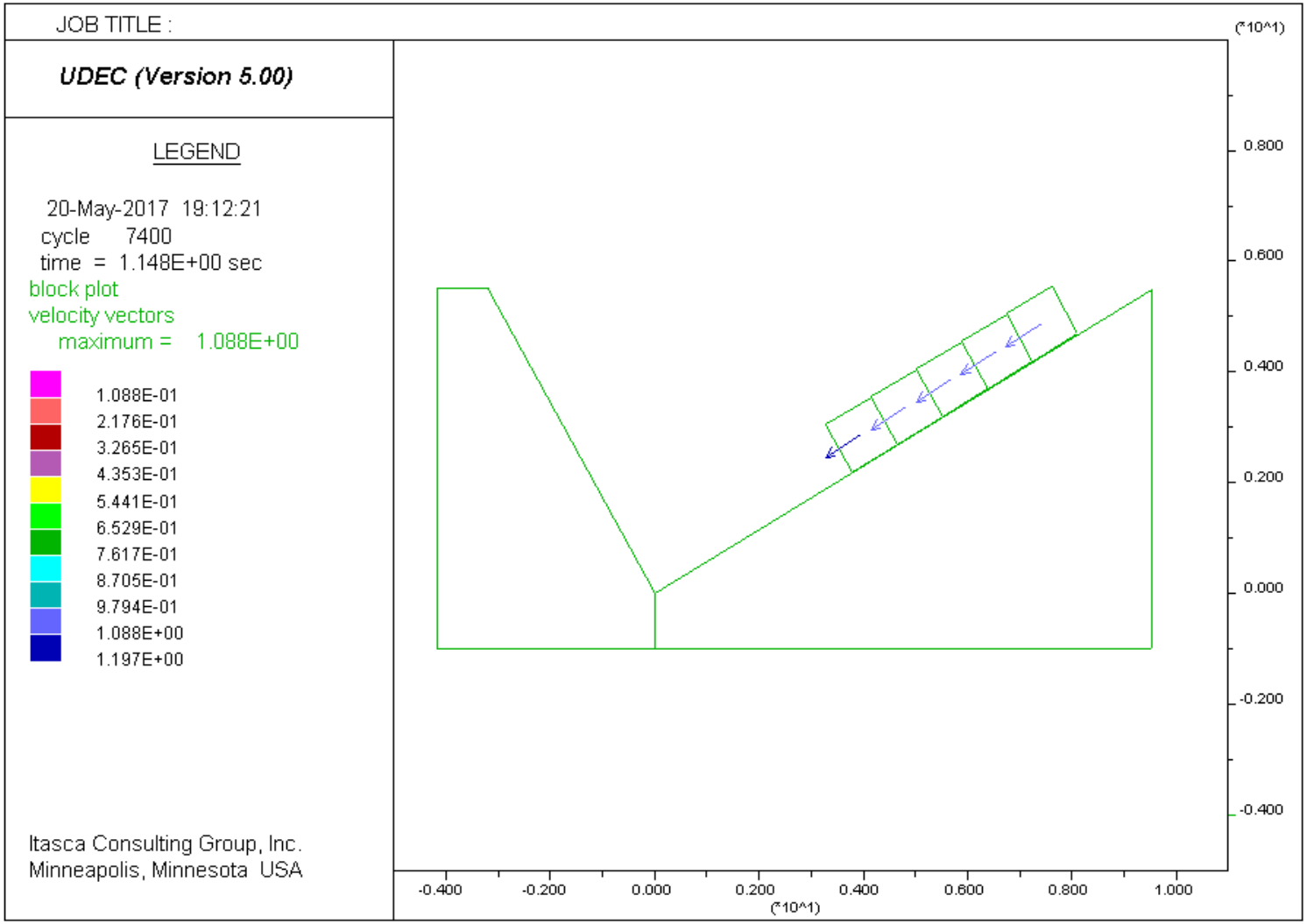
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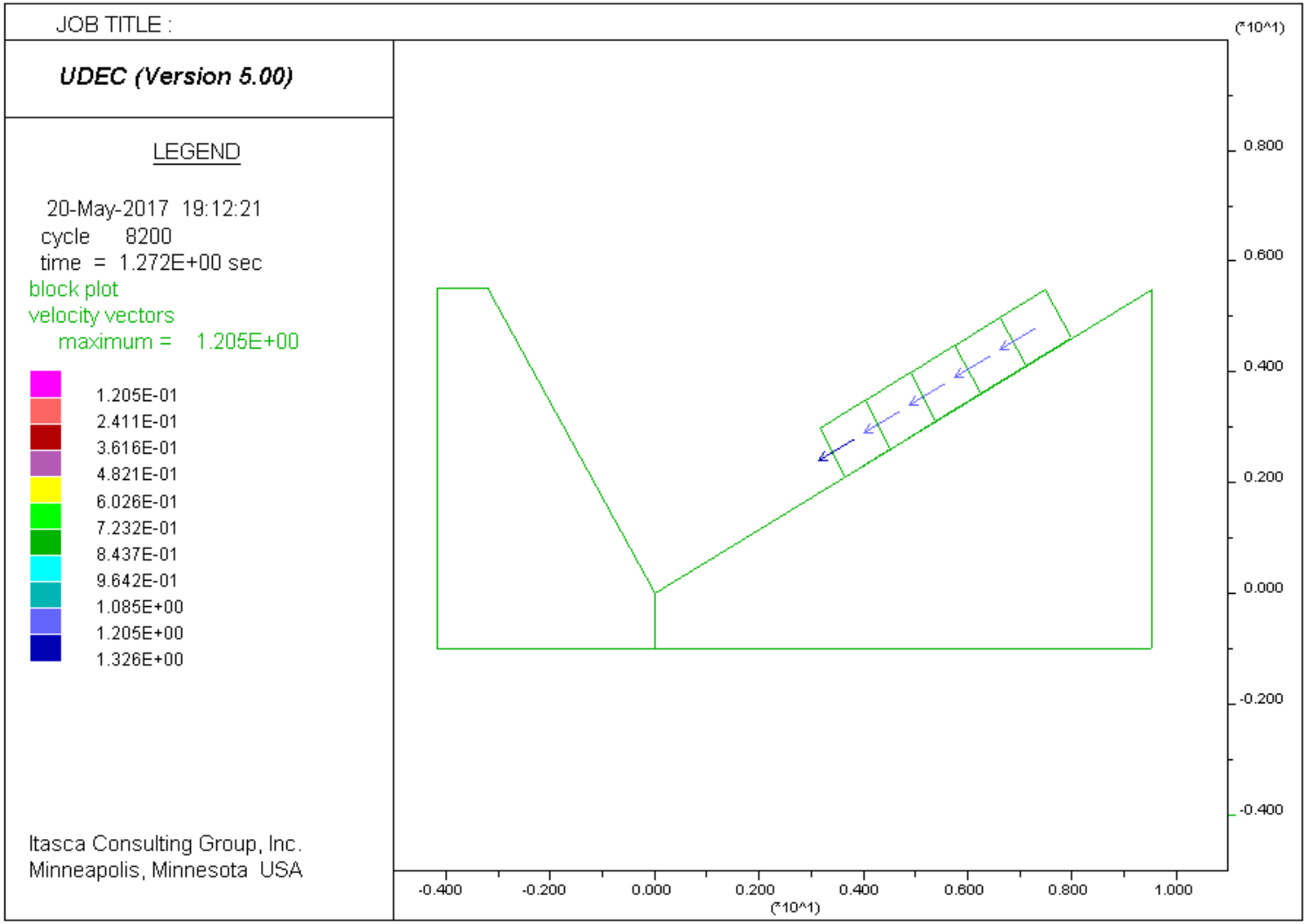
velocity vectors
maximum = 1.088E+00
1.088E-01
2.176E-01
3.265E-01
4.353E-01
5.441E-01
6.529E-01
7.617E-01
8.705E-01
9.794E-01
1.088E+00
1.197E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:21
cycle 8200
time = 1.272E+00 sec
block plot
velocity vectors
maximum = 1.205E+00
1.205E-01
2.411E-01
3.616E-01
4.821E-01
6.026E-01
7.232E-01
8.437E-01
9.642E-01
1.085E+00
1.205E+00
1.326E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
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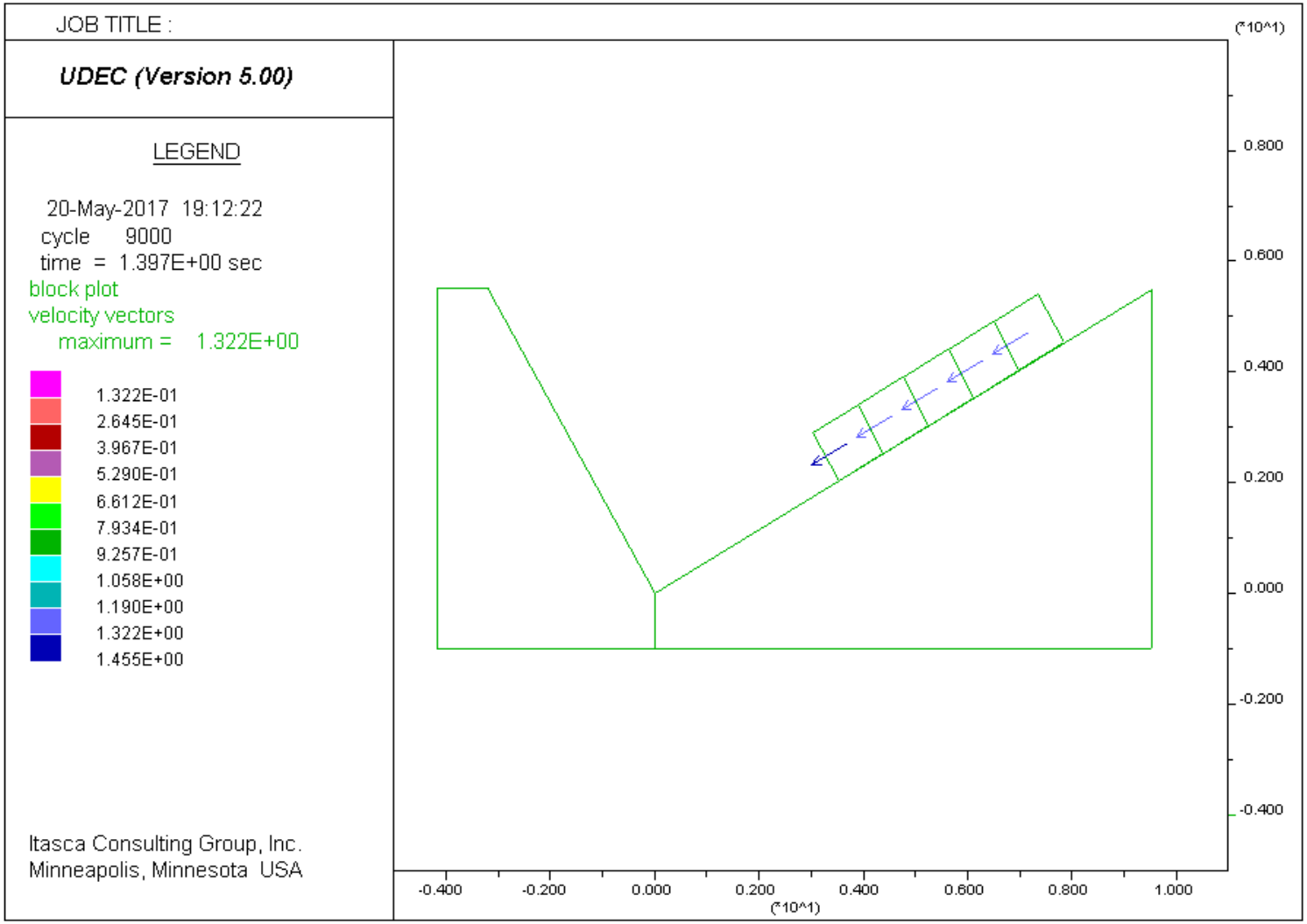
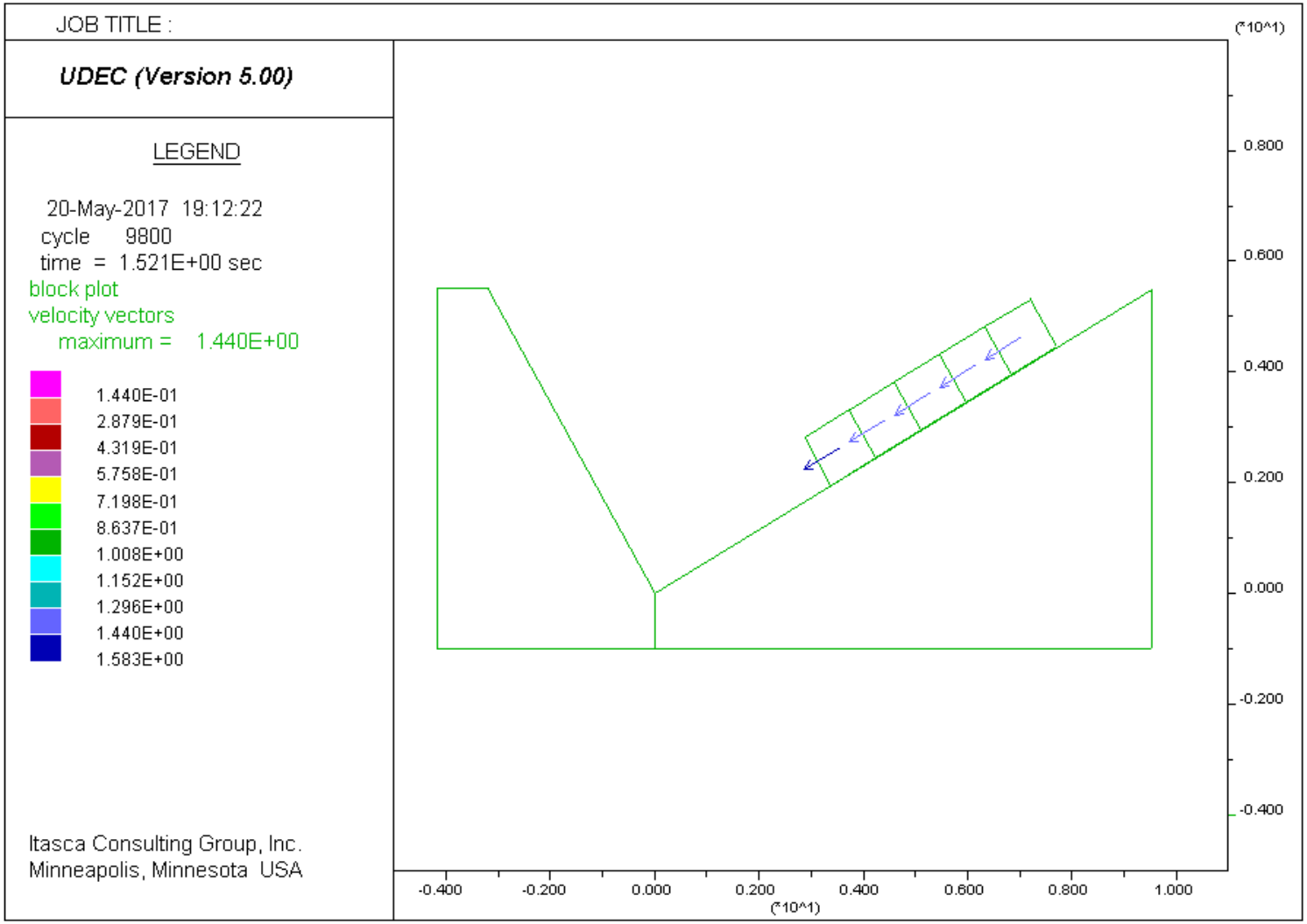
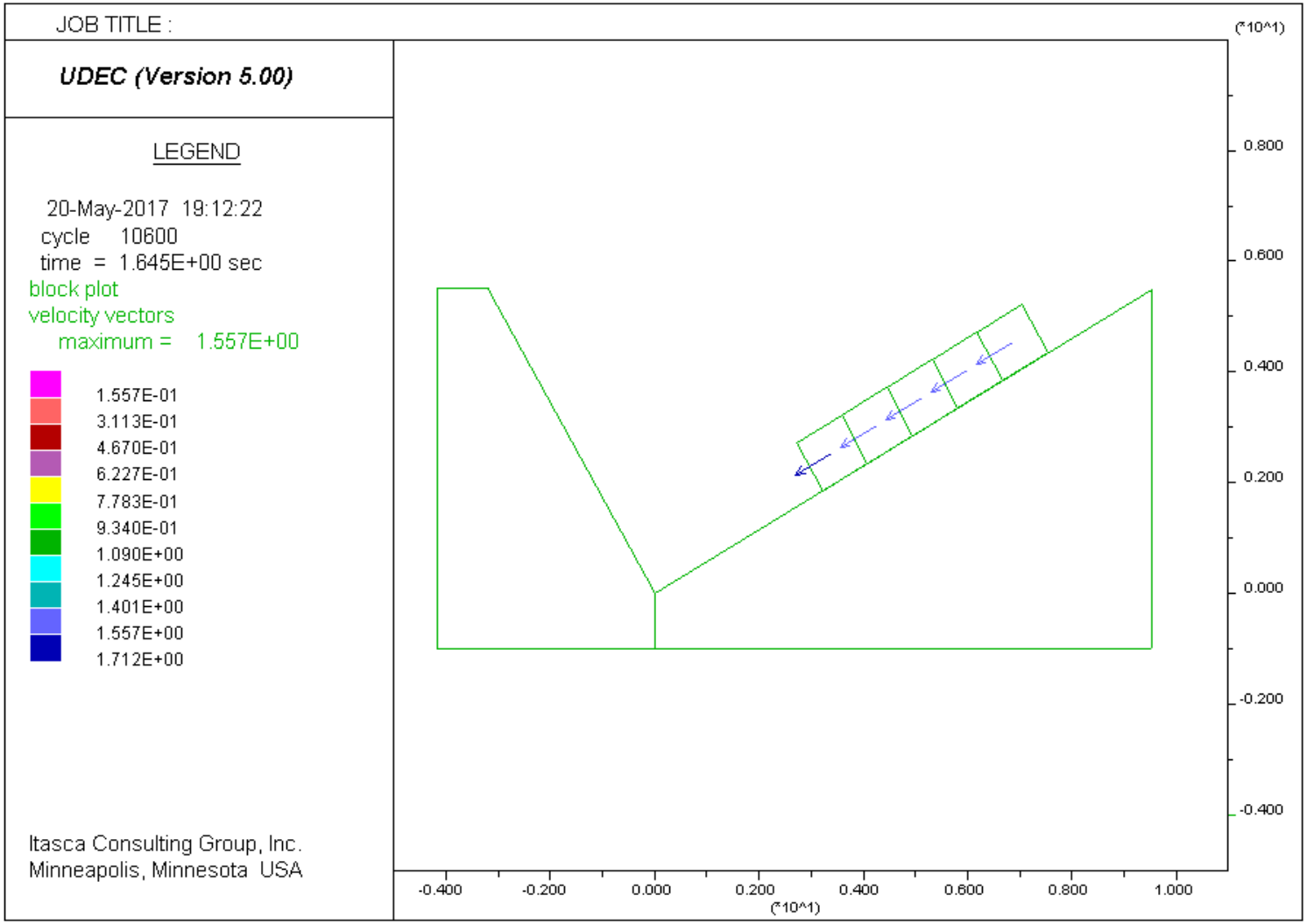
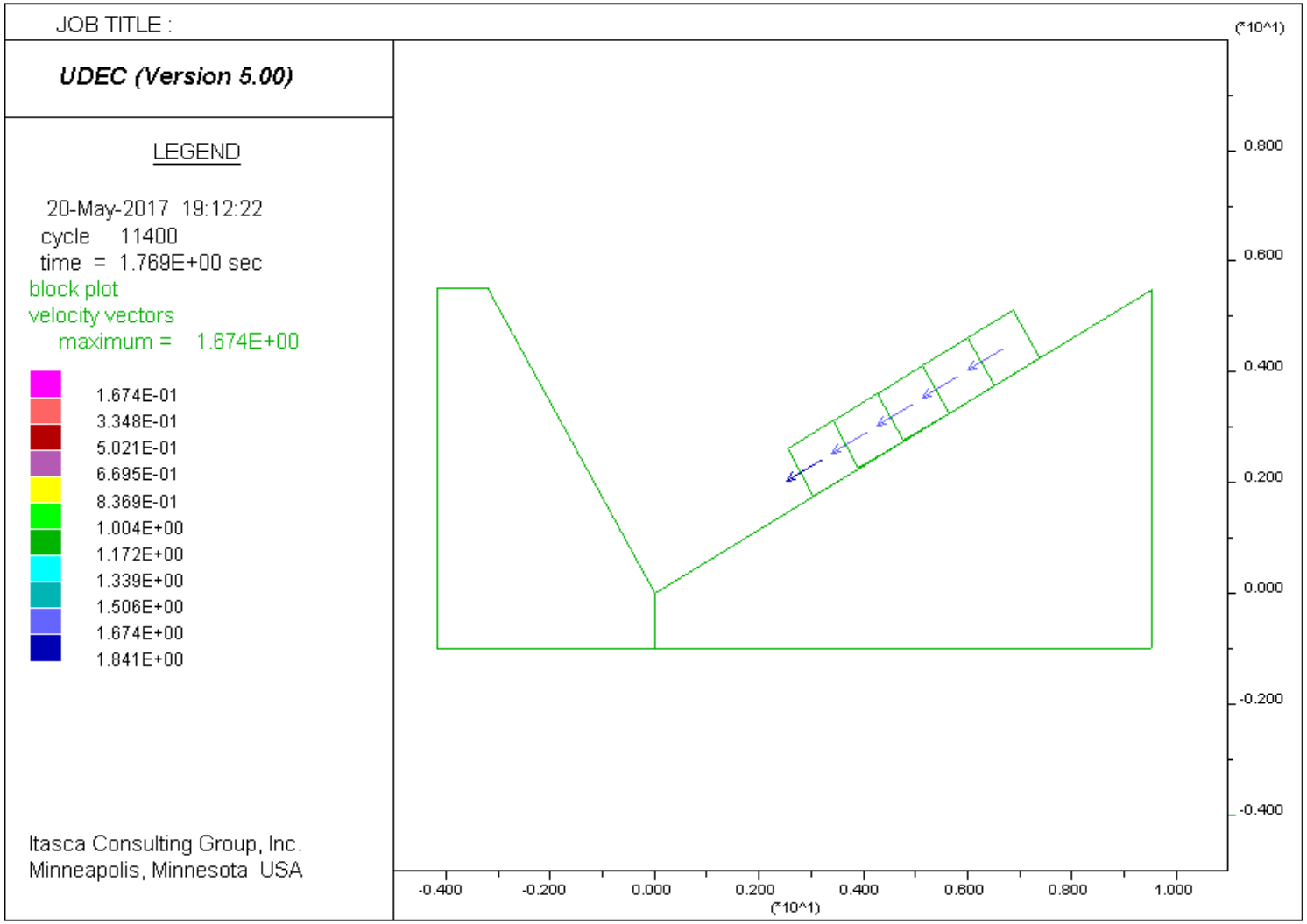
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:22
cycle 9000
time = 1.397E+00 sec
block plot
velocity vectors
maximum = 1.322E+00
1.322E-01
2.645E-01
3.967E-01
5.290E-01
6.612E-01
7.934E-01
9.257E-01
1.058E+00
1.190E+00
1.322E+00
1.455E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:22
cycle 9800
time = 1.521E+00 sec
block plot
velocity vectors
maximum = 1.440E+00
1.440E-01
2.879E-01
4.319E-01
5.758E-01
7.198E-01
8.637E-01
1.008E+00
1.152E+00
1.296E+00
1.440E+00
1.583E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:22
cycle 10600
time = 1.645E+00 sec
block plot
velocity vectors
maximum = 1.557E+00
1.557E-01
3.113E-01
4.670E-01
6.227E-01
7.783E-01
9.340E-01
1.090E+00
1.245E+00
1.401E+00
1.557E+00
1.712E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:22
cycle 11400
time = 1.769E+00 sec
block plot
velocity vectors
maximum = 1.674E+00
1.674E-01
3.348E-01
5.021E-01
6.695E-01
8.369E-01
1.004E+00
1.172E+00
1.339E+00
1.506E+00
1.674E+00
1.841E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
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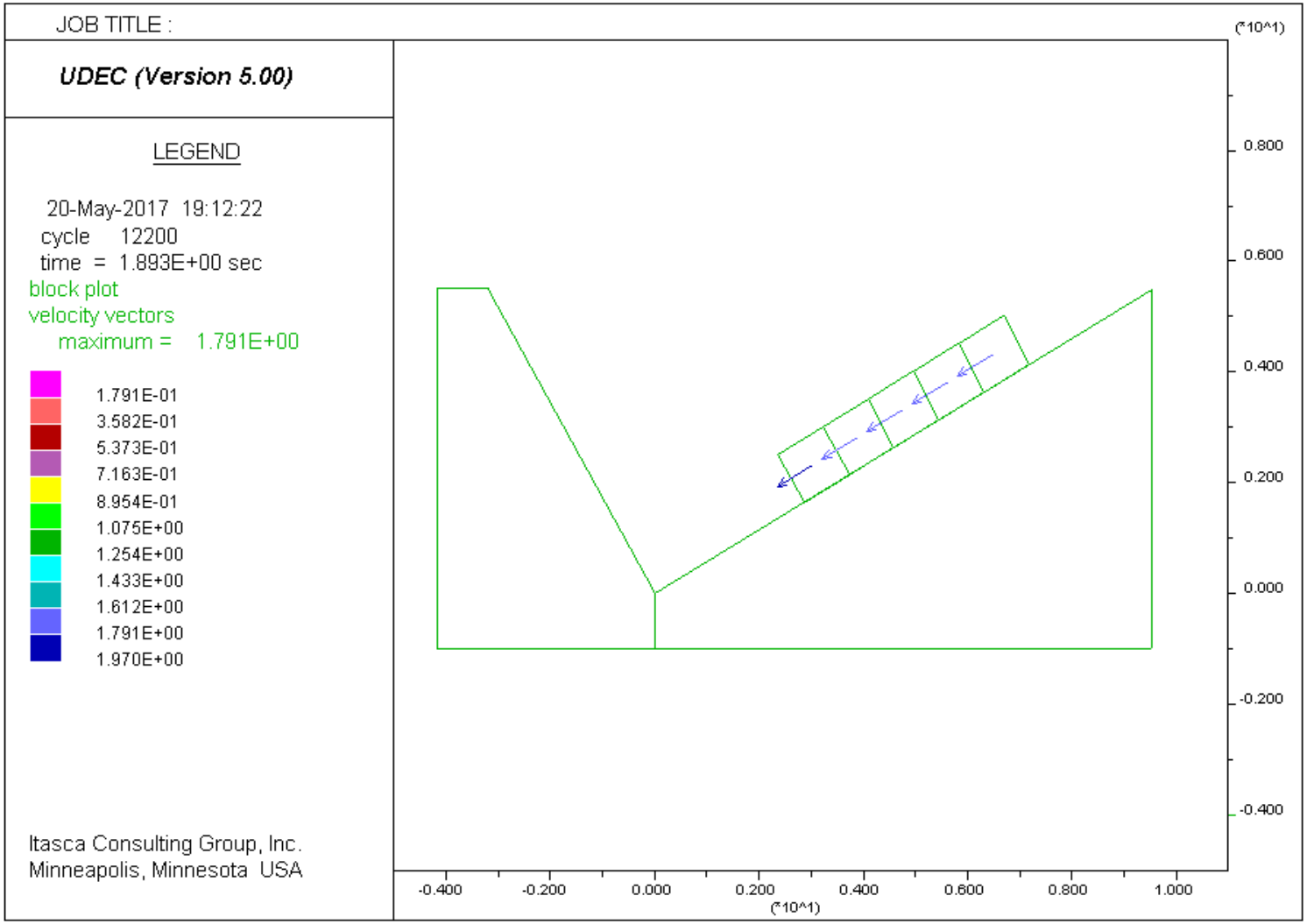
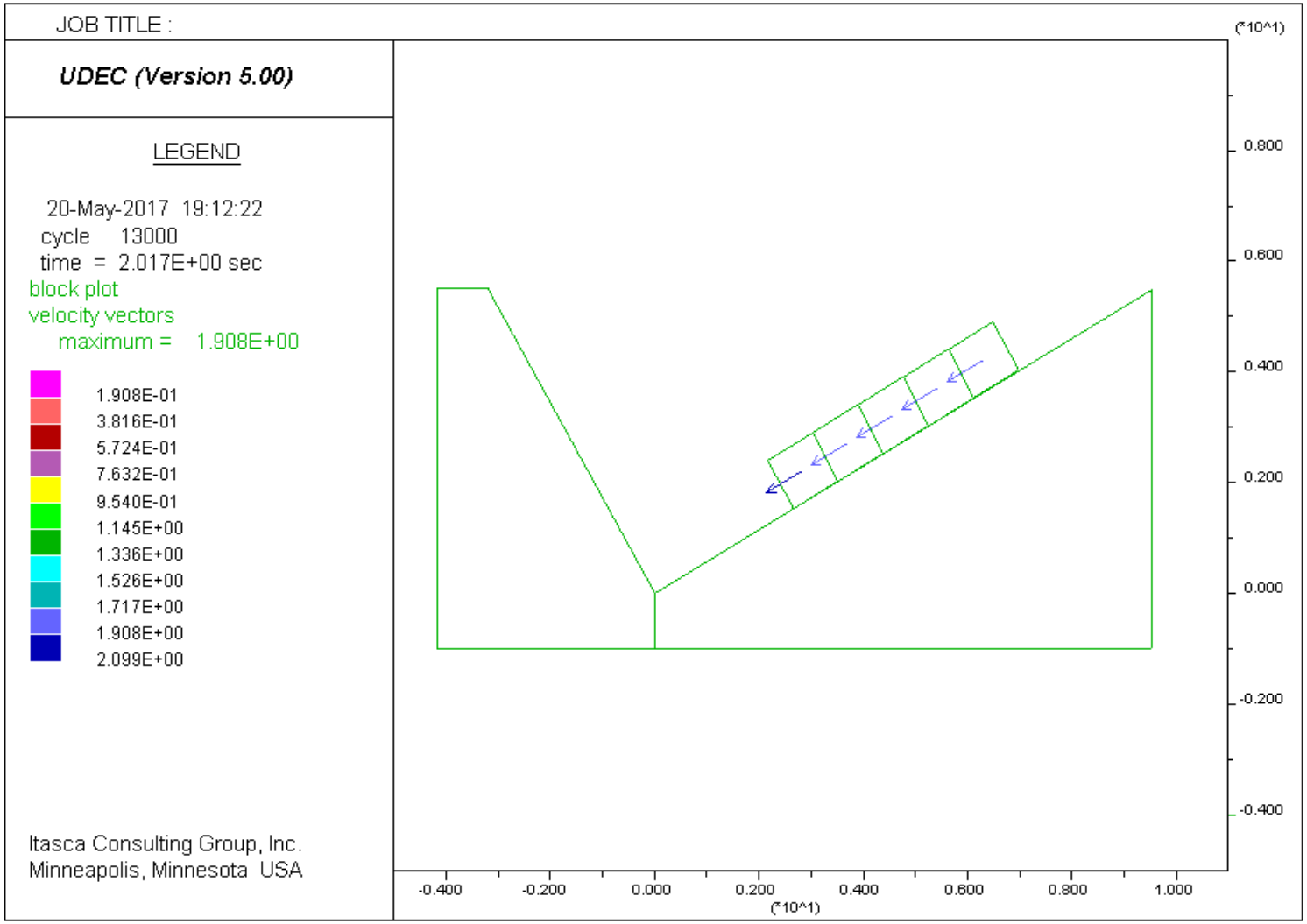
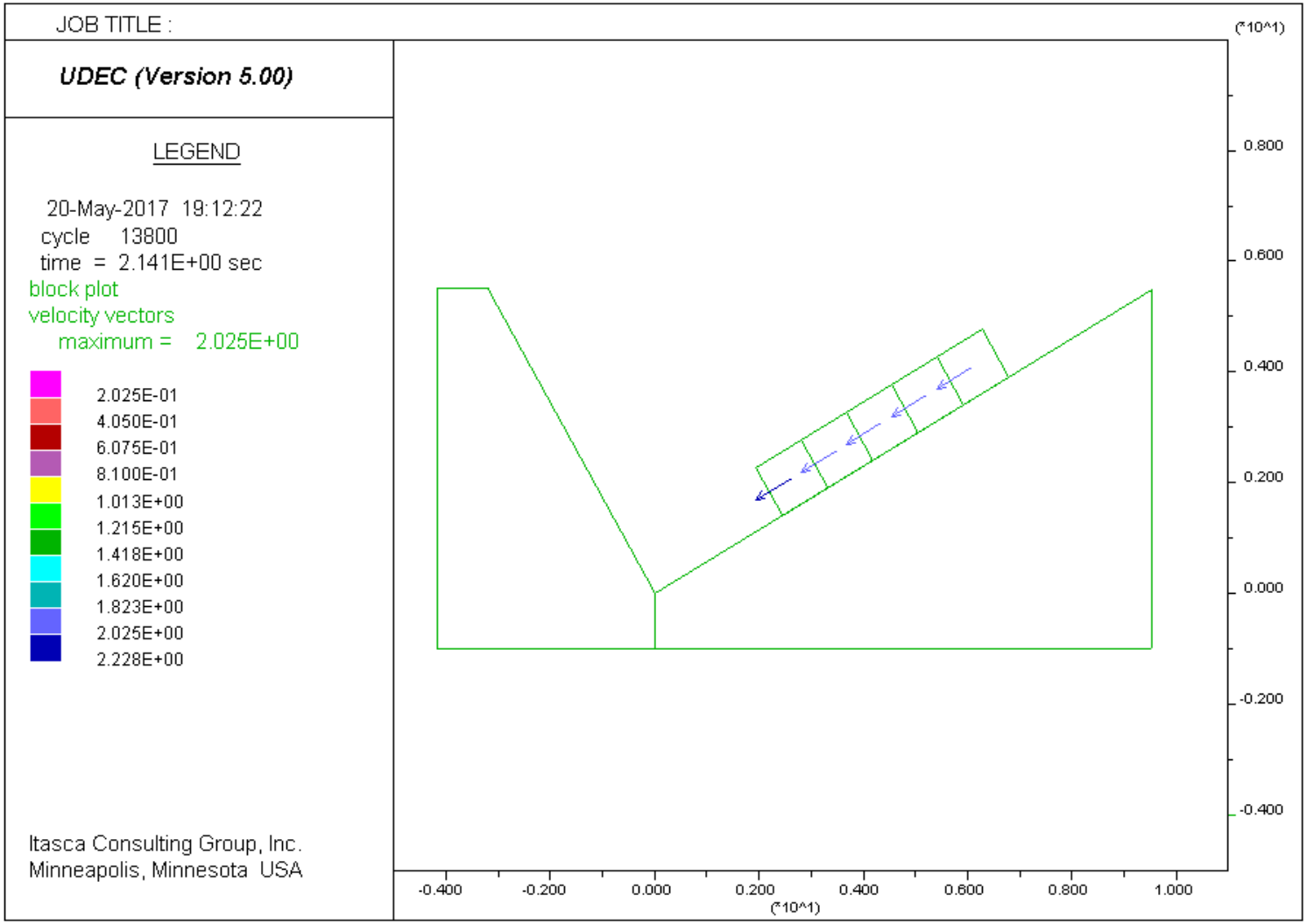
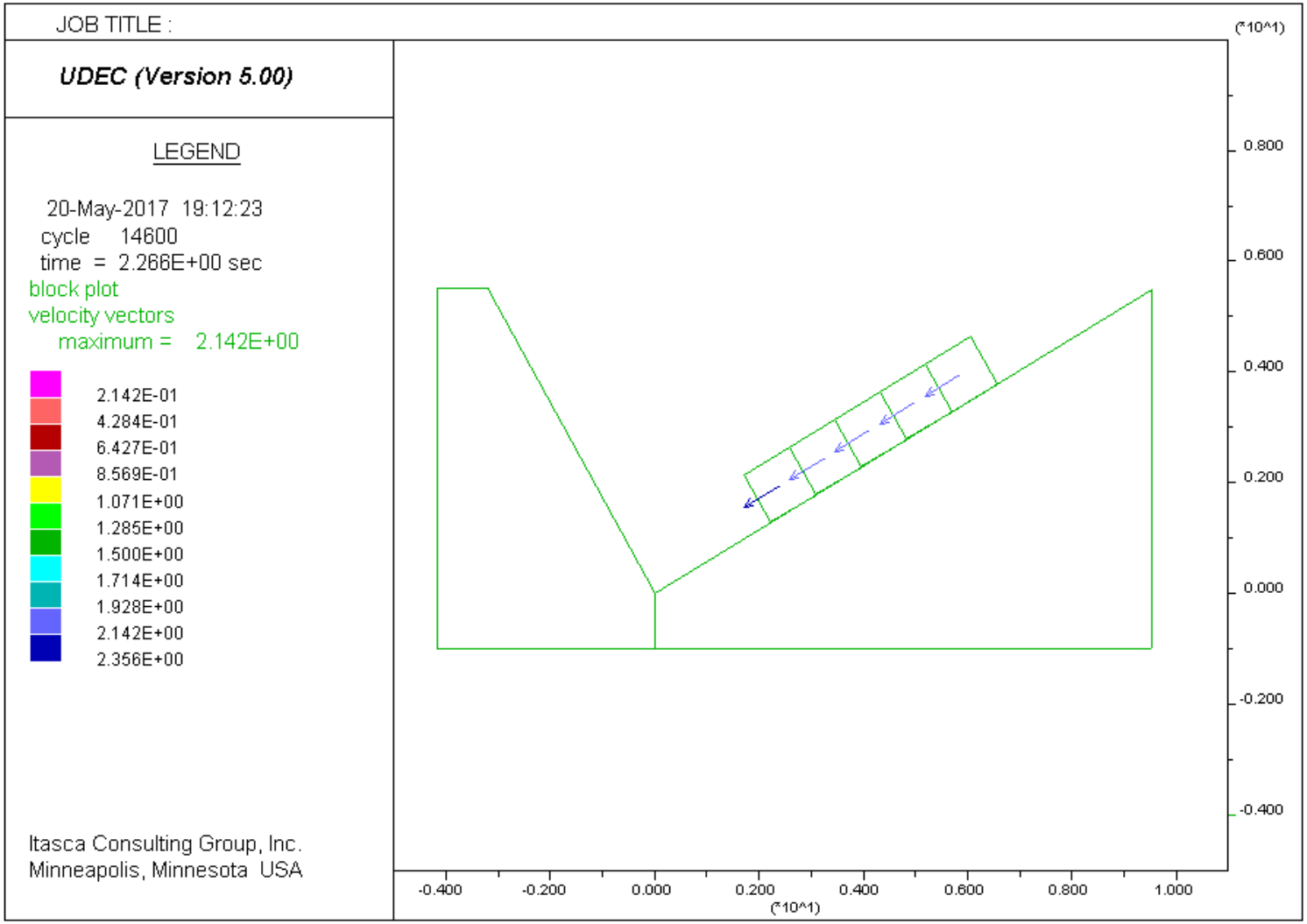
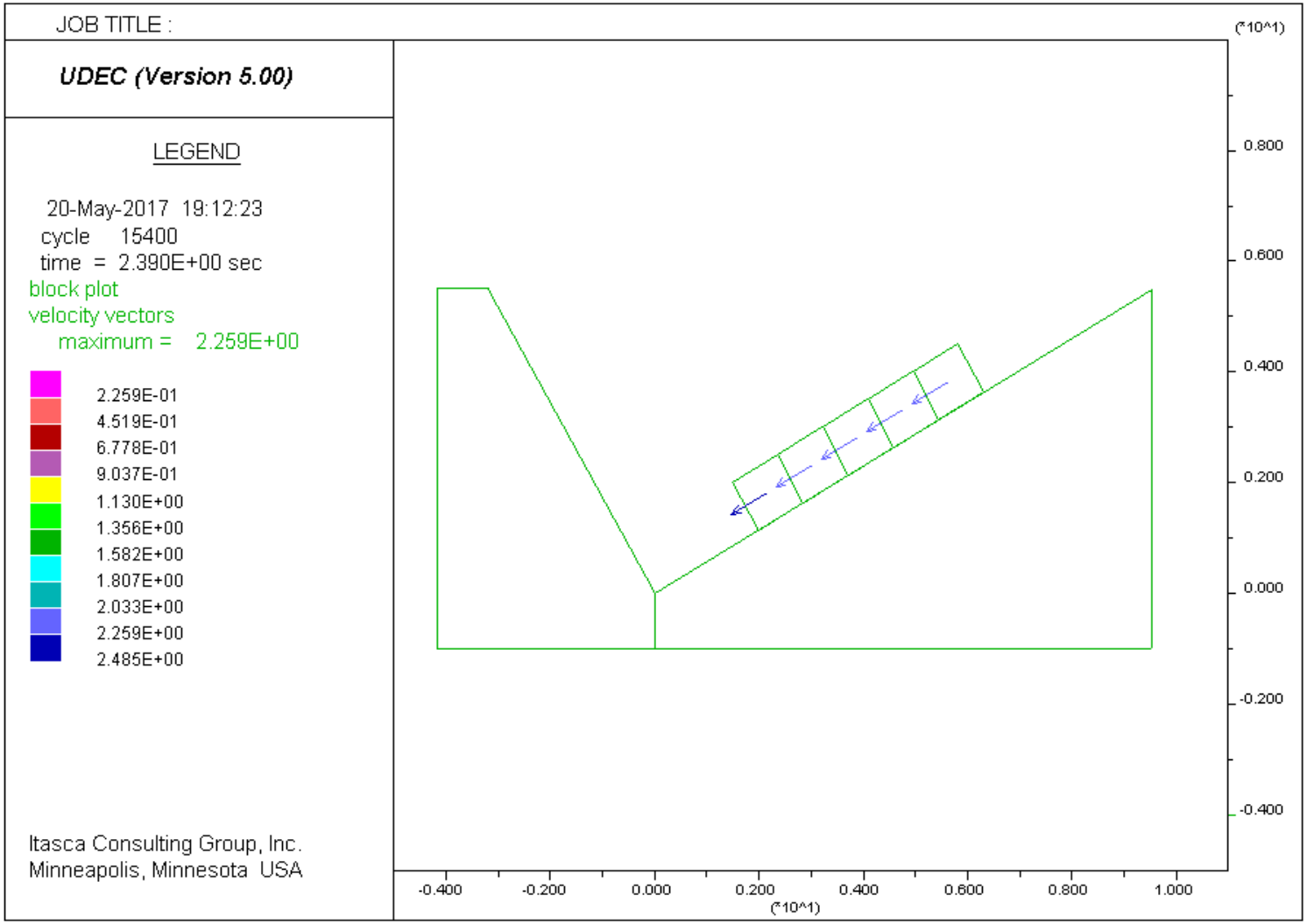
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)

