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Microstructural penetrometry of asteroid regolith analogues and Titan's surface

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Abstract: We investigate essential aspects of penetrometer design required to measure particle properties on asteroids using a combination of laboratory analogue regoliths and spaceflight data returned by the Huygens probe from Titan. Penetrometery in granular material is complicated due to multiple and interdependent mechanical processes that occur during penetration. A numerical impact model is developed that simulates the behaviour of a penetrometer and its force sensor in a granular medium. The model is based on the Huygens ACC-E instrument that successfully returned penetrometery data from the surface of Titan. Penetrometry measurements are made in analogue asteroid regoliths using a laboratory copy of ACC-E. The average particle size in the targets ranged from 0.1 to 0.9 of the penetrometer tip diameter. To describe the structure seen in the data a number of metrics are defined to characterise the peaks seen in the returned signal. The significance of the variation of the metrics (such as peak height or width) with particle mass and radius are analysed in terms of penetrometer properties such as impact velocity, elastic properties and data logging parameters.

We find the penetrometer can be used to measure average particle radius and mass adequately for a mid-range of particle radii. Electronic noise effects mostly the results from very small and very large particles. For high mass particles there is evidence that particle-particle impacts, within the target are being felt by the tip that make any straight forward interpretations using peak frequency a challenge. Using our numerical model the Huygens penetrometry data from Titan is analysed. A particle diameter, of around half a centimetre, is found to be consistant with the penetrometry data returned by Huygens. Recommendations and lessons learned, regarding data interpretation techniques are made for asteroid penetrometry (or any other extraterrestrial surface) when using this instrument.

Cover Letter

Dear Icarus,

We would like to submit a revised version of our paper called "Microstructural penetrometry of asteroid regolith analogue and of Titan's surface" to your journal.

The comments from referee #1 have been addressed with the corrections made in the manuscript noted for reference.

Best regard,
Mark Paton

Response to referee #1 comments and list of corrections