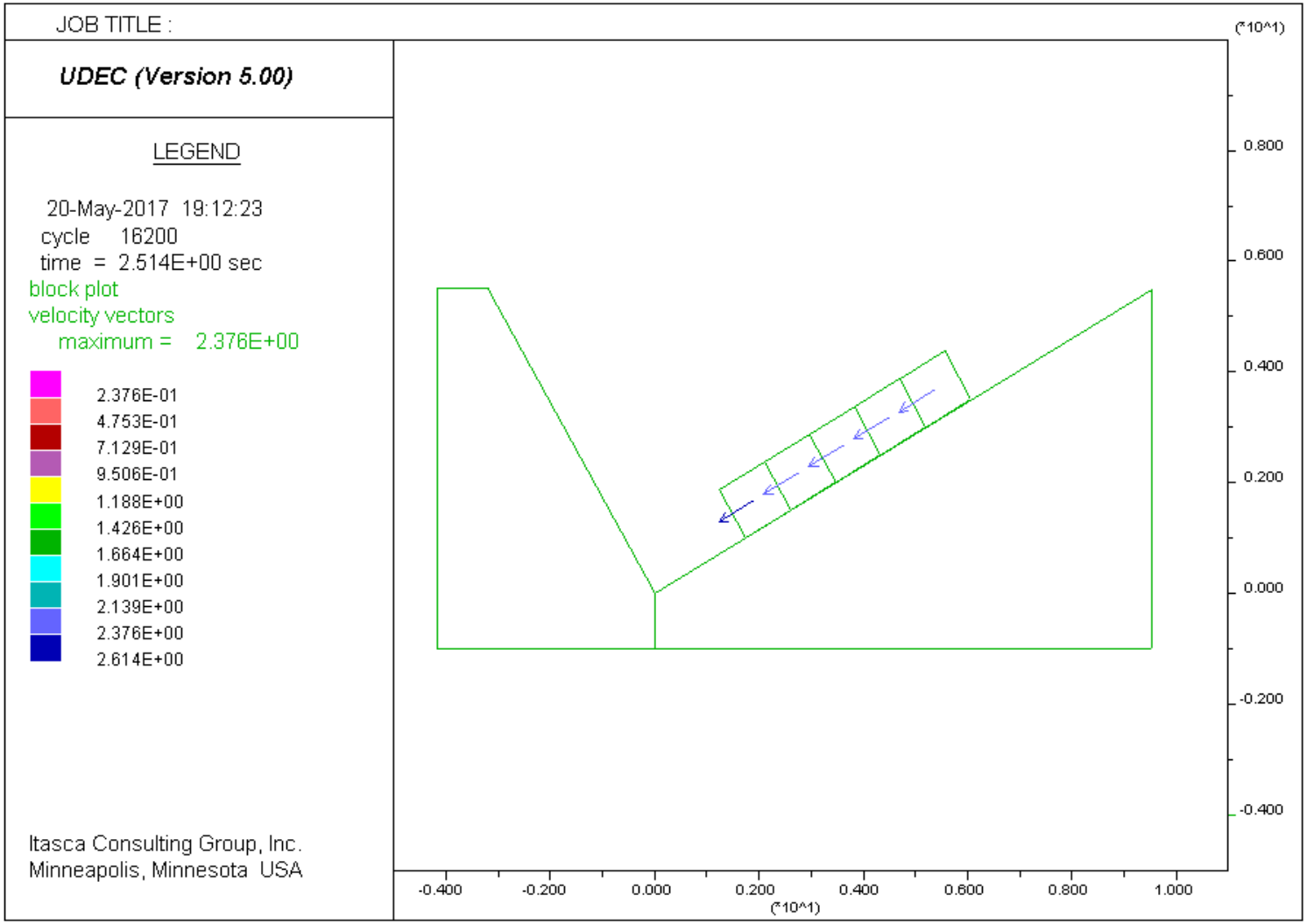

JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:22
cycle 12200
time = 1.893E+00 sec
block plot
velocity vectors
maximum = 1.791E+00
1.791E-01
3.582E-01
5.373E-01
7.163E-01
8.954E-01
1.075E+00
1.254E+00
1.433E+00
1.612E+00
1.791E+00
1.970E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)

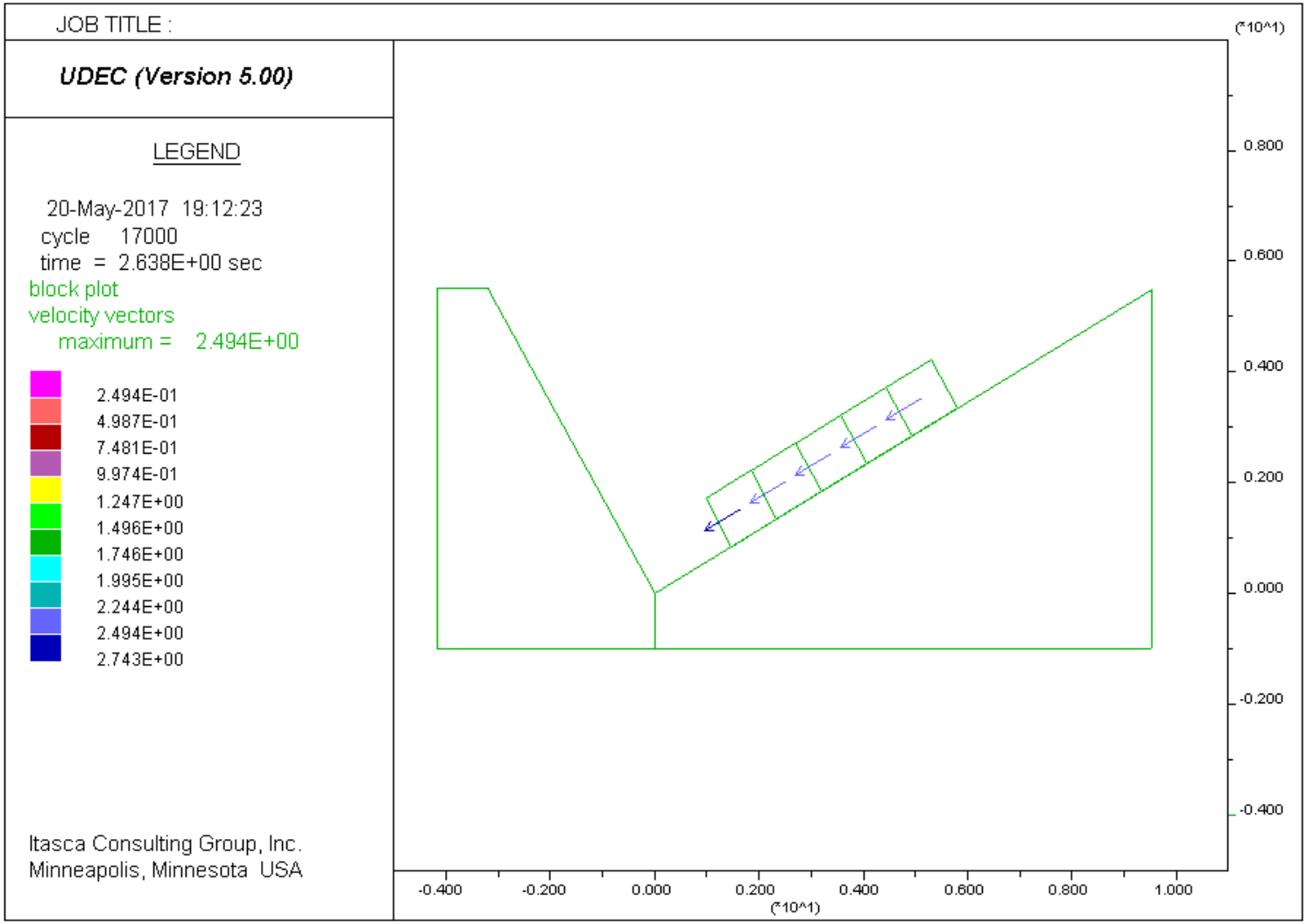

JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:22
cycle 13000
time = 2.017E+00 sec
block plot
velocity vectors
maximum = 1.908E+00
1.908E-01
3.816E-01
5.724E-01
7.632E-01
9.540E-01
1.145E+00
1.336E+00
1.526E+00
1.717E+00
1.908E+00
2.099E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)

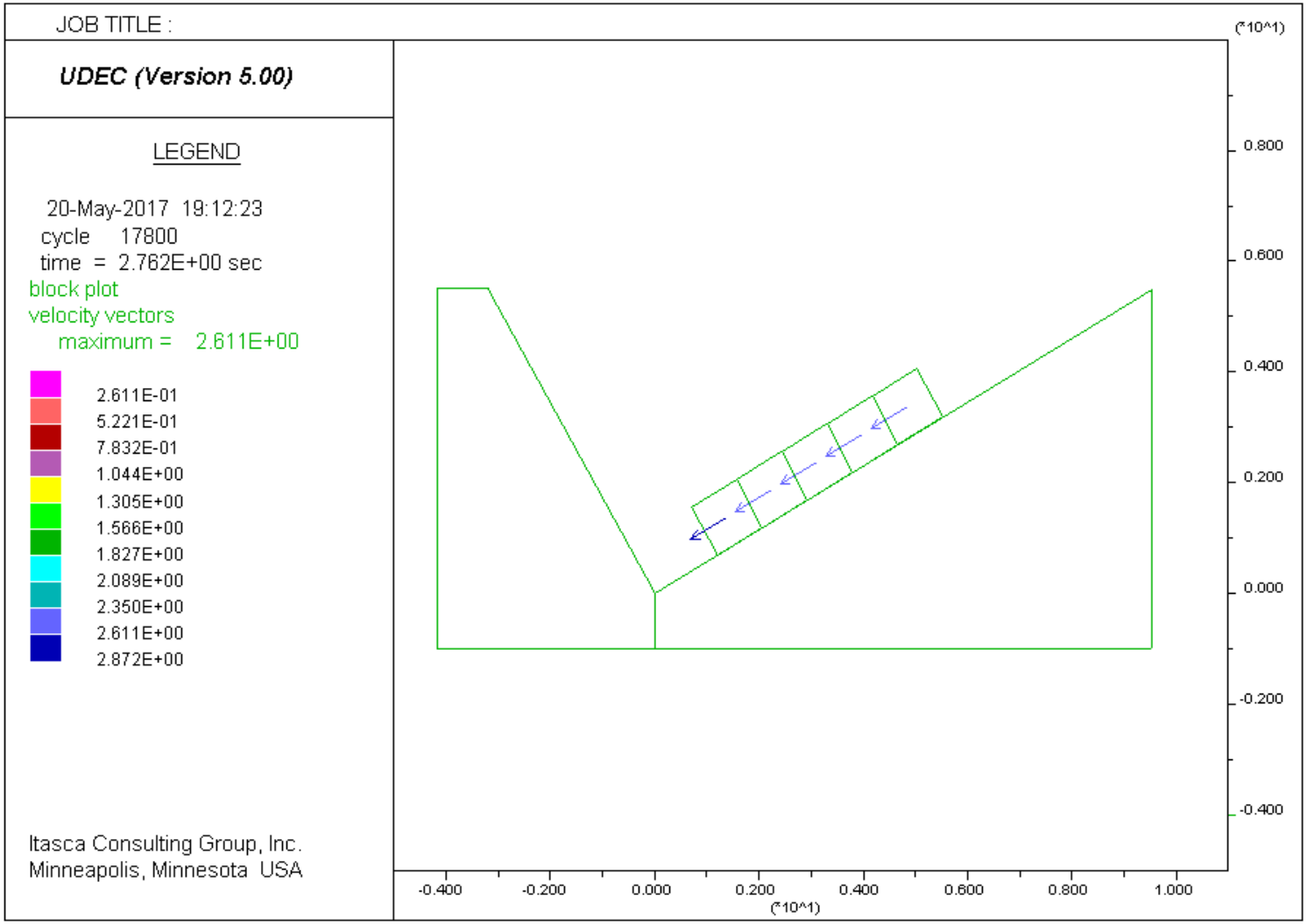

JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:22
cycle 13800
time = 2.141E+00 sec
block plot
velocity vectors
maximum = 2.025E+00
2.025E-01
4.050E-01
6.075E-01
8.100E-01
1.013E+00
1.215E+00
1.418E+00
1.620E+00
1.823E+00
2.025E+00
2.228E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)

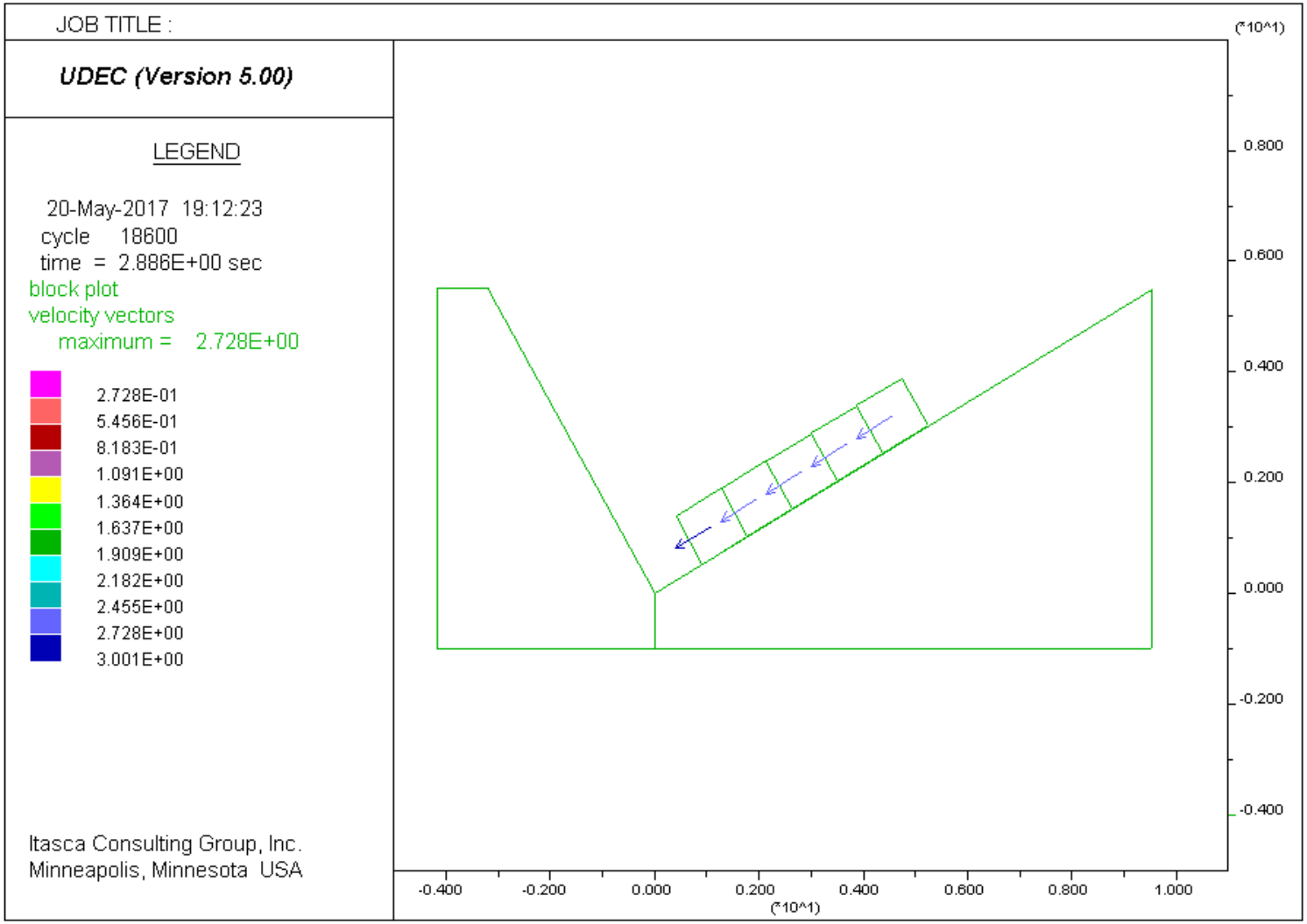

JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:23
cycle 14600
time = 2.266E+00 sec
block plot
velocity vectors
maximum = 2.142E+00
2.142E-01
4.284E-01
6.427E-01
8.569E-01
1.071E+00
1.285E+00
1.500E+00
1.714E+00
1.928E+00
2.142E+00
2.356E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)

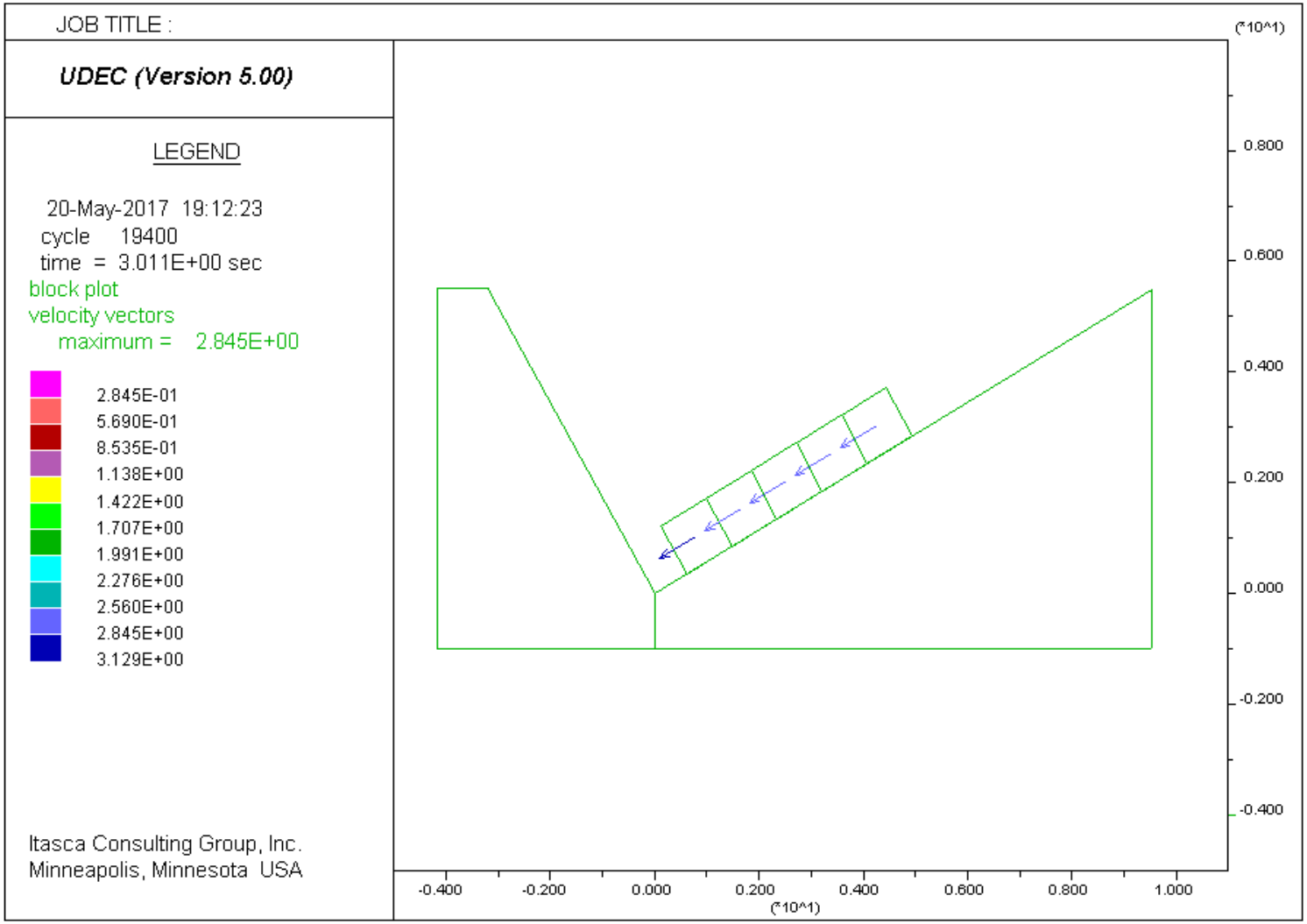

JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:23
cycle 15400
time = 2.390E+00 sec
block plot
velocity vectors
maximum = 2.259E+00
2.259E-01
4.519E-01
6.778E-01
9.037E-01
1.130E+00
1.356E+00
1.582E+00
1.807E+00
2.033E+00
2.259E+00
2.485E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)

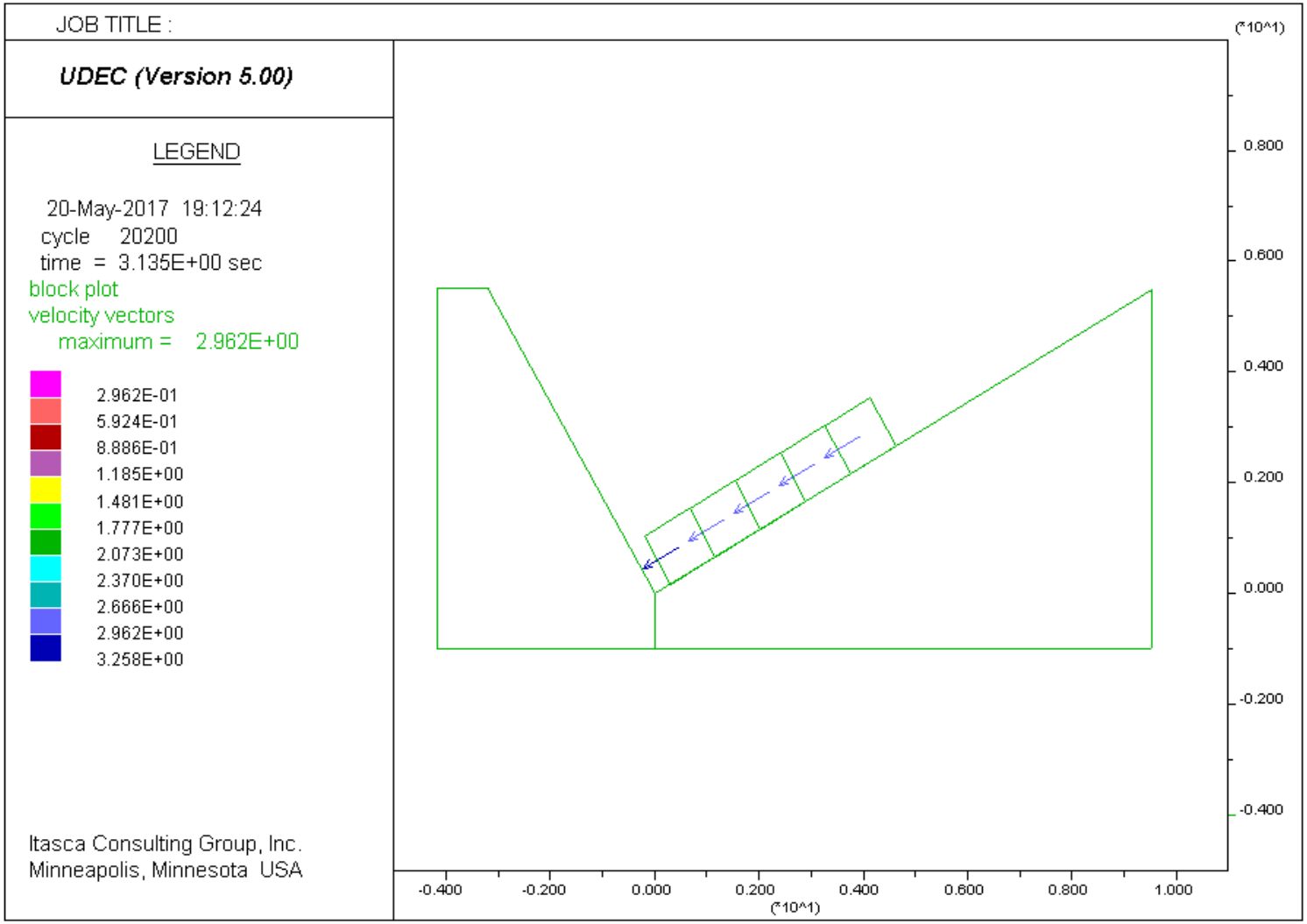

JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:23
cycle 16200
time = 2.514E+00 sec
block plot
velocity vectors
maximum = 2.376E+00
2.376E-01
4.753E-01
7.129E-01
9.506E-01
1.188E+00
1.426E+00
1.664E+00
1.901E+00
2.139E+00
2.376E+00
2.614E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:23
cycle 17000
time = 2.638E+00 sec
block plot
velocity vectors
maximum = 2.494E+00
2.494E-01
4.987E-01
7.481E-01
9.974E-01
1.247E+00
1.496E+00
1.746E+00
1.995E+00
2.244E+00
2.494E+00
2.743E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:23
cycle 17800
time = 2.762E+00 sec
block plot
velocity vectors
maximum = 2.611E+00
2.611E-01
5.221E-01
7.832E-01
1.044E+00
1.305E+00
1.566E+00
1.827E+00
2.089E+00
2.350E+00
2.611E+00
2.872E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:23
cycle 18600
time = 2.886E+00 sec
block plot
velocity vectors
maximum = 2.728E+00
2.728E-01
5.456E-01
8.183E-01
1.091E+00
1.364E+00
1.637E+00
1.909E+00
2.182E+00
2.455E+00
2.728E+00
3.001E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:23
cycle 19400
time = 3.011E+00 sec
block plot
velocity vectors
maximum = 2.845E+00
2.845E-01
5.690E-01
8.535E-01
1.138E+00
1.422E+00
1.707E+00
1.991E+00
2.276E+00
2.560E+00
2.845E+00
3.129E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:24
cycle 20200
time = 3.135E+00 sec
block plot
velocity vectors
maximum = 2.962E+00
2.962E-01
5.924E-01
8.886E-01
1.185E+00
1.481E+00
1.777E+00
2.073E+00
2.370E+00
2.666E+00
2.962E+00
3.258E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
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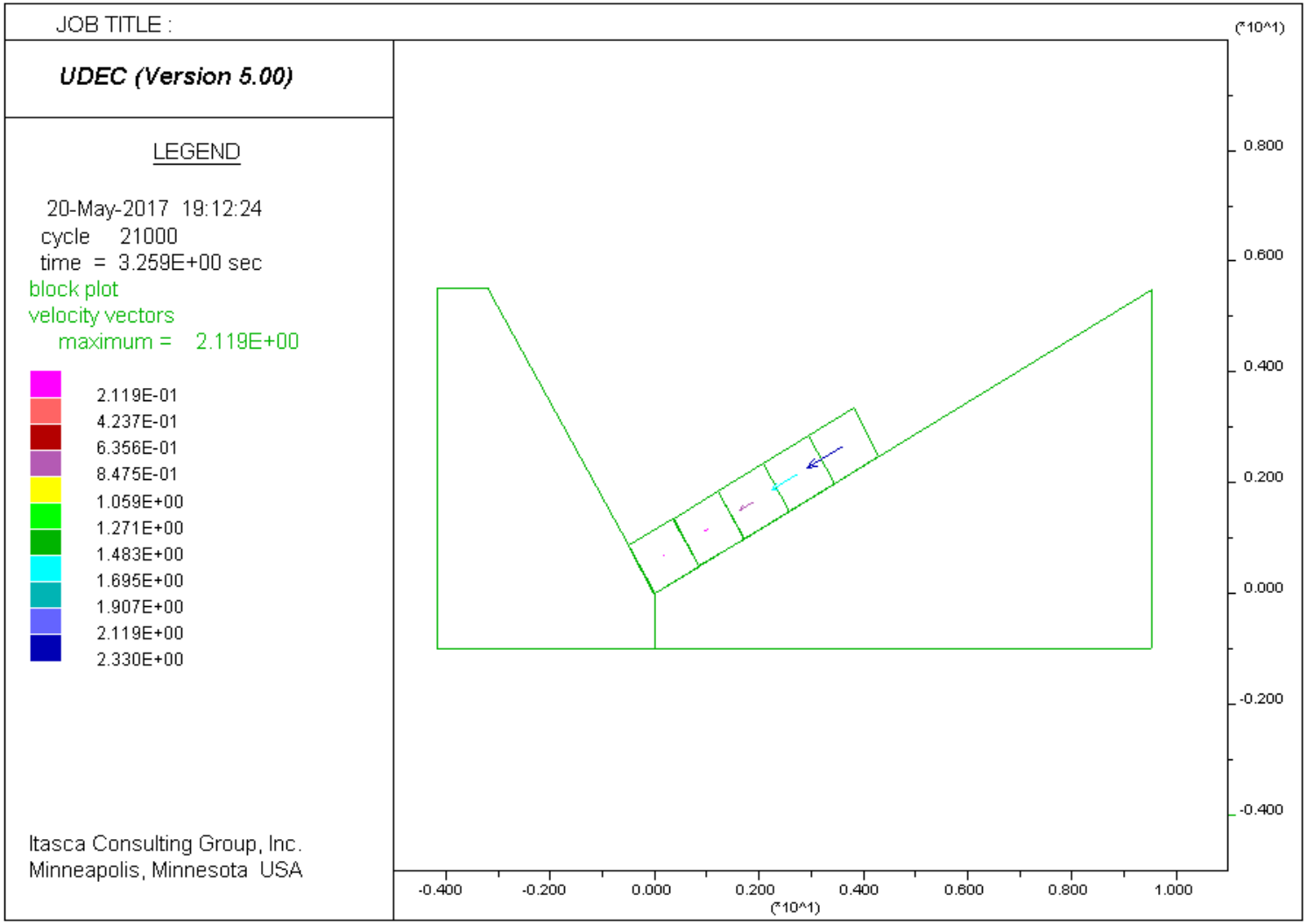
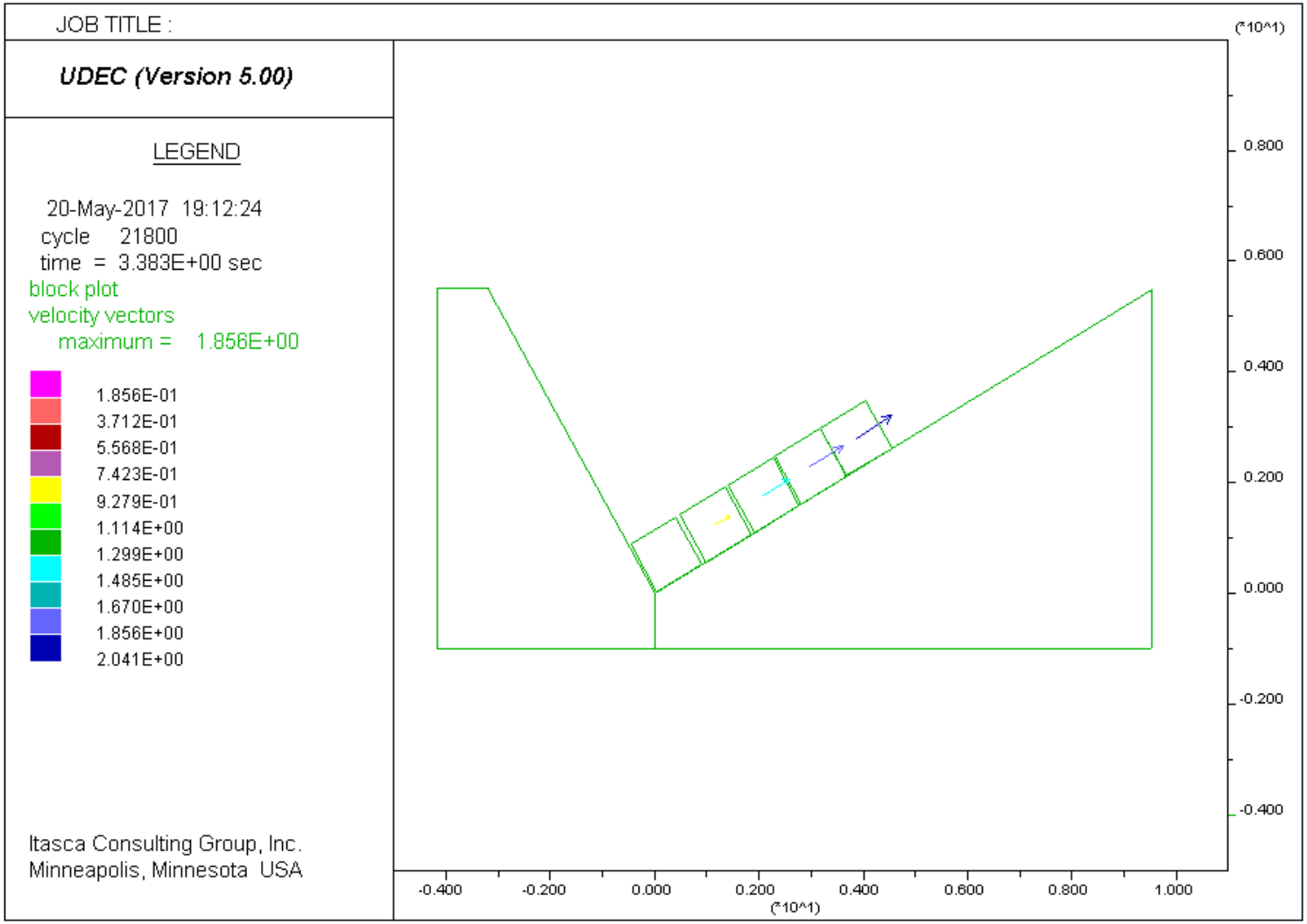
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:24
cycle 21000
time = 3.259E+00 sec
block plot
velocity vectors
maximum = 2.119E+00
2.119E-01
4.237E-01
6.356E-01
8.475E-01
1.059E+00
1.271E+00
1.483E+00
1.695E+00
1.907E+00
2.119E+00
2.330E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:24
cycle 21800
time = 3.383E+00 sec
block plot
velocity vectors
maximum = 1.856E+00
1.856E-01
3.712E-01
5.568E-01
7.423E-01
9.279E-01
1.114E+00
1.299E+00
1.485E+00
1.670E+00
1.856E+00
2.041E+00
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
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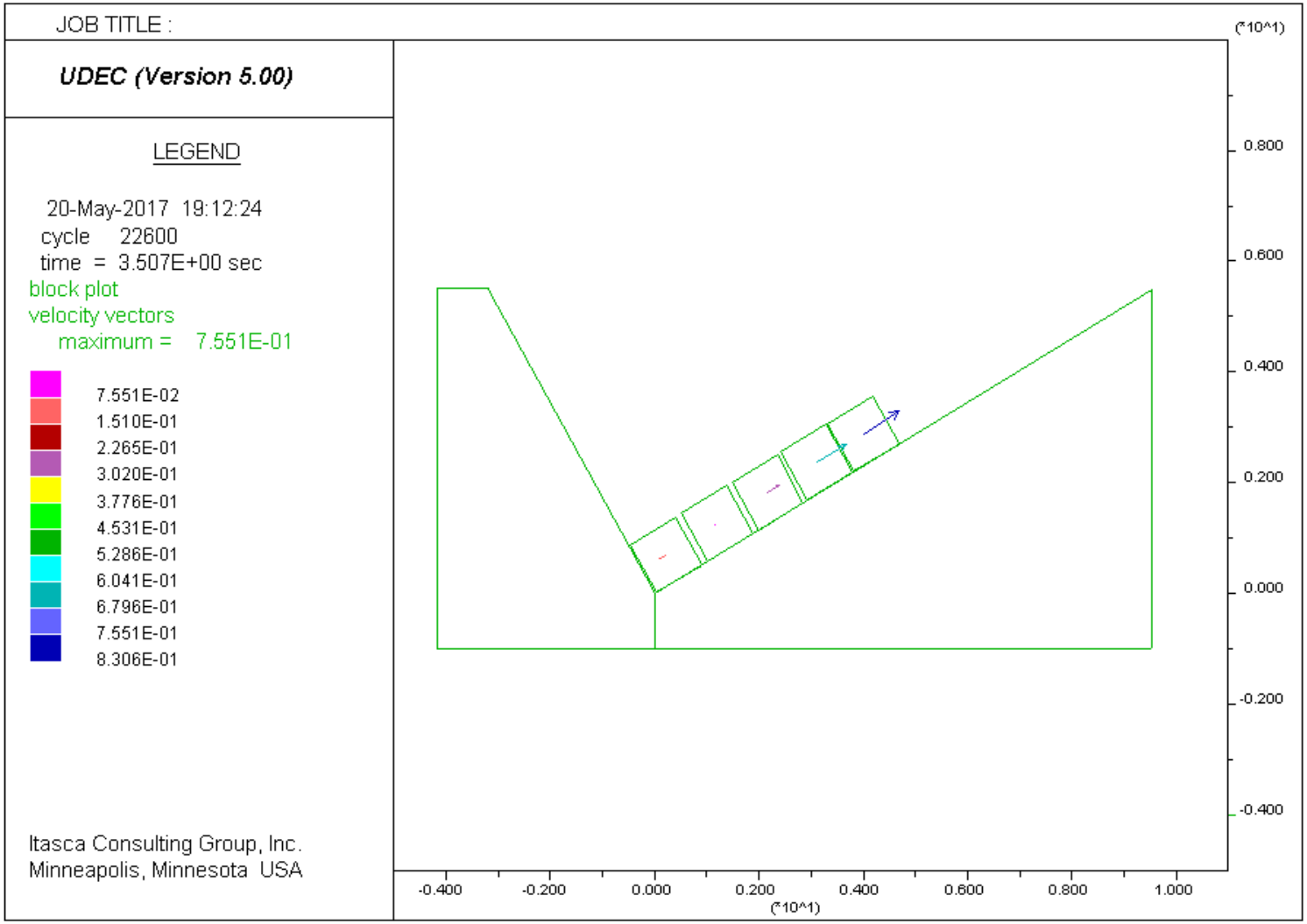
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:24
cycle 22600
time = 3.507E+00 sec
block plot
velocity vectors
maximum = 7.551E-01
7.551E-02
1.510E-01
2.265E-01
3.020E-01
3.776E-01
4.531E-01
5.286E-01
6.041E-01
6.796E-01
7.551E-01
8.306E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
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-0.400
-0.200
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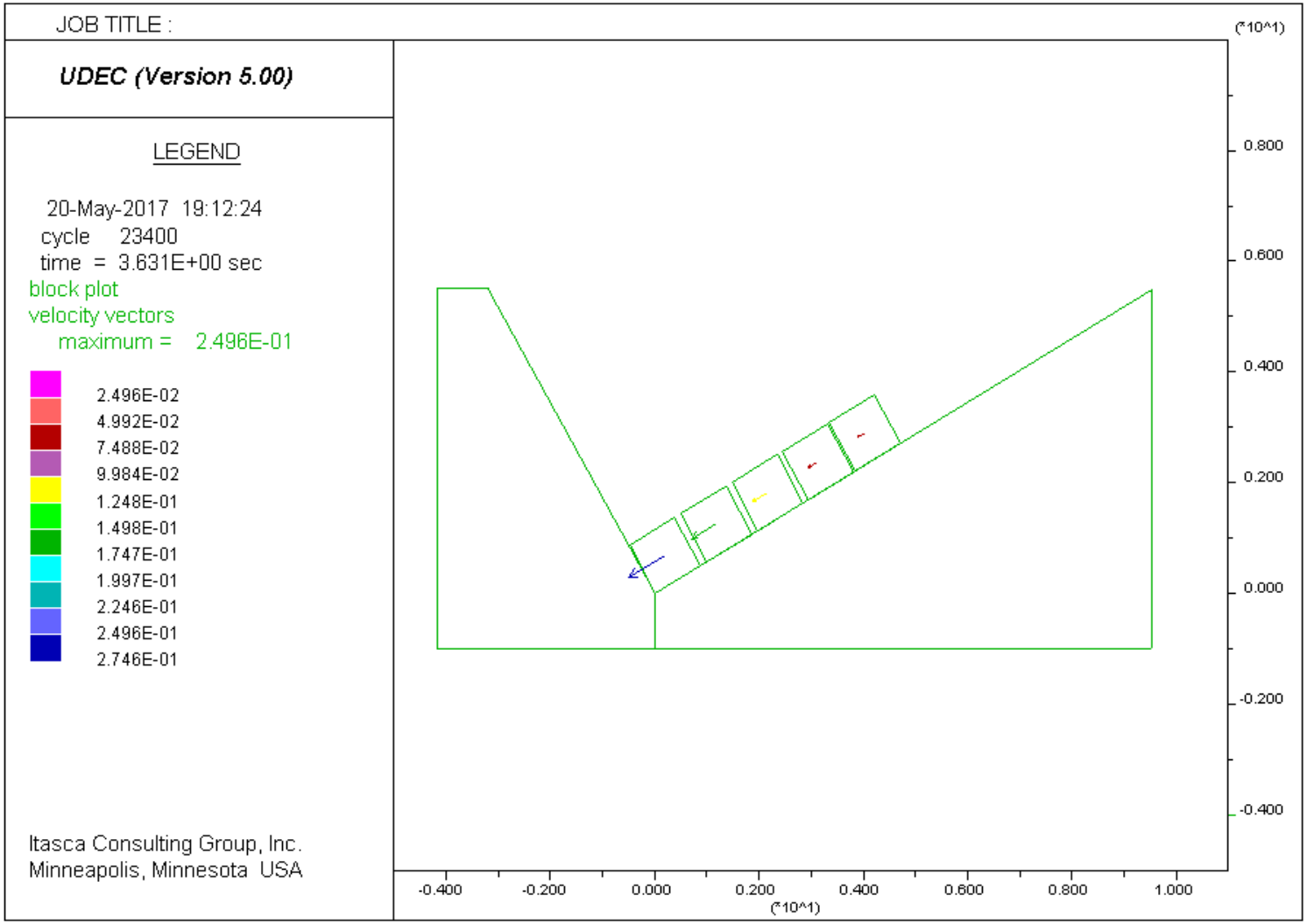
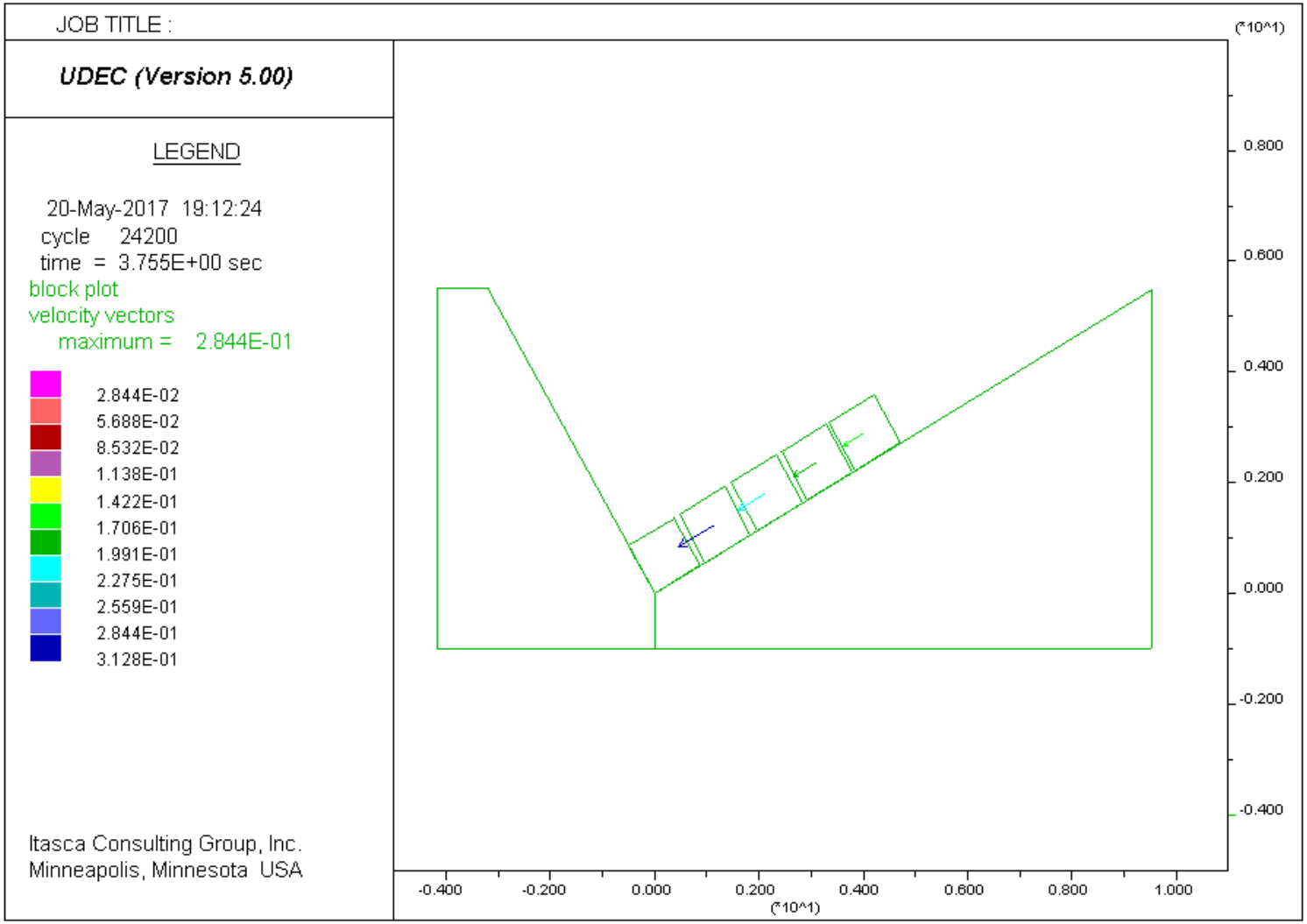
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:24
cycle 23400
time = 3.631E+00 sec
block plot
velocity vectors
maximum = 2.496E-01
2.496E-02
4.992E-02
7.488E-02
9.984E-02
1.248E-01
1.498E-01
1.747E-01
1.997E-01
2.246E-01
2.496E-01
2.746E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
LEGEND
20-May-2017 19:12:24
cycle 24200
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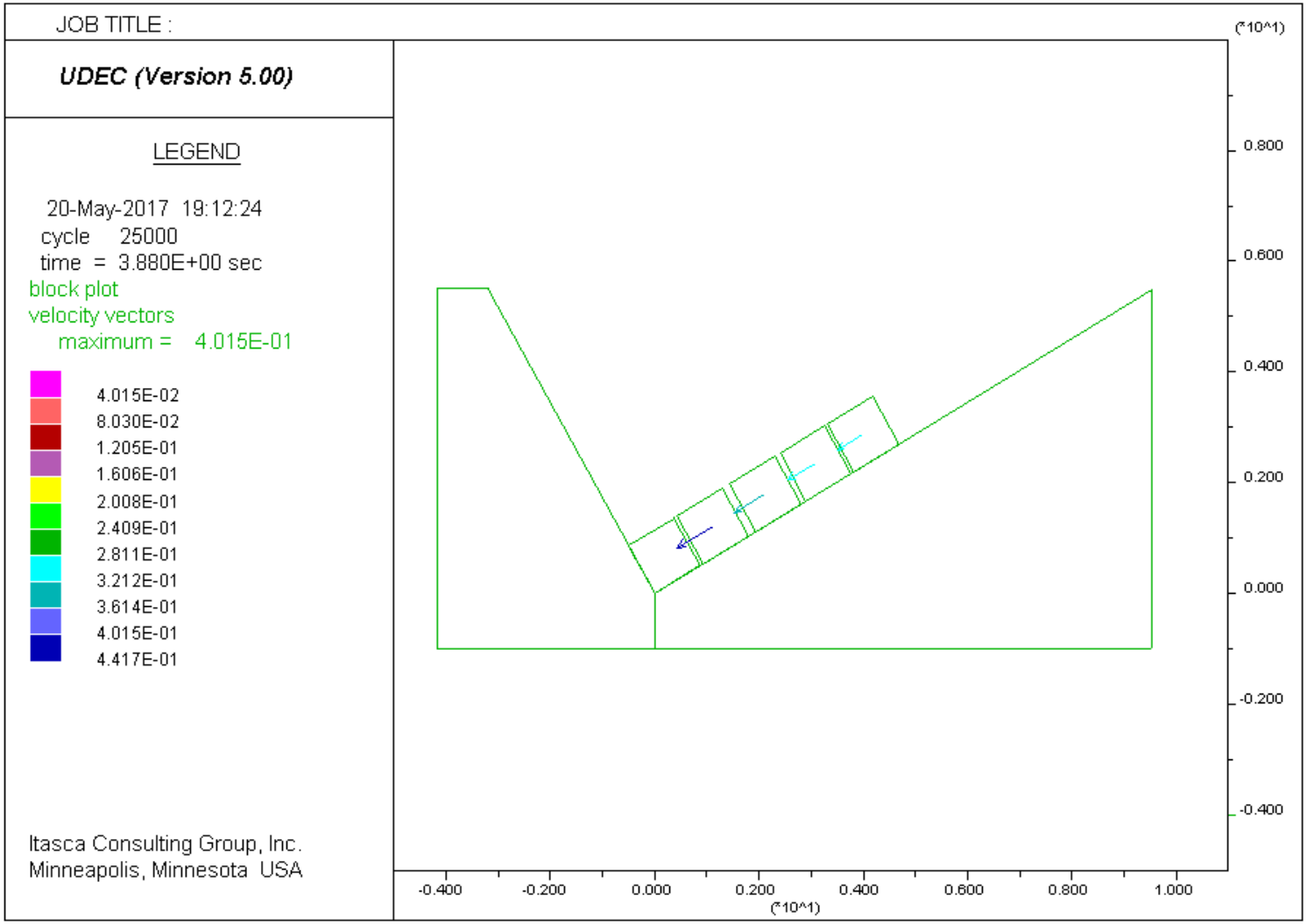
block plot
velocity vectors
maximum = 2.844E-01
2.844E-02
5.688E-02
8.532E-02
1.138E-01
1.422E-01
1.706E-01
1.991E-01
2.275E-01
2.559E-01
2.844E-01
3.128E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)


JOB TITLE :
UDEC (Version 5.00)
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block plot
velocity vectors
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4.015E-02
8.030E-02
1.205E-01
1.606E-01
2.008E-01
2.409E-01
2.811E-01
3.212E-01
3.614E-01
4.015E-01
4.417E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
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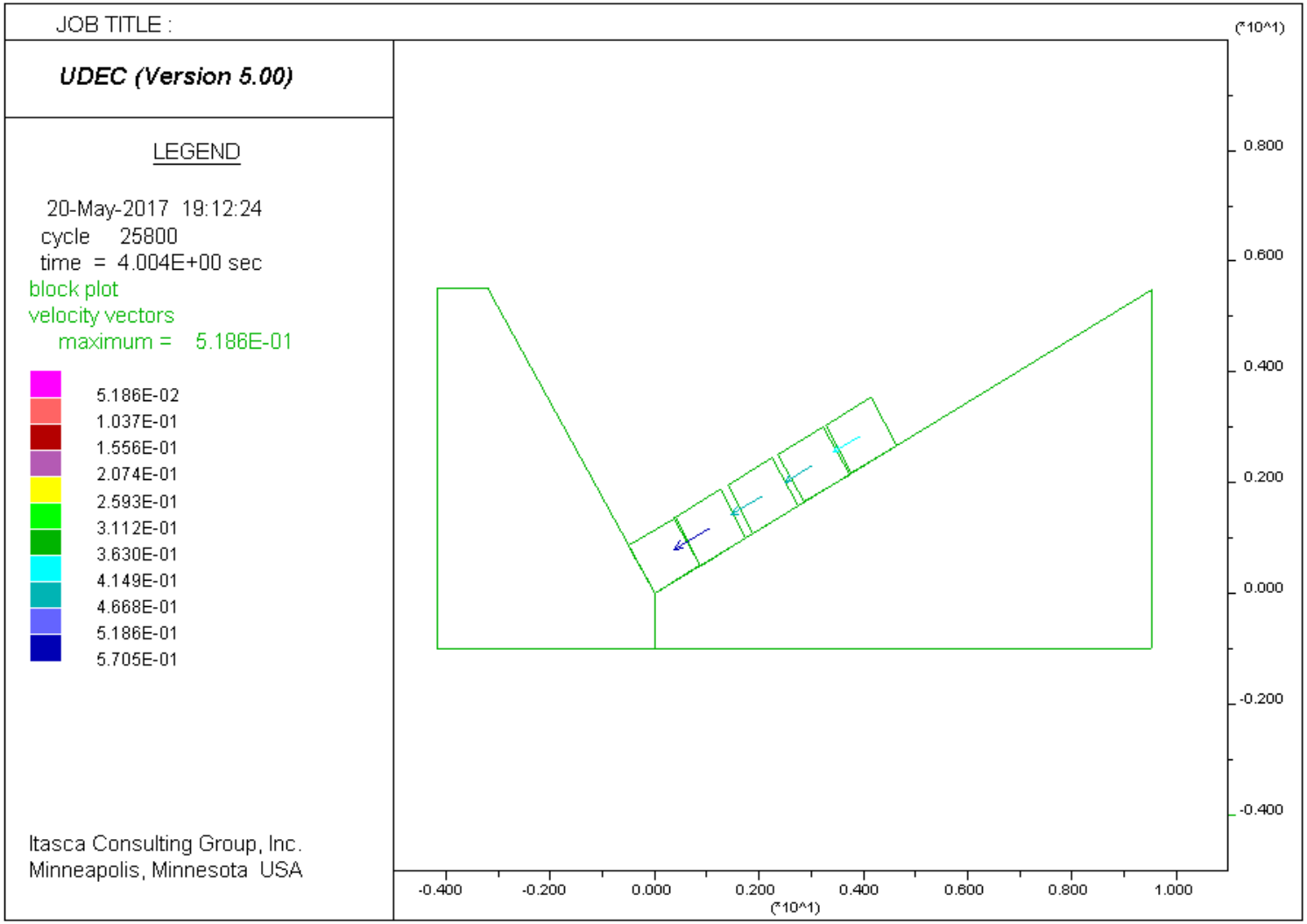
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)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block plot
velocity vectors
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3.112E-01
3.630E-01
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5.186E-01
5.705E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
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0.600
0.400
0.200
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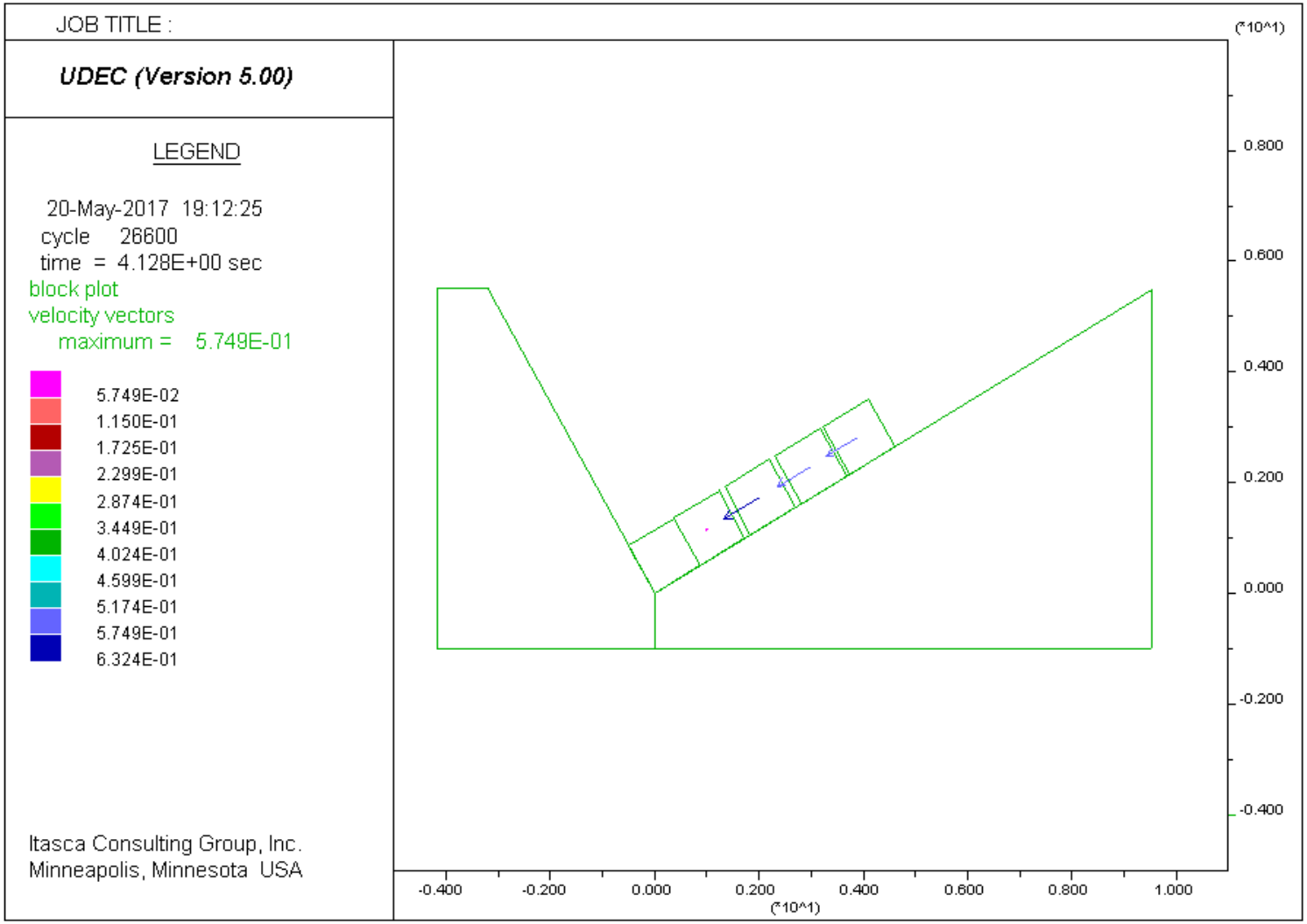
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
(*10^1)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block plot
velocity vectors
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2.874E-01
3.449E-01
4.024E-01
4.599E-01
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5.749E-01
6.324E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
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0.600
0.400
0.200
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0.000
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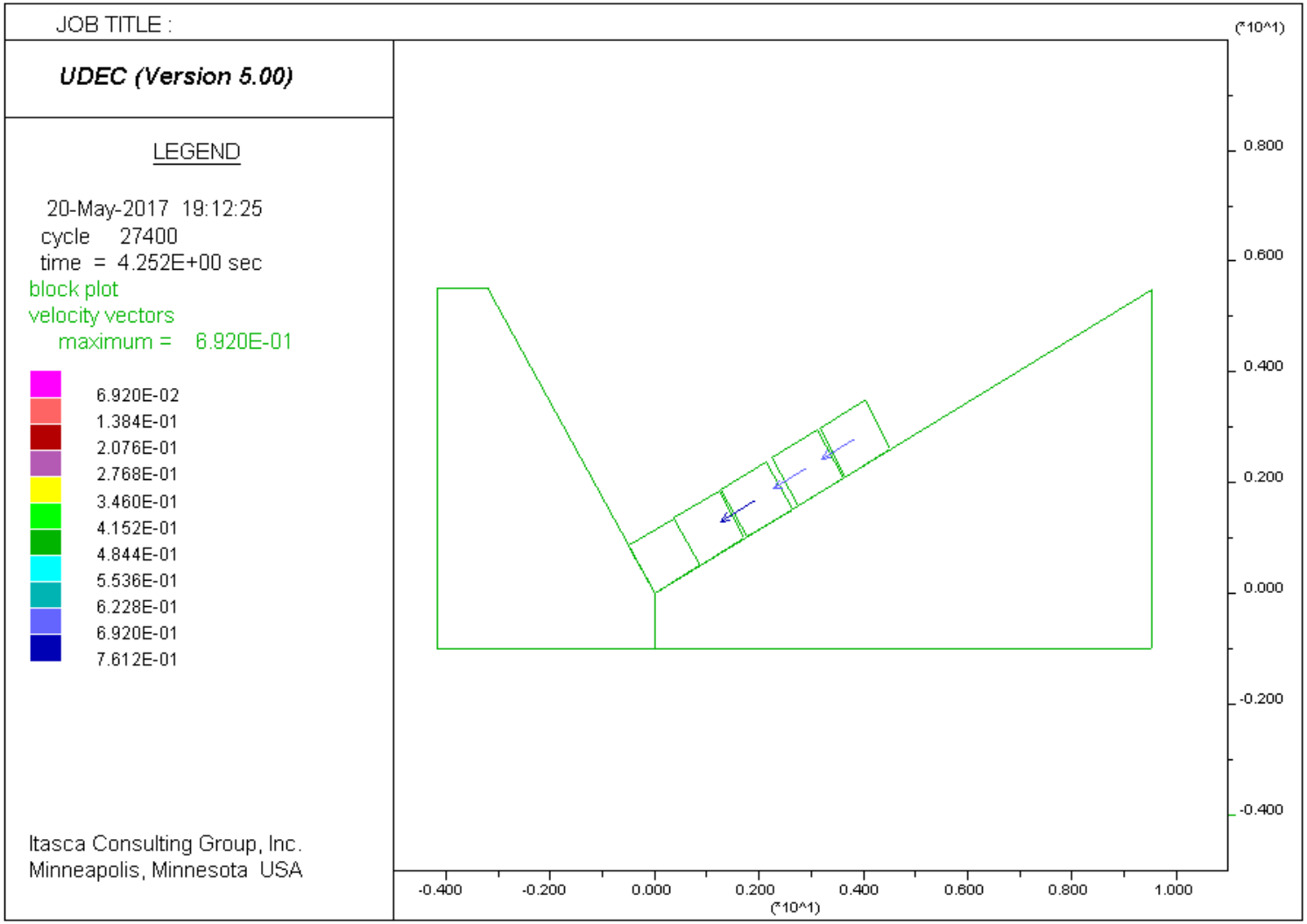
0.400
0.600
0.800
1.000
(*10^1)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block plot
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6.920E-01
7.612E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
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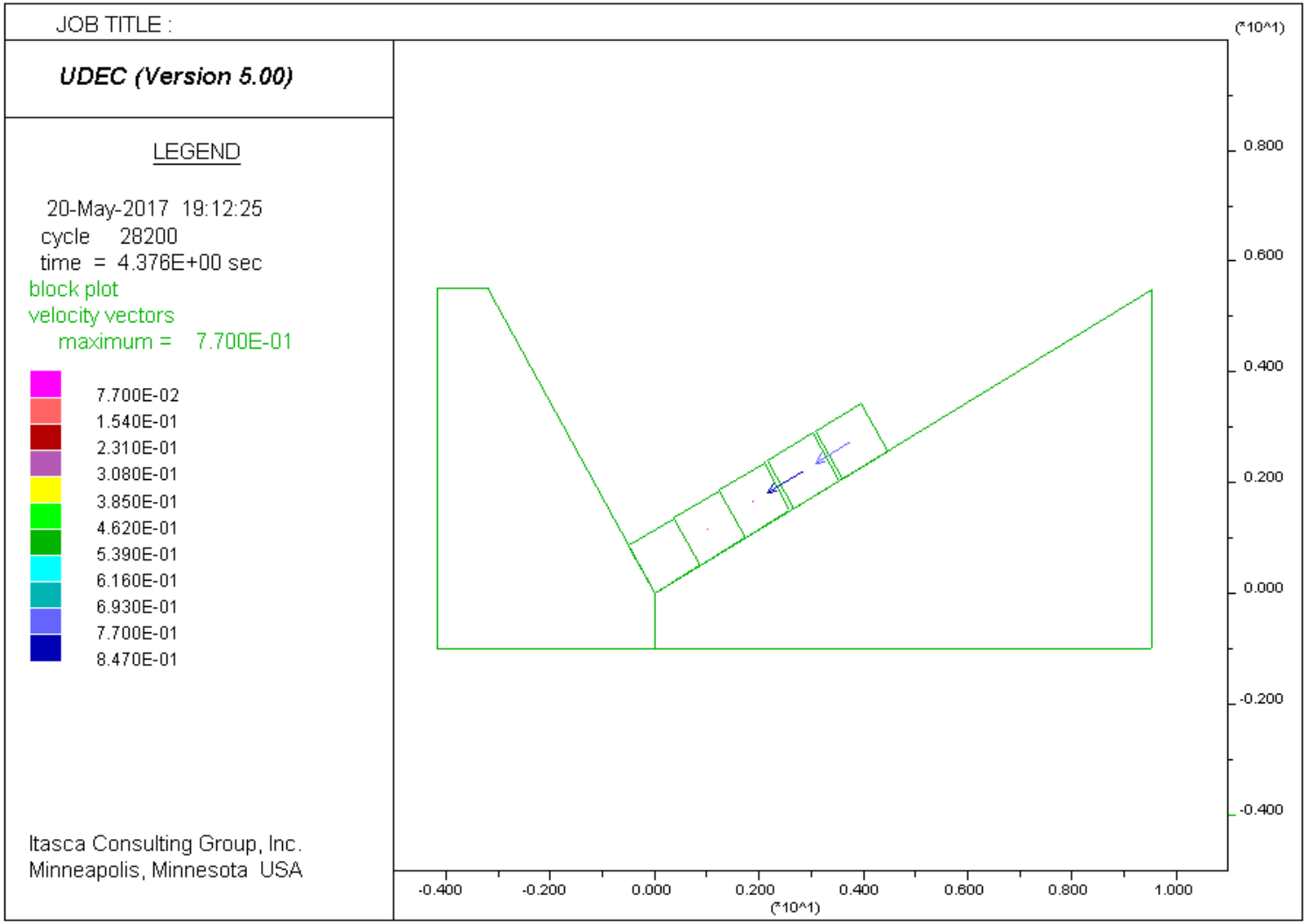
0.600
0.800
1.000
(*10^1)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block plot
velocity vectors
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1.540E-01
2.310E-01
3.080E-01
3.850E-01
4.620E-01
5.390E-01
6.160E-01
6.930E-01
7.700E-01
8.470E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
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0.600
0.400
0.200
0.000
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0.000
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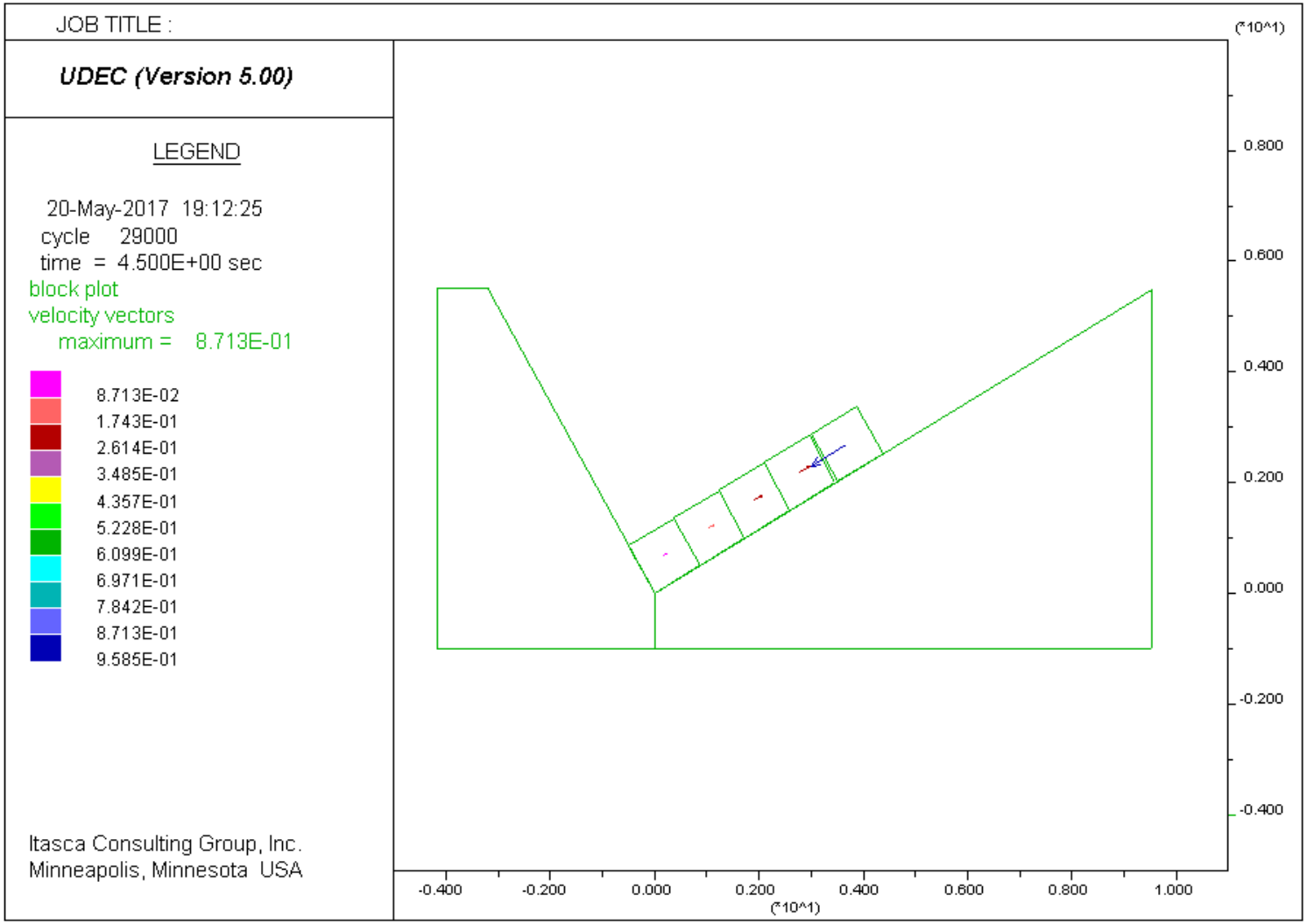
0.400
0.600
0.800
1.000
(*10^1)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block plot
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1.743E-01
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4.357E-01
5.228E-01
6.099E-01
6.971E-01
7.842E-01
8.713E-01
9.585E-01
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
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0.600
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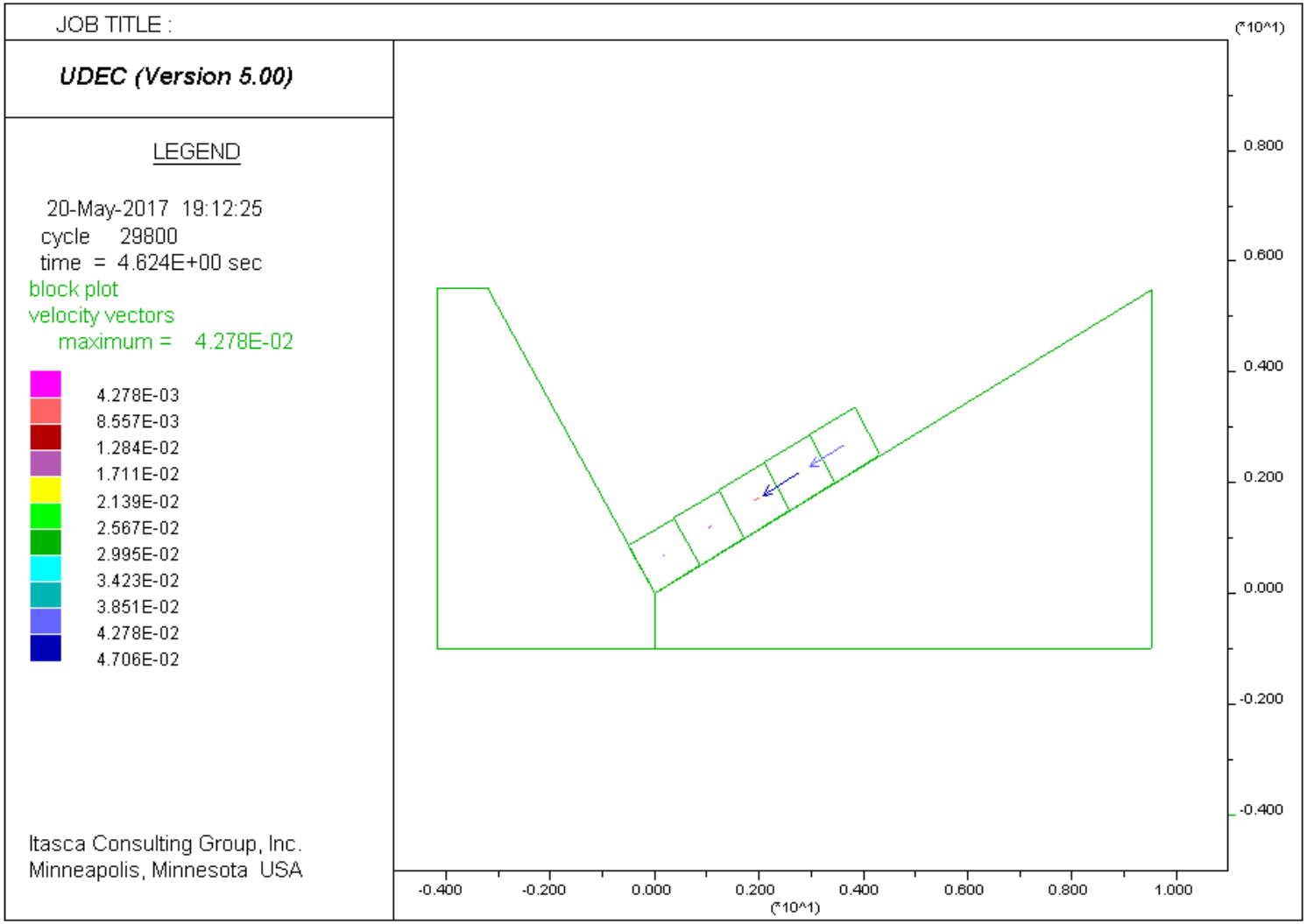
(*10^1)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block plot
velocity vectors
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2.139E-02
2.567E-02
2.995E-02
3.423E-02
3.851E-02
4.278E-02
4.706E-02
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
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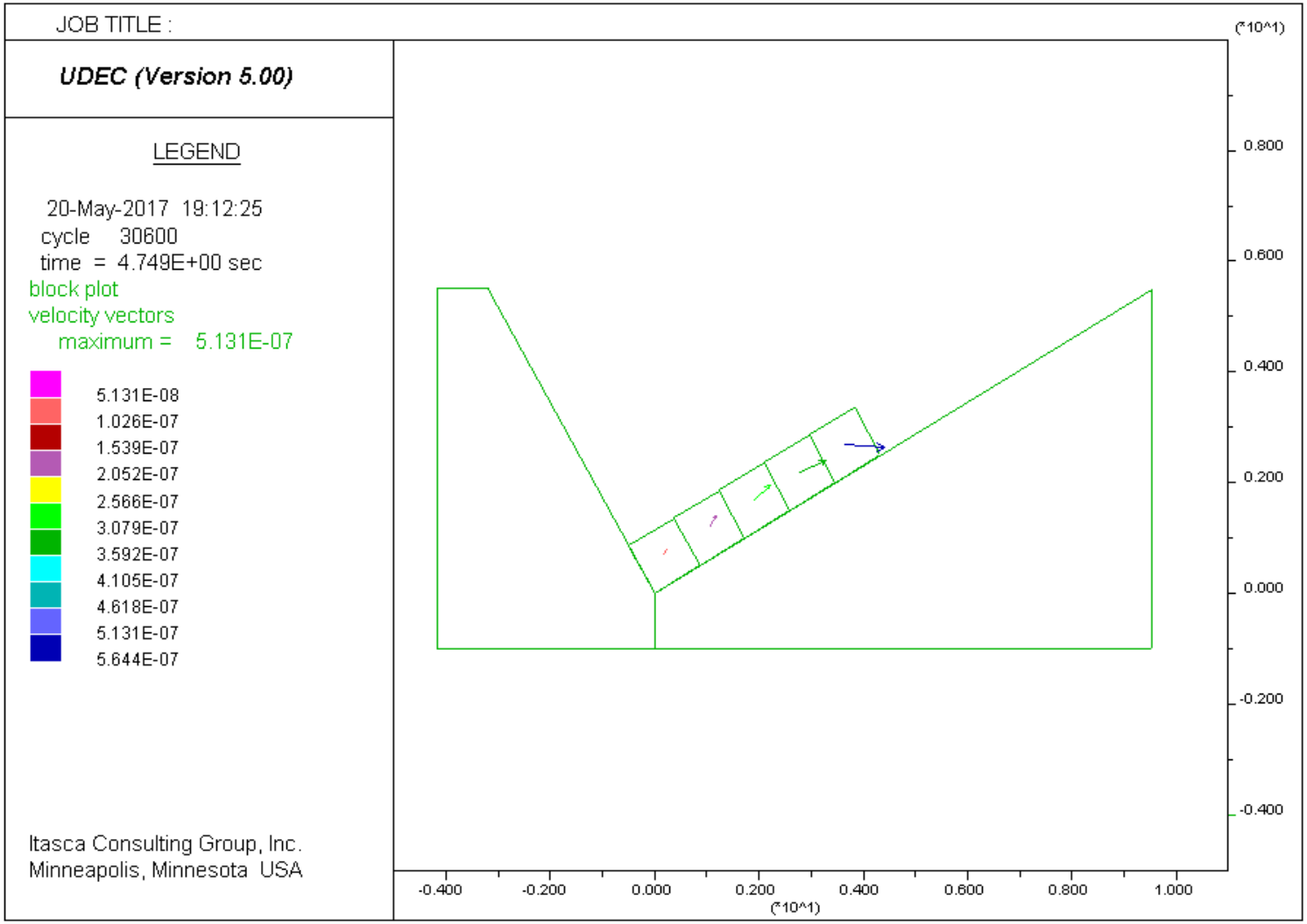
(*10^1)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velocity vectors
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5.131E-08
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3.079E-07
3.592E-07
4.105E-07
4.618E-07
5.131E-07
5.644E-07
Itasca Consulting Group, Inc.
Minneapolis, Minnesota USA
(*10^1)
0.800
0.600
0.400
0.200
0.000
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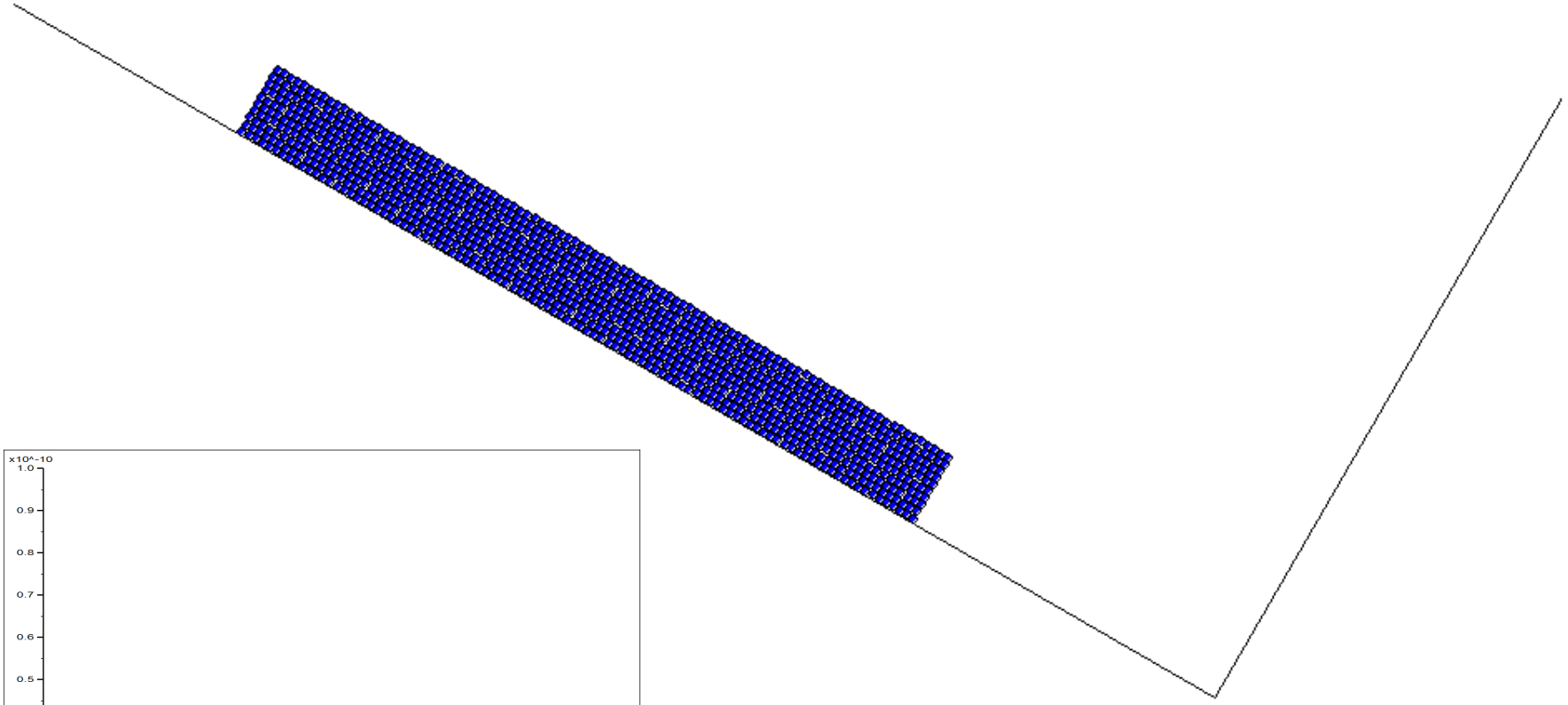
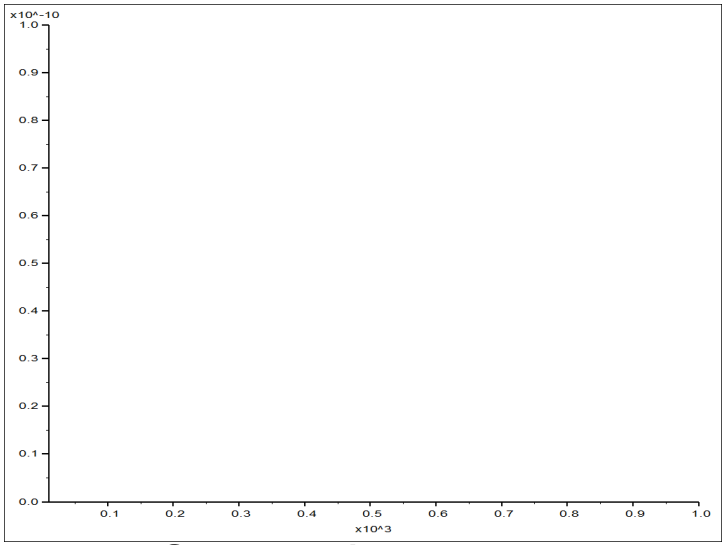
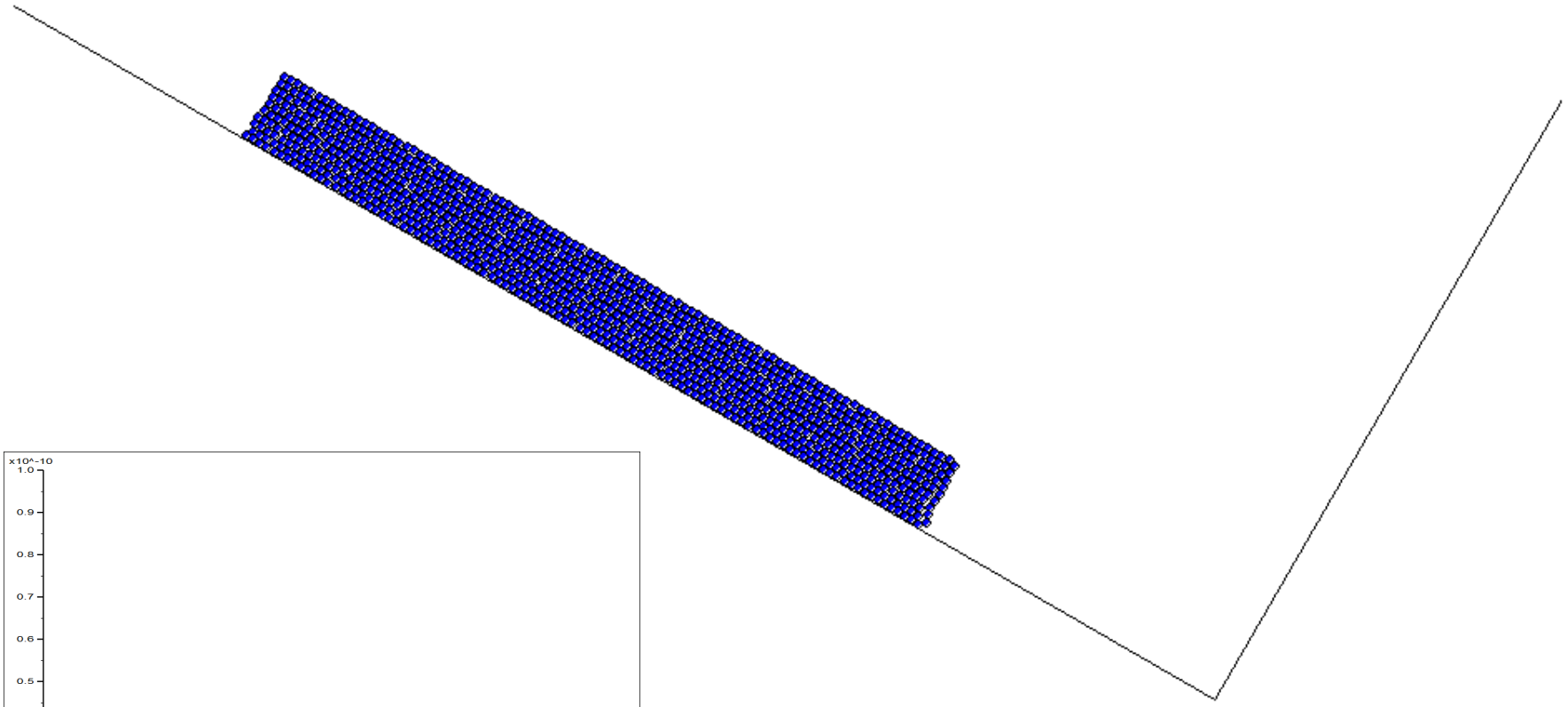
0.800
1.000
(*10^1)

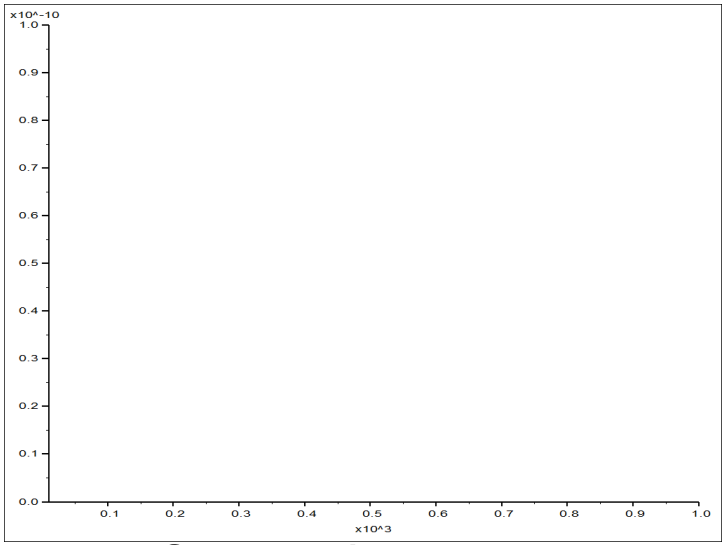




Contact force [N]

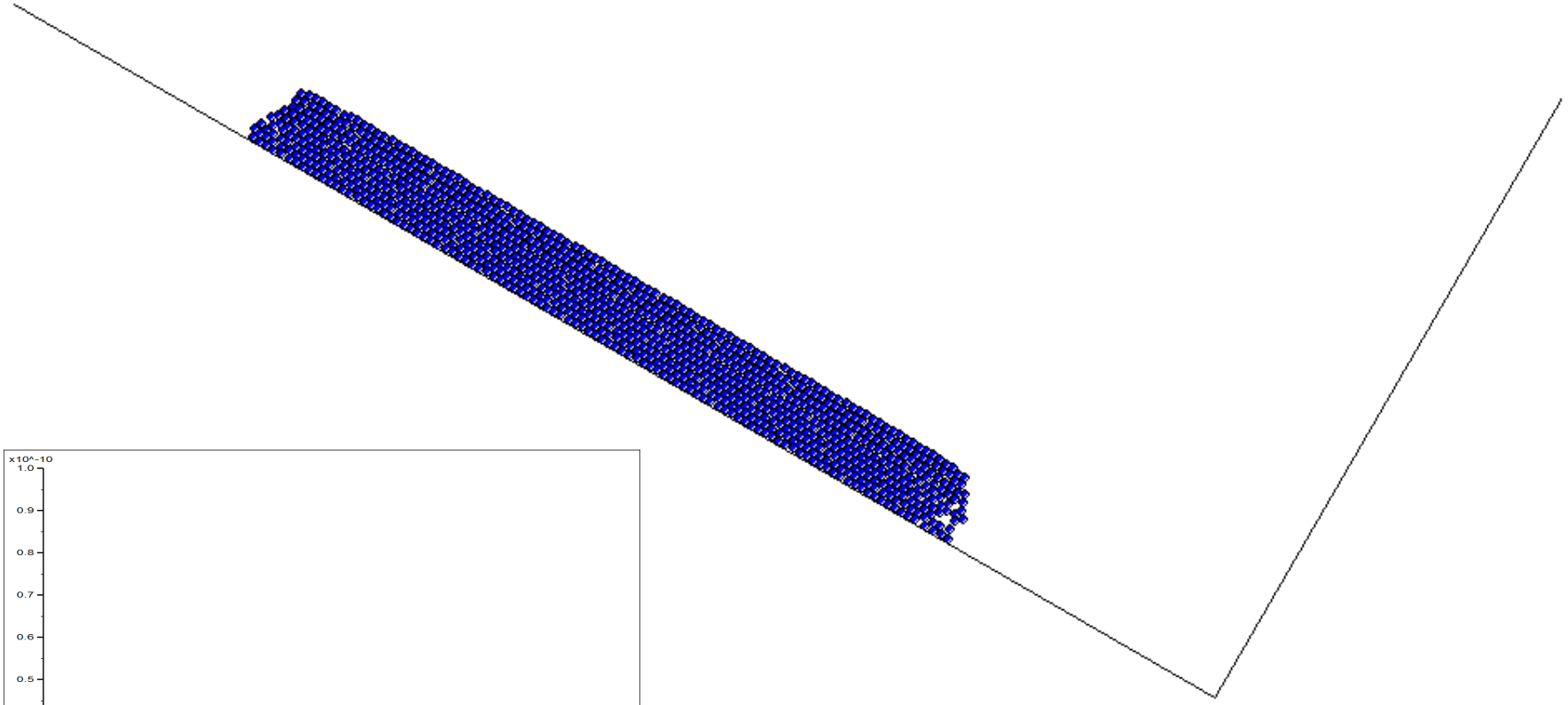
Calculation steps

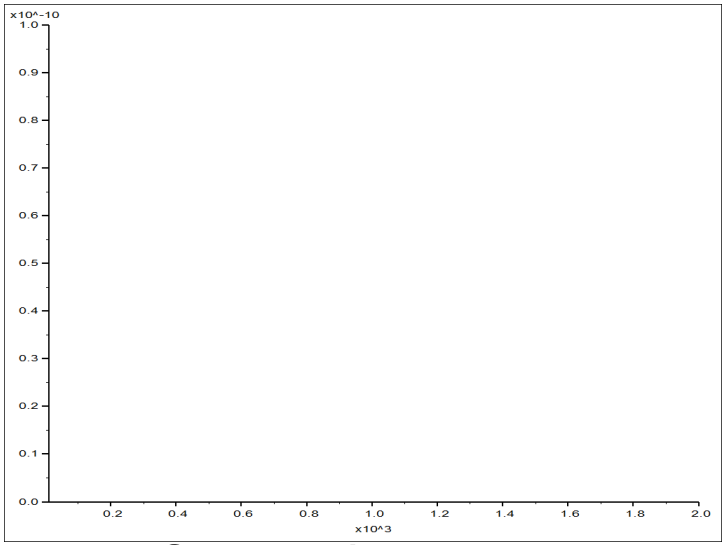




Contact force [N]

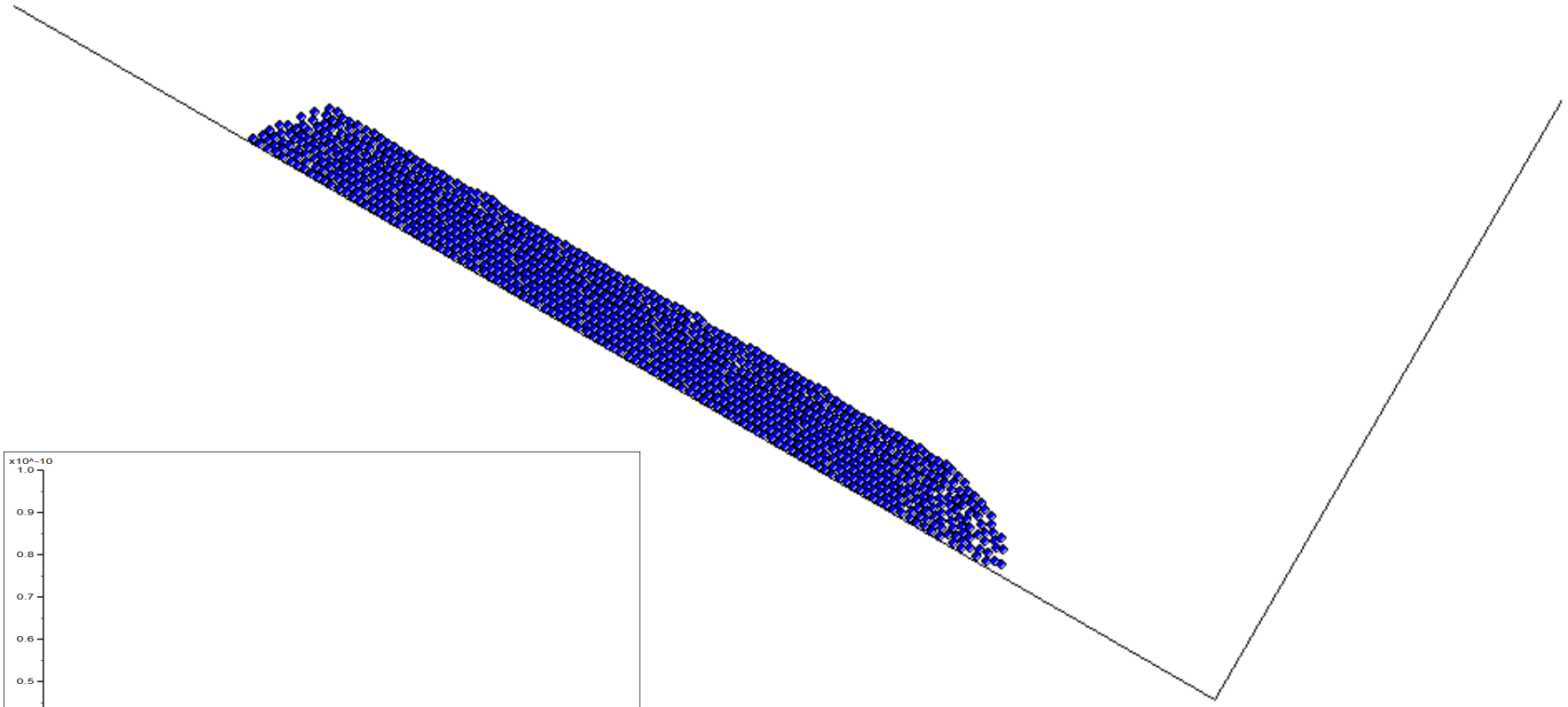
Calculation steps

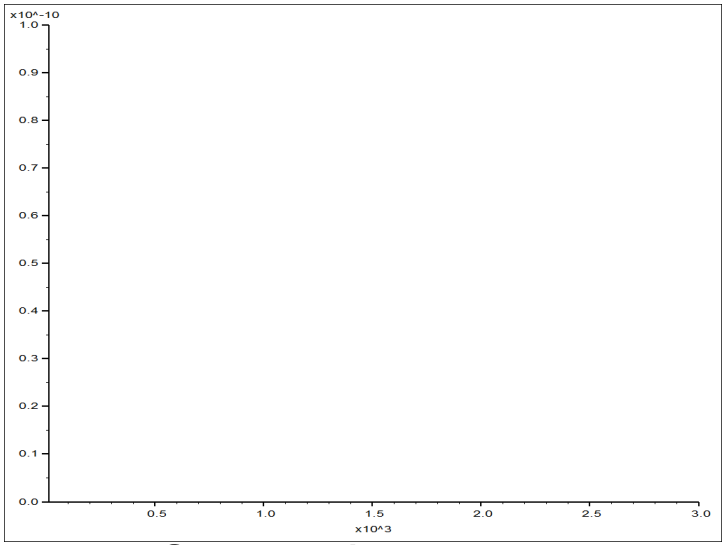




Contact force [N]

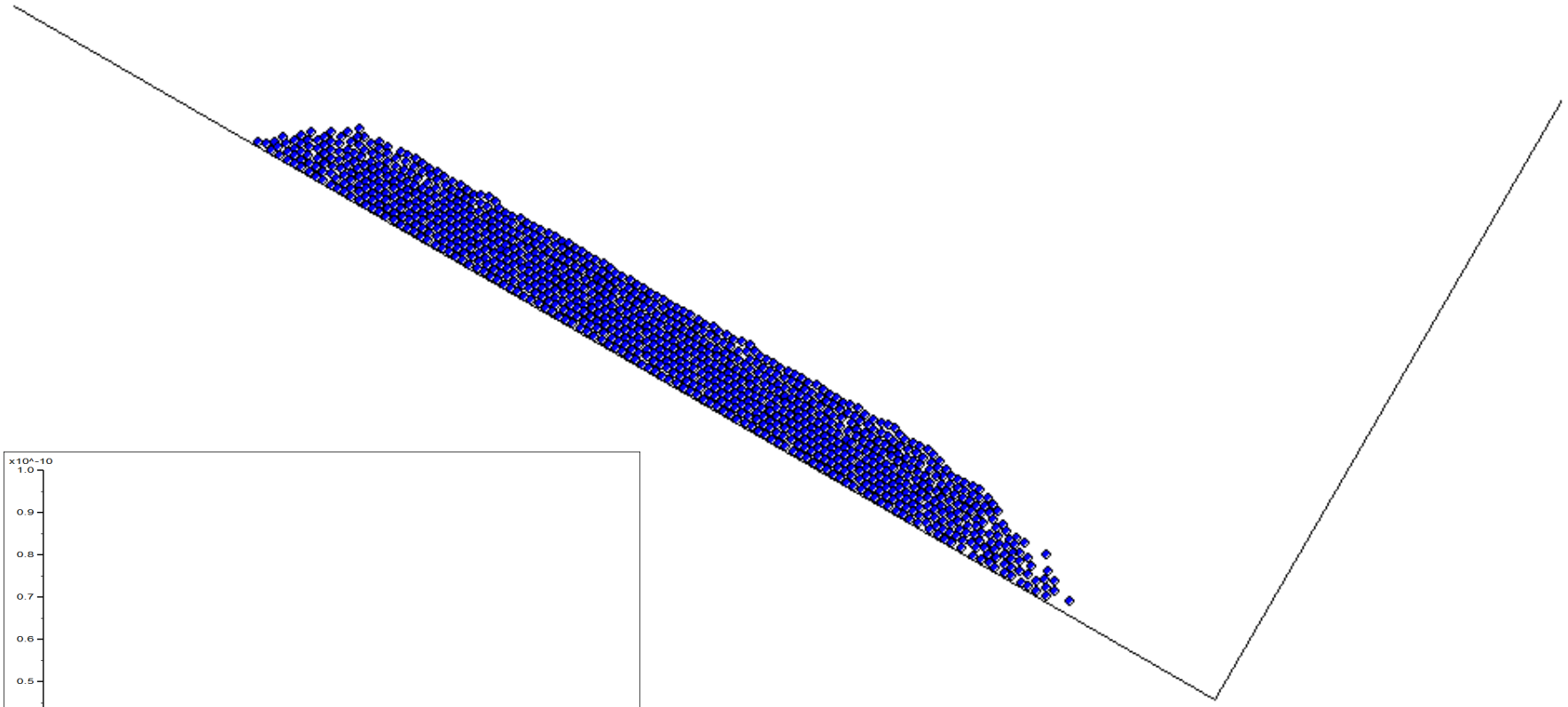
Calculation steps

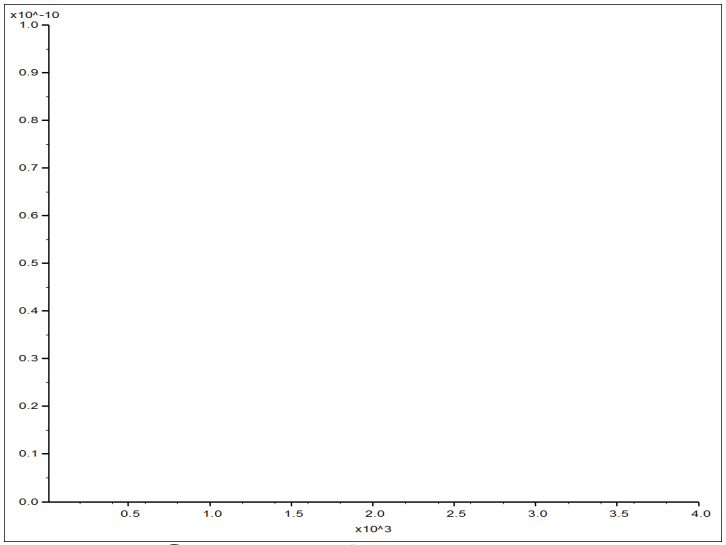




Contact force [N]

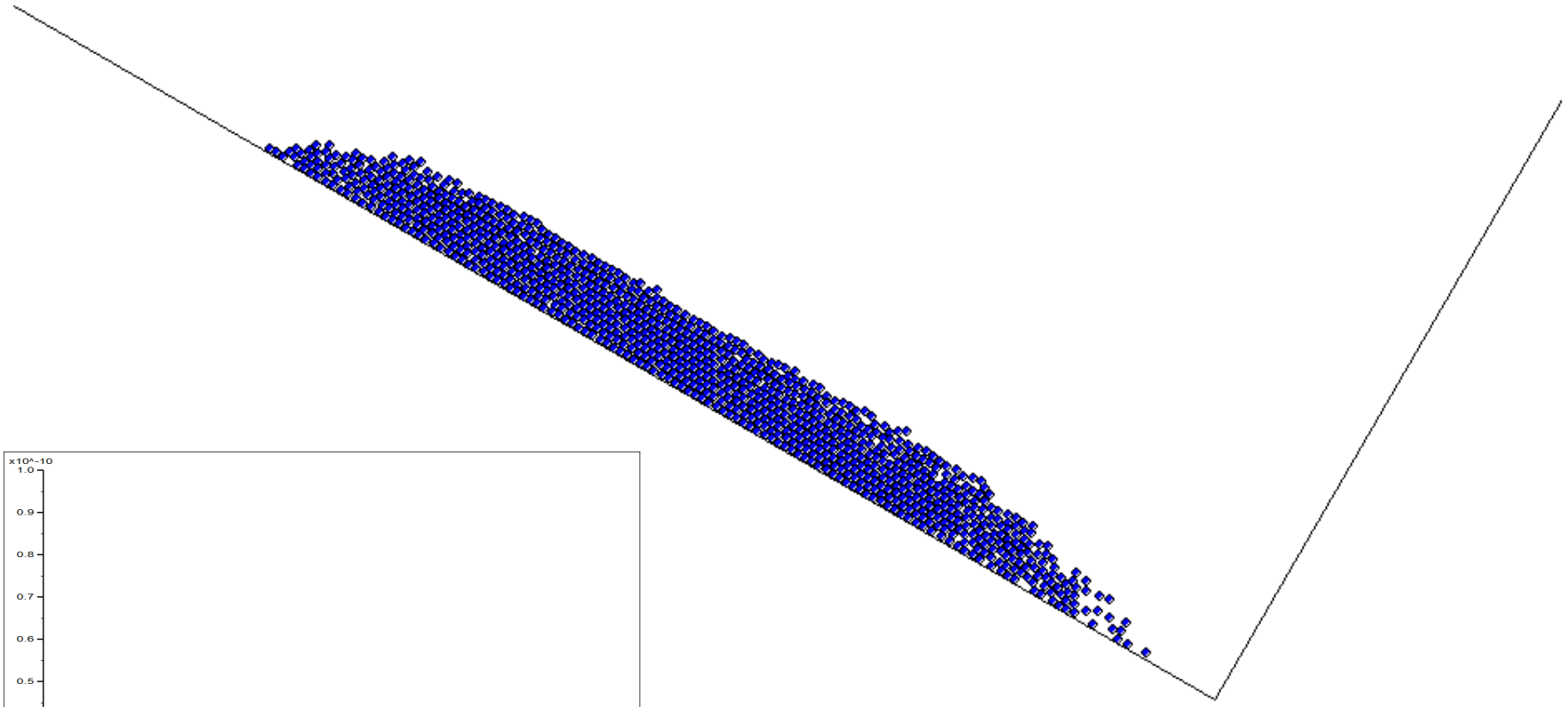
Calculation steps

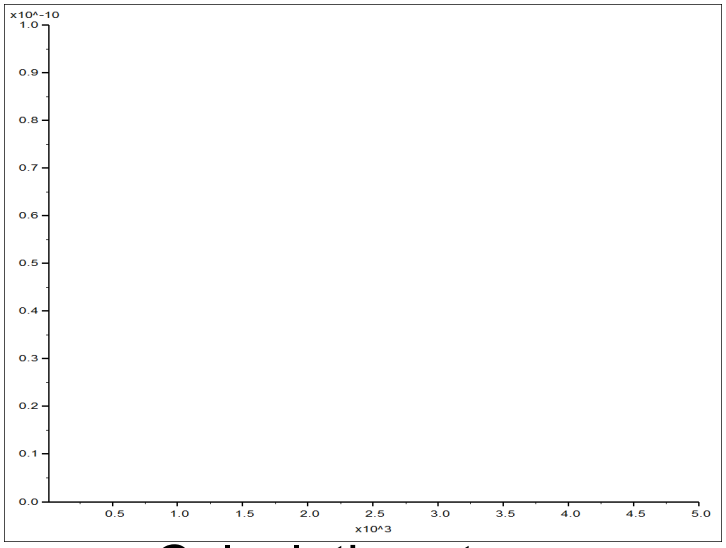




Contact force [N]

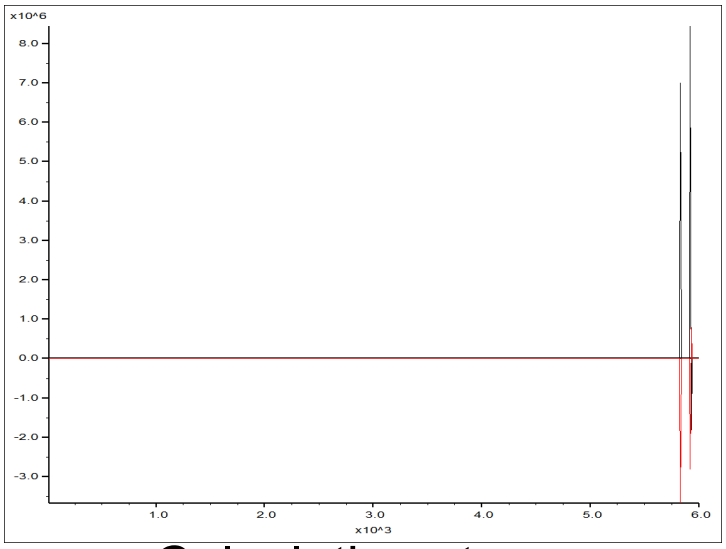
Calculation steps





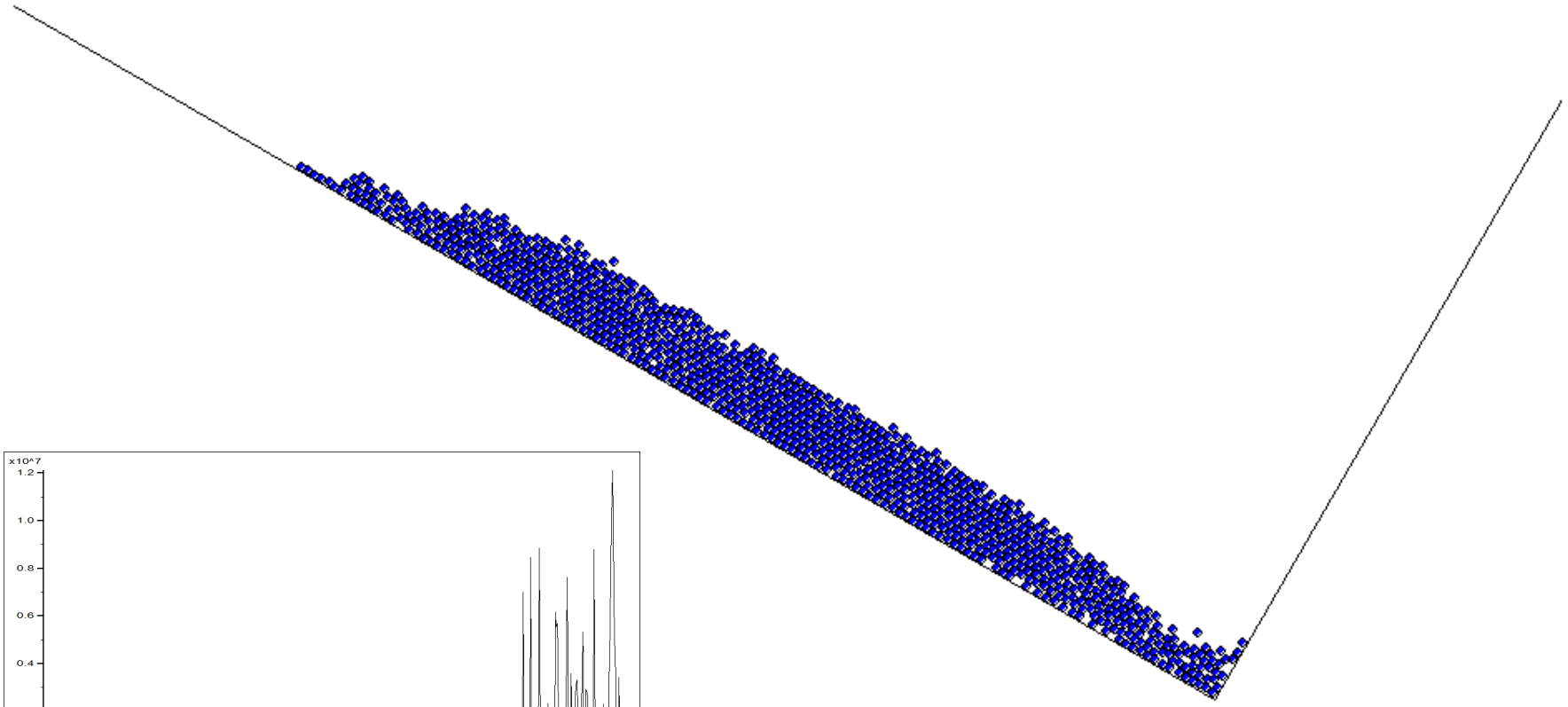
Contact force [N]

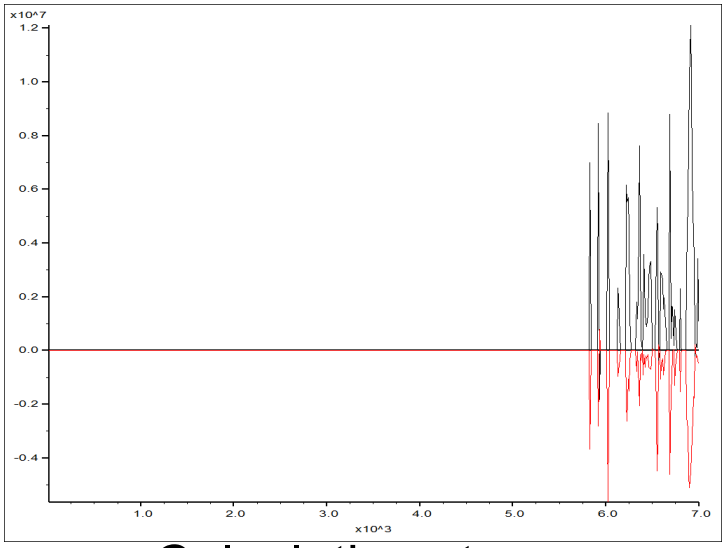
Calculation steps



Contact force [N]

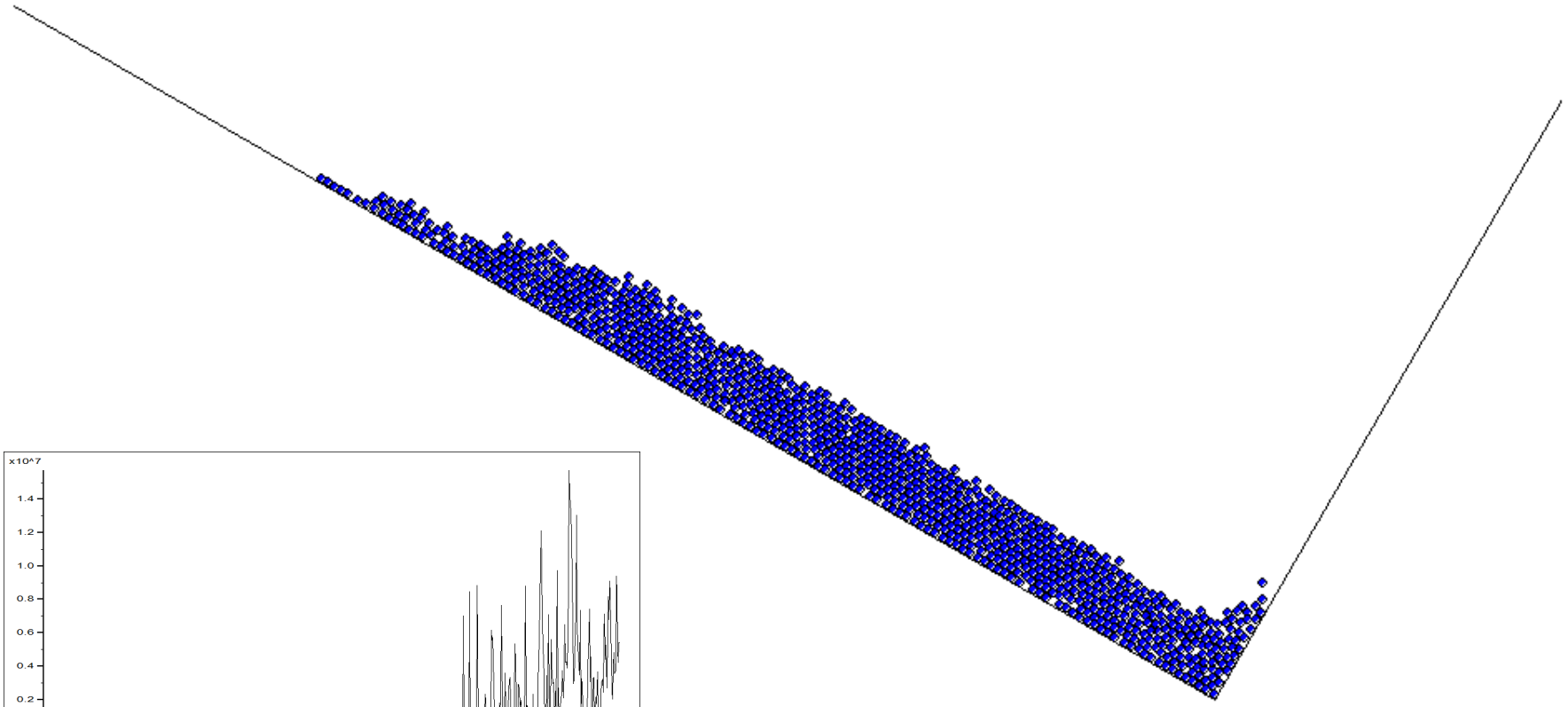
Calculation steps

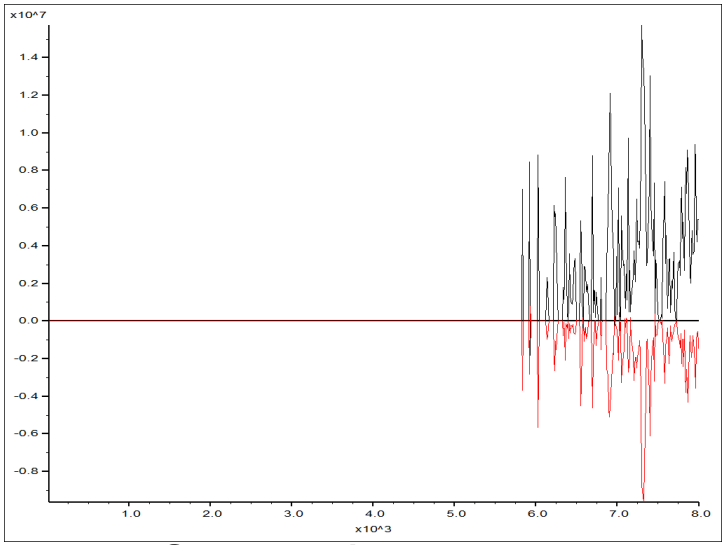




Contact force [N]

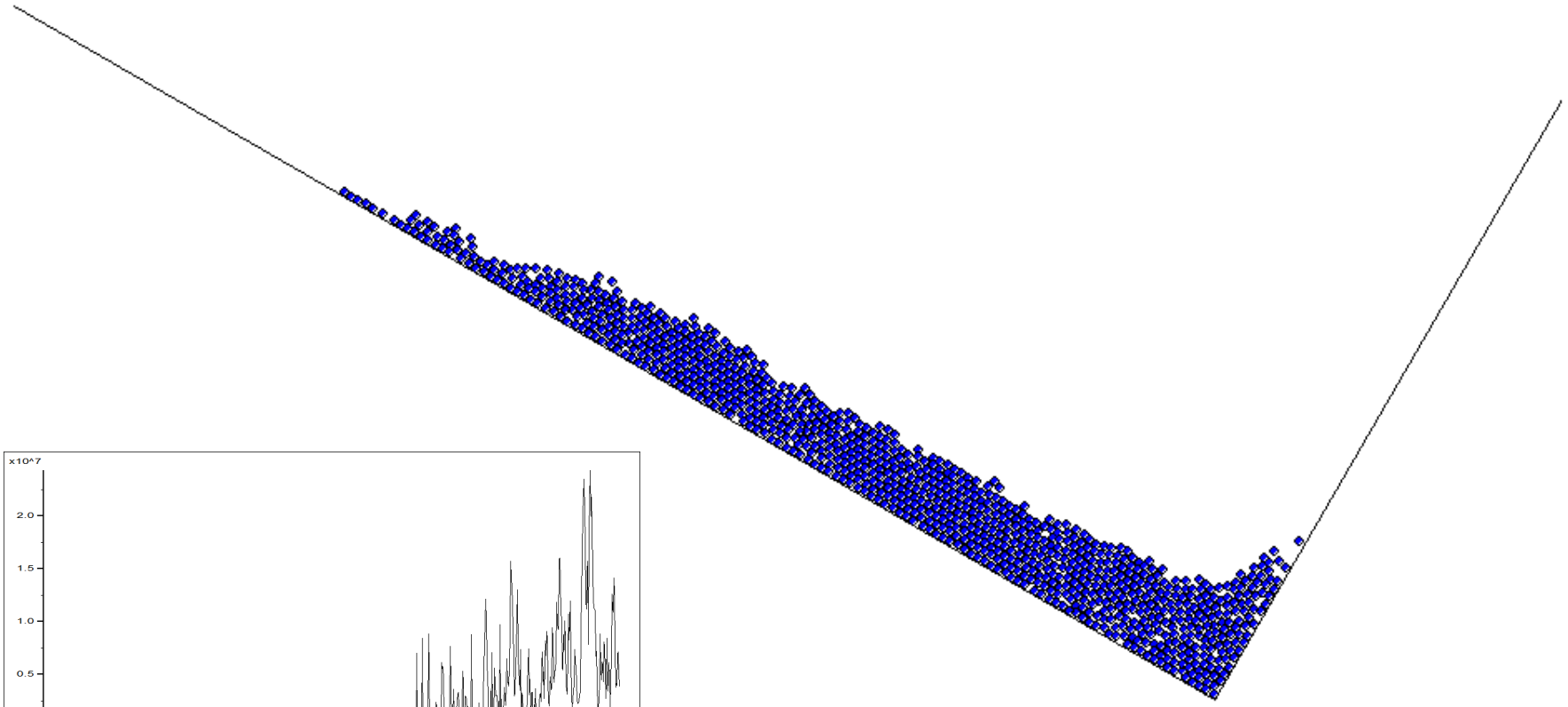
Calculation steps

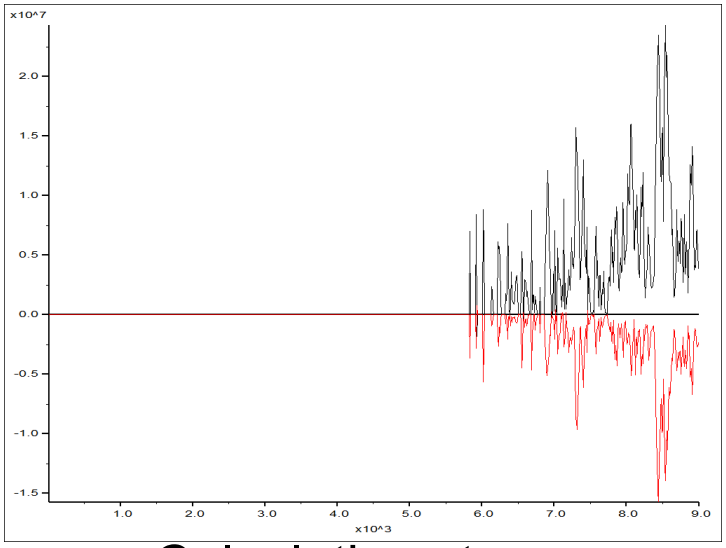




Contact force [N]

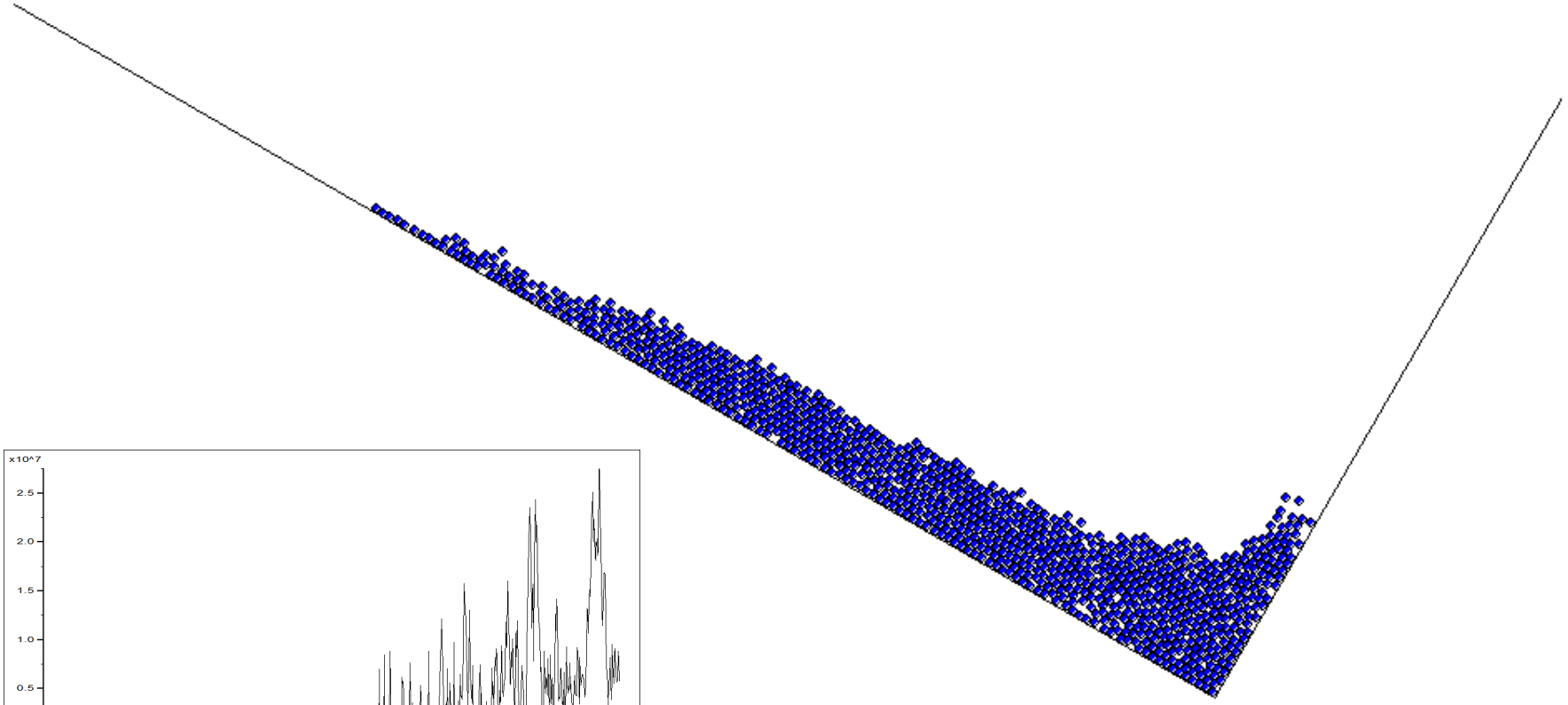
Calculation steps

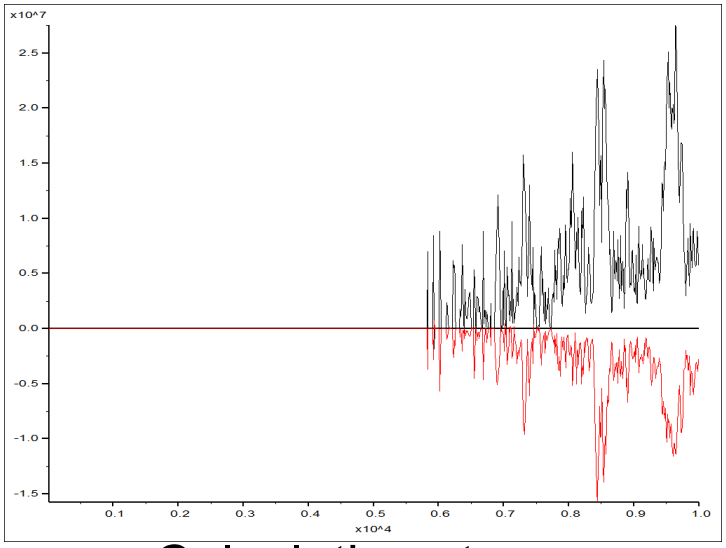




Contact force [N]

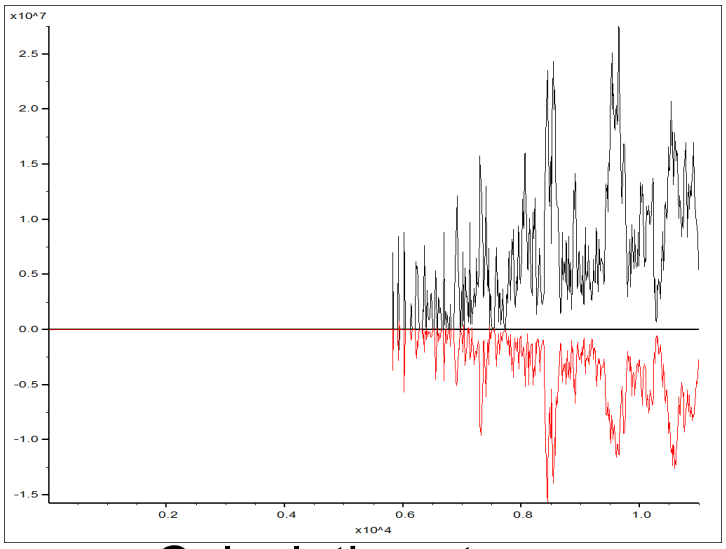
Calculation steps





Contact force [N]

Calculation steps



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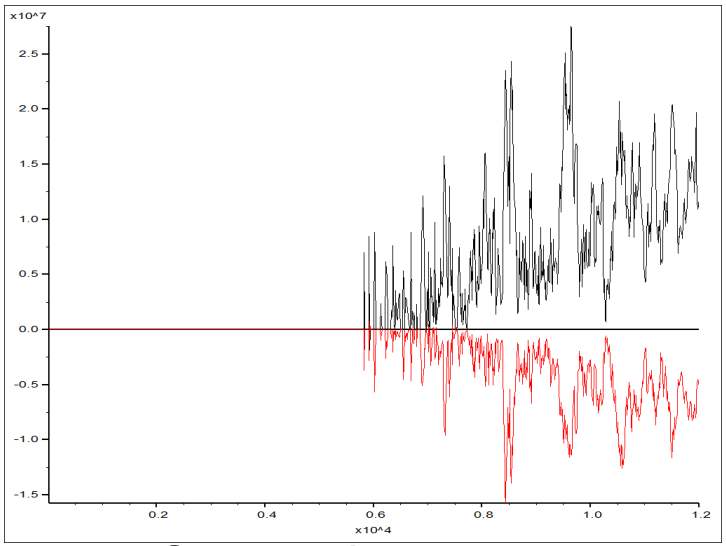
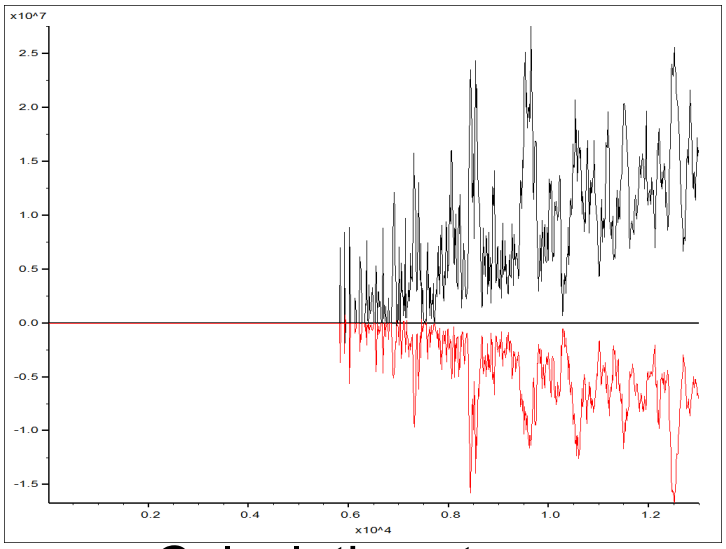
Calculation steps



Contact force [N]

Calculation steps



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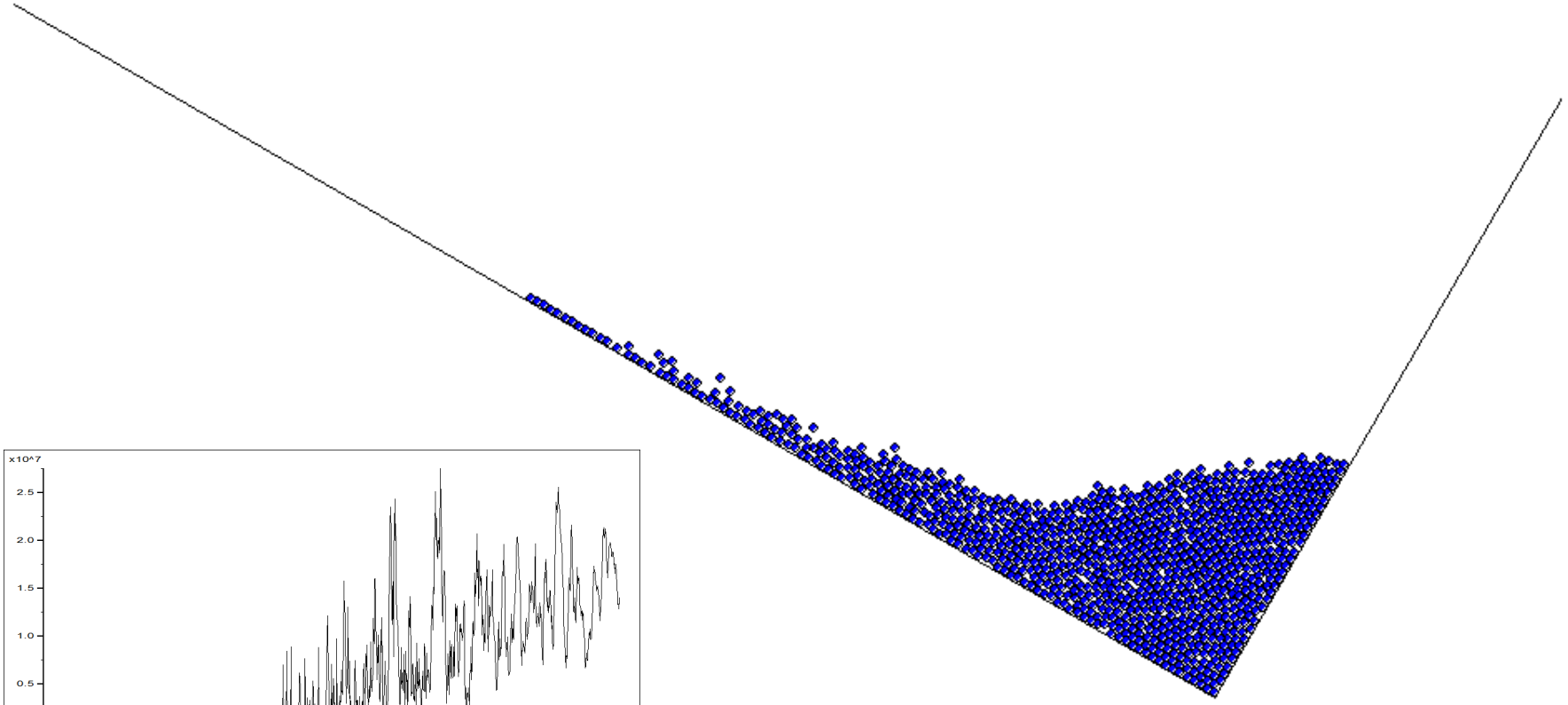
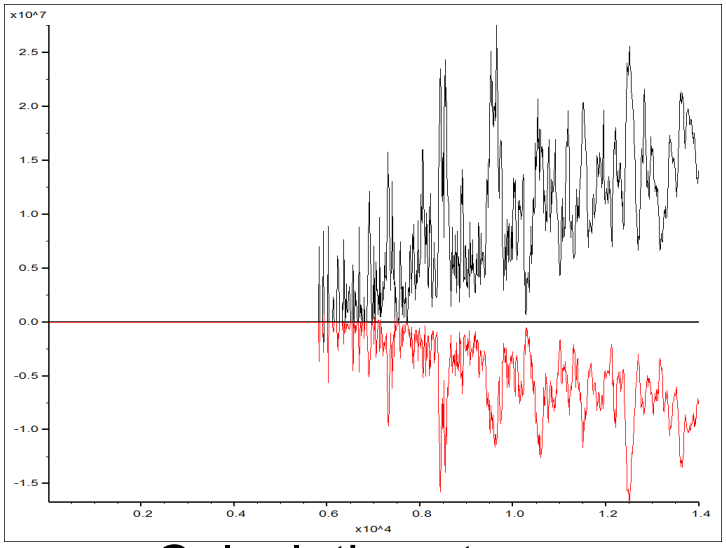
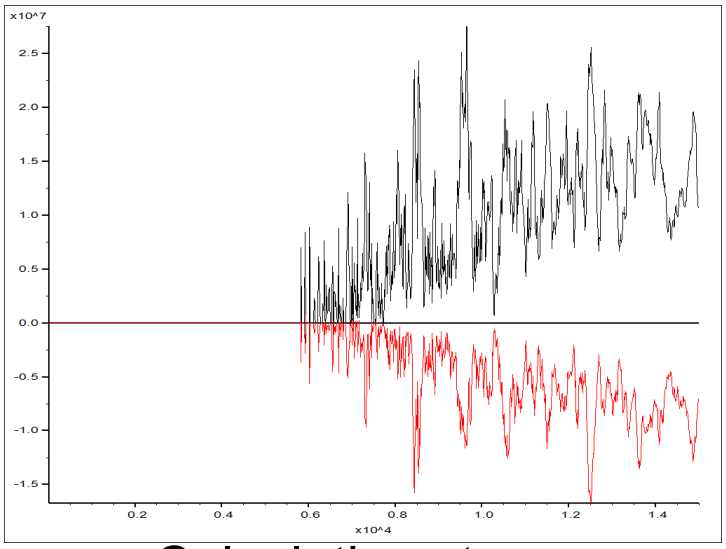
Calculation steps





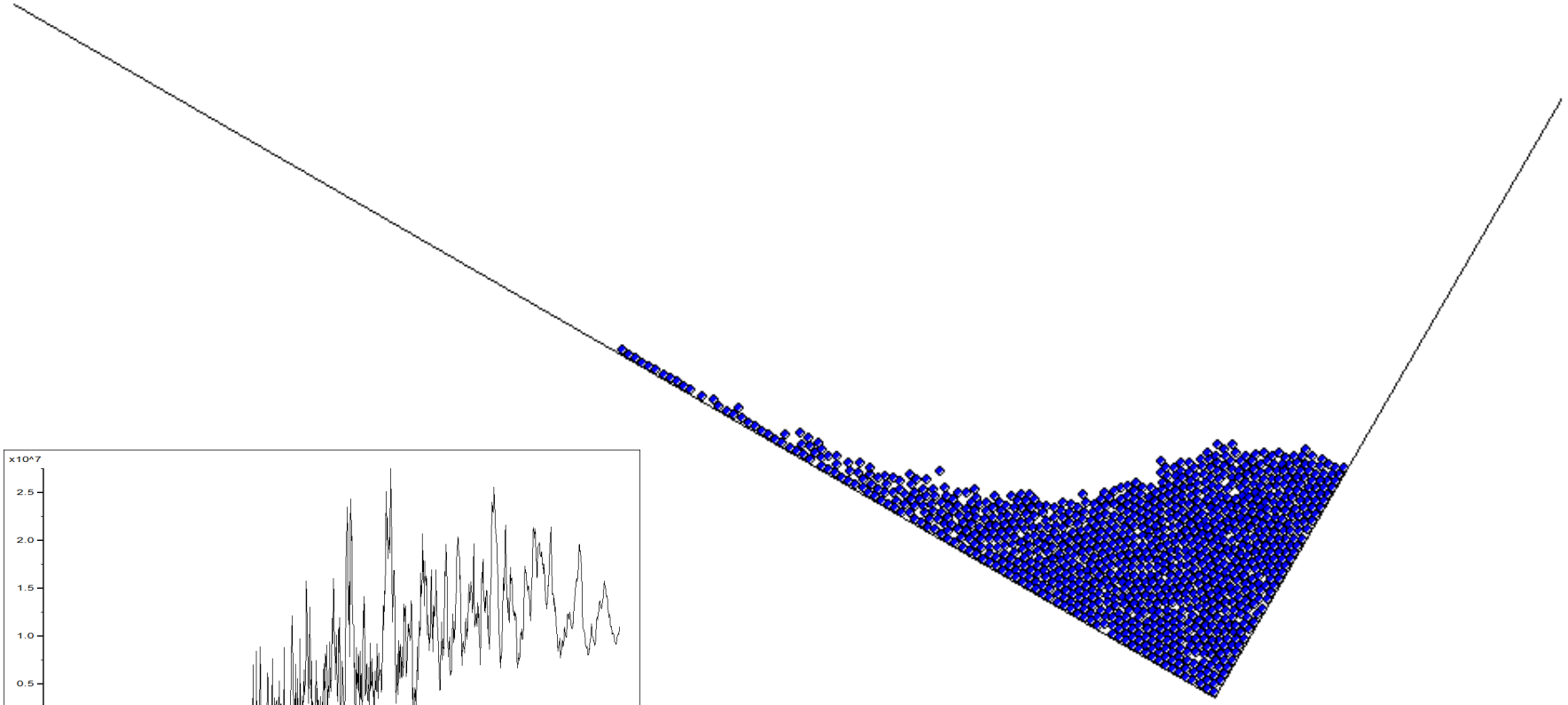
Contact force [N]

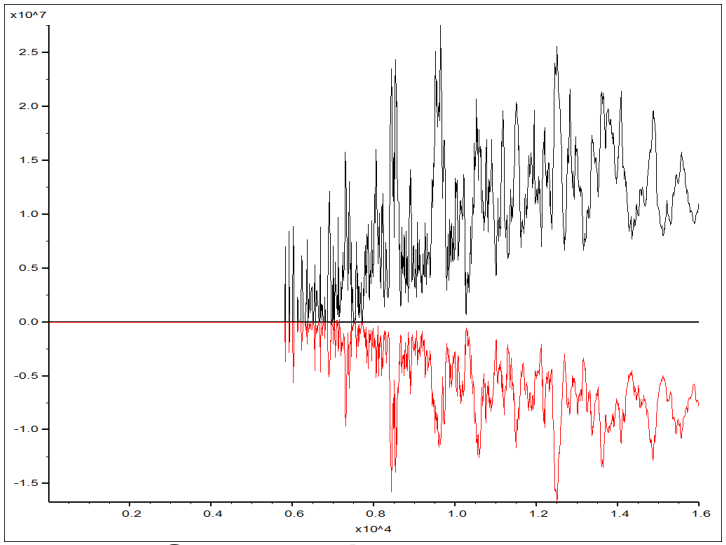
Calculation steps



Contact force [N]

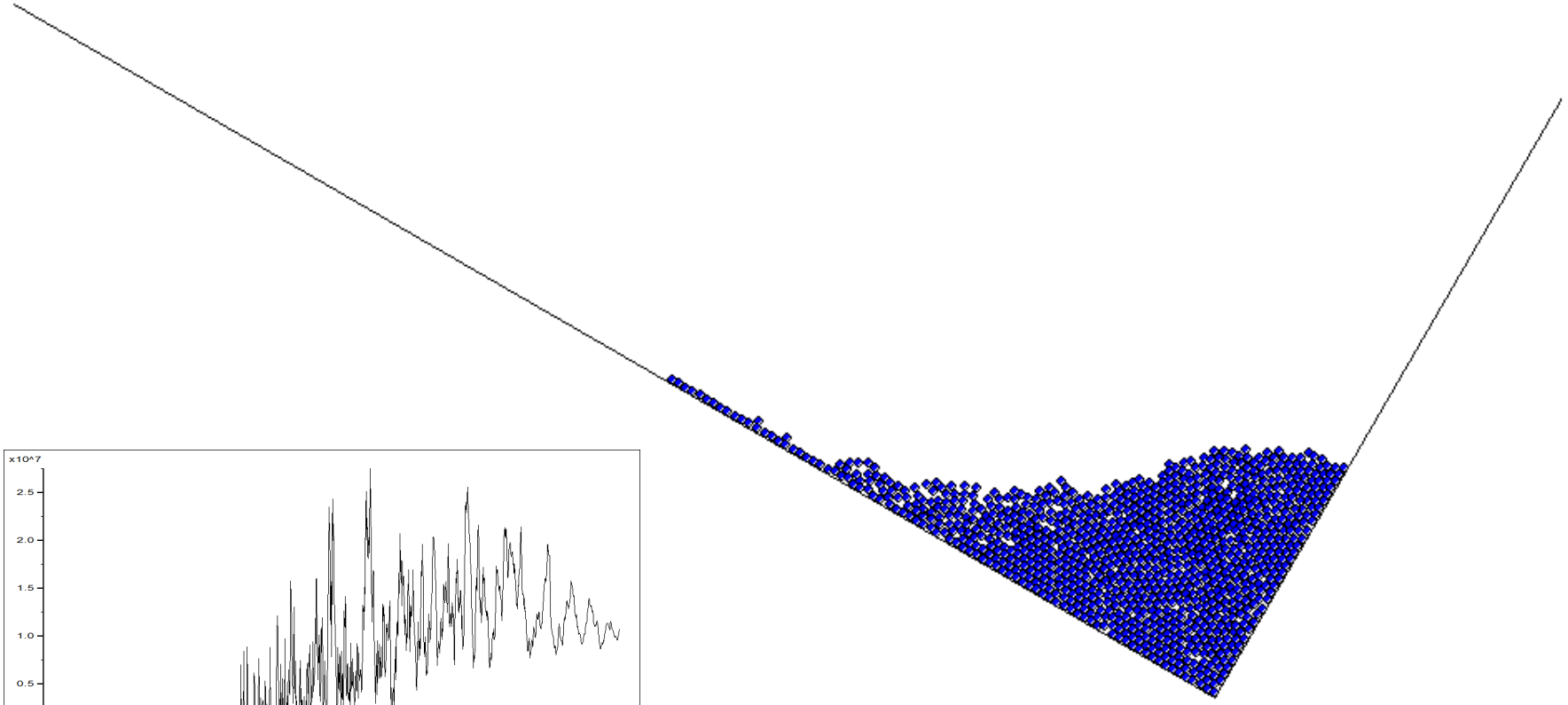
Calculation steps

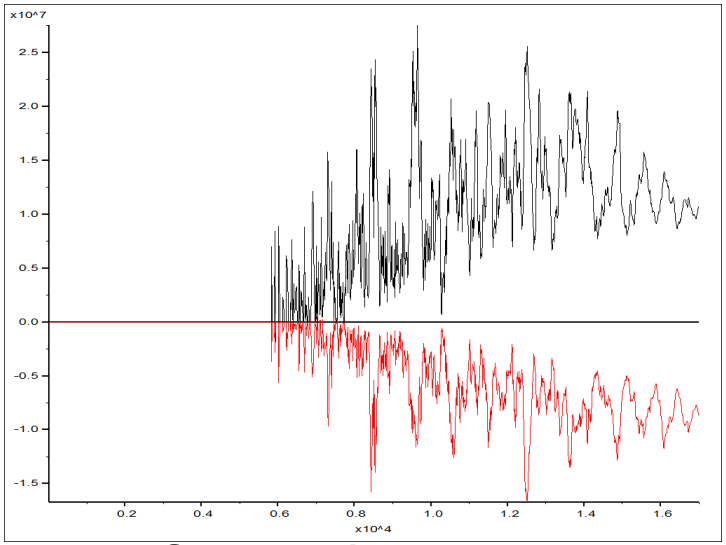




Contact force [N]

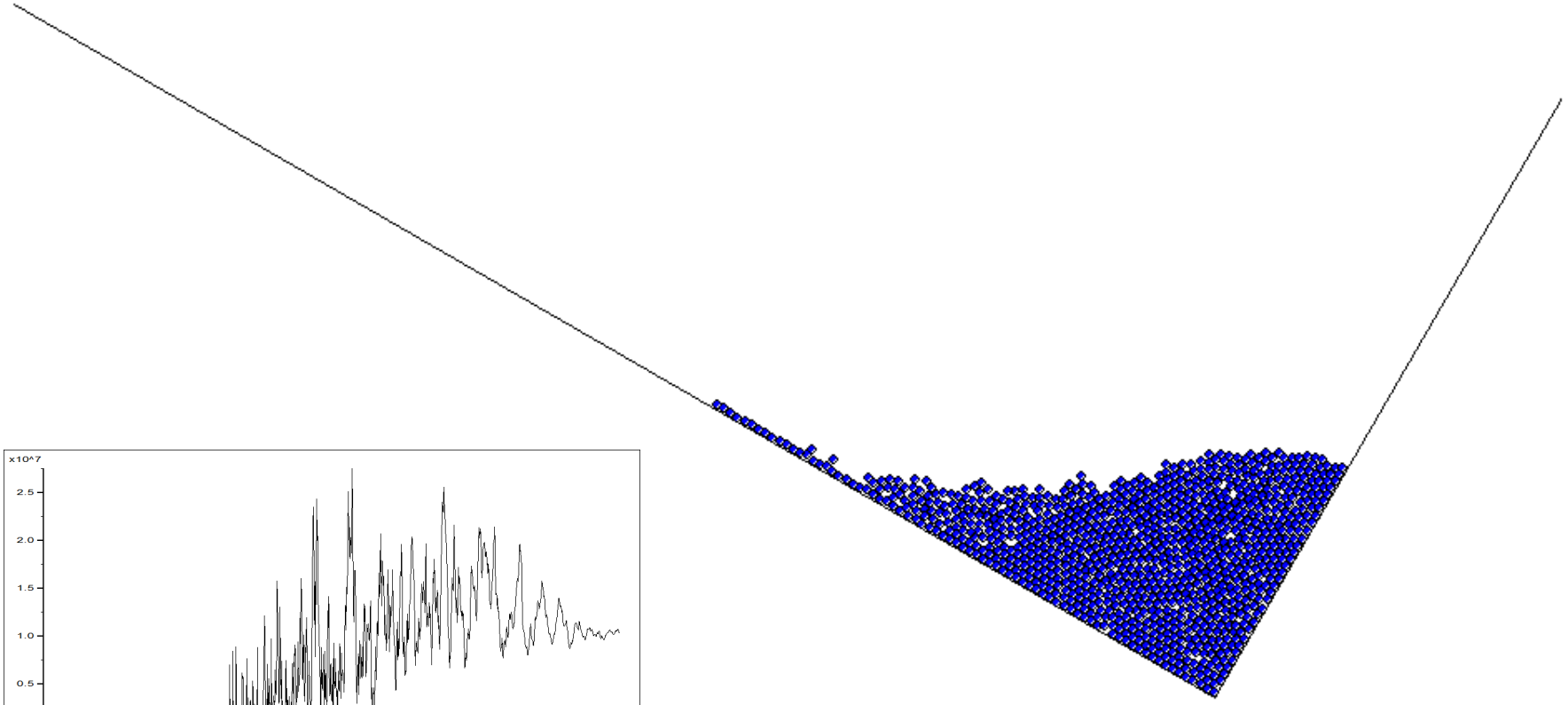
Calculation steps

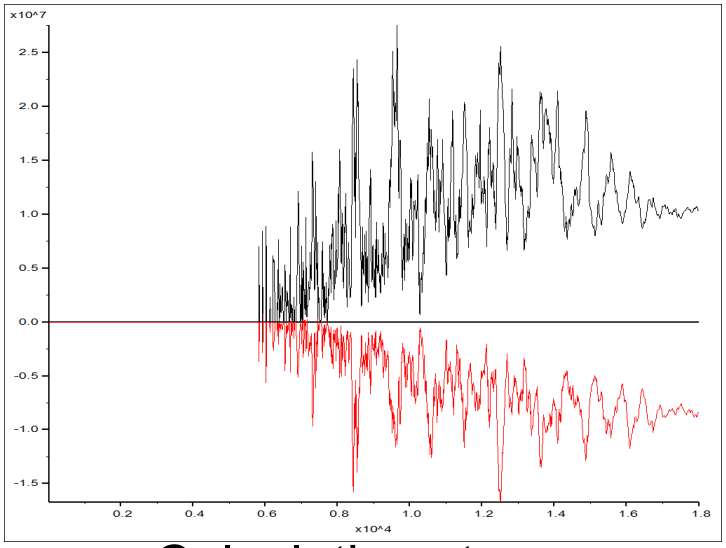




Contact force [N]

Calculation steps





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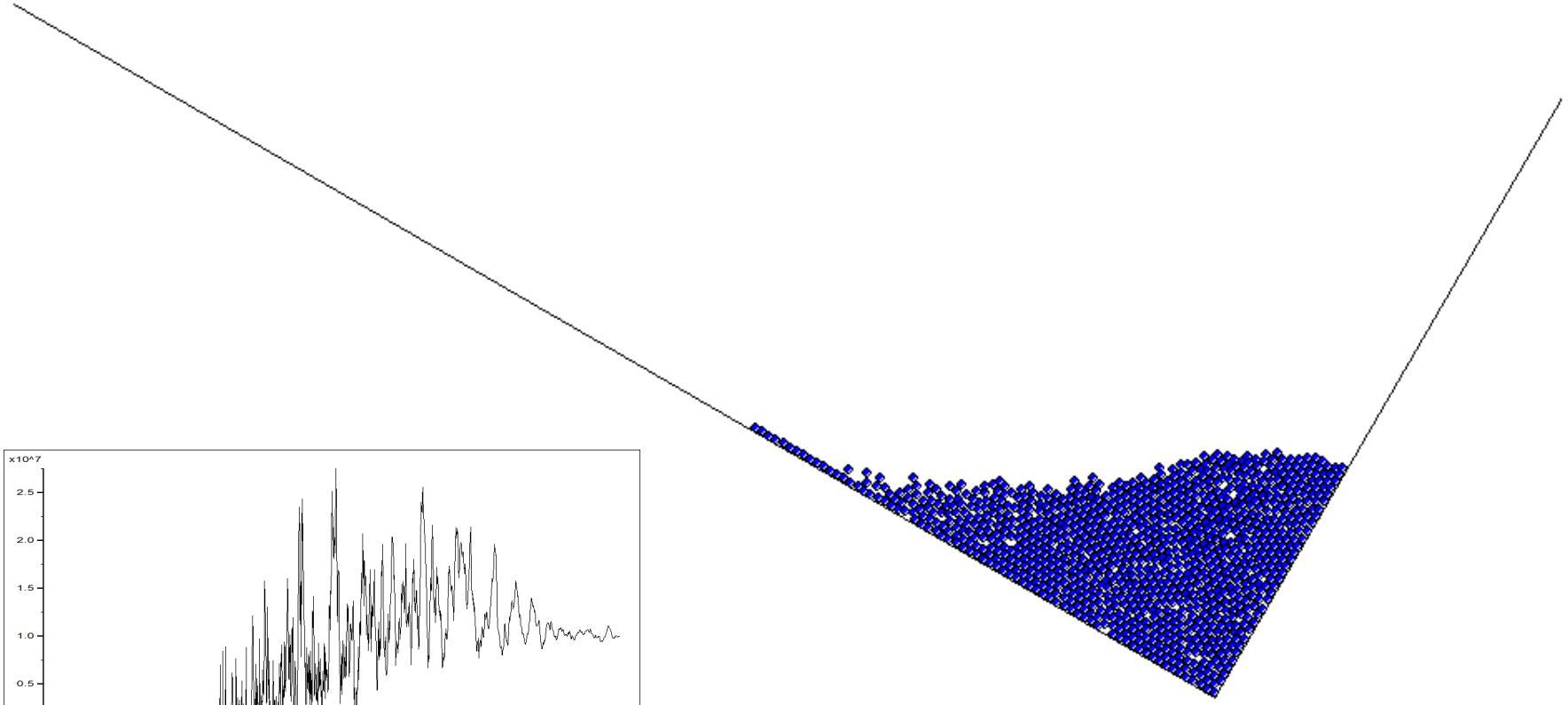
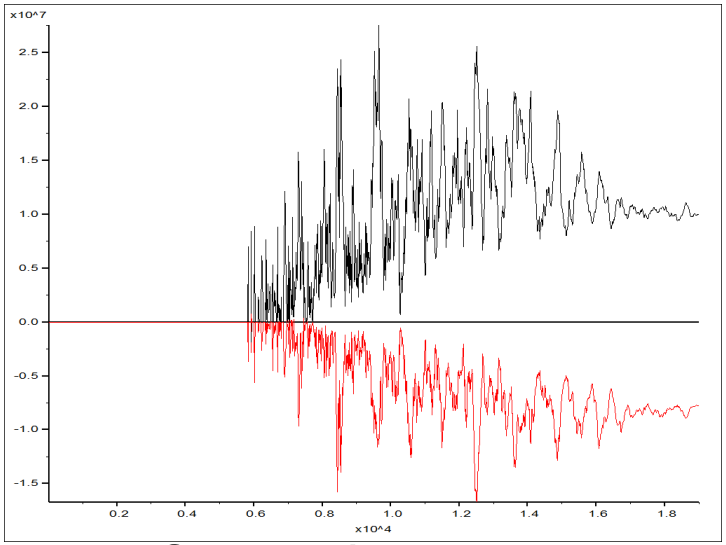
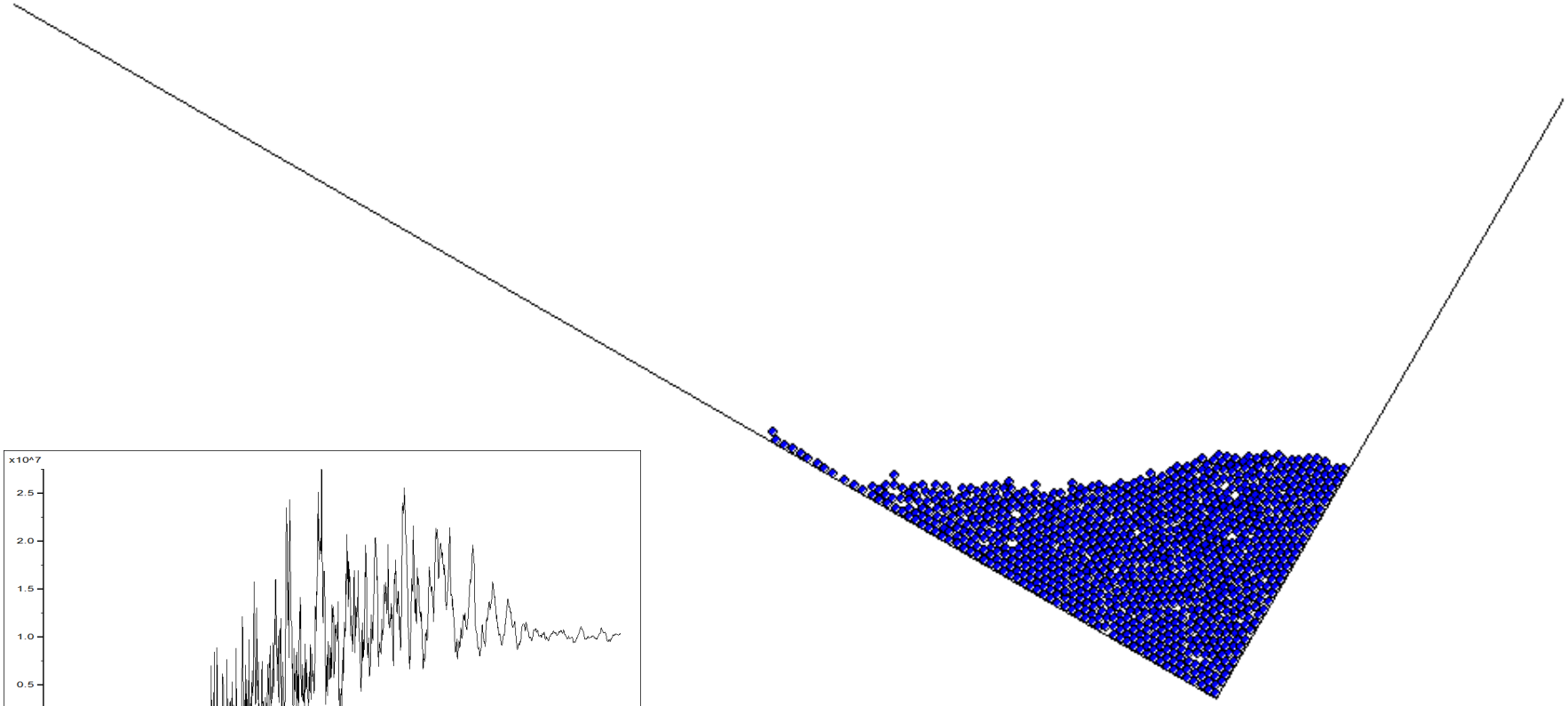
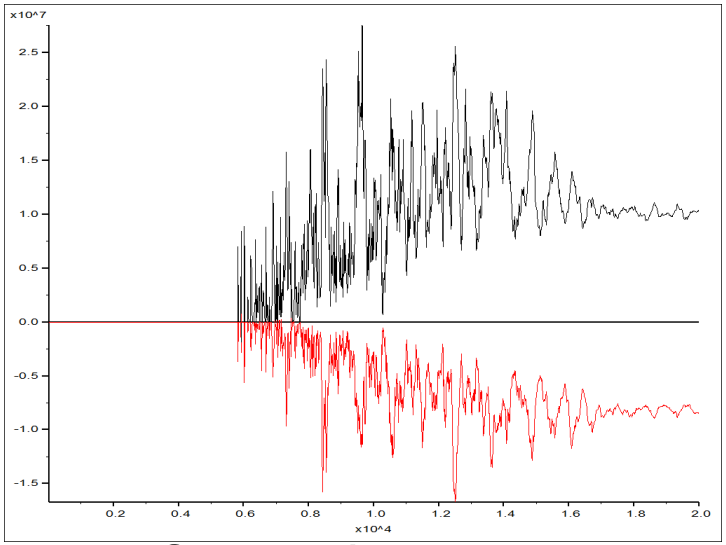




Contact force [N]

Calculation steps





Contact force [N]

Calculation steps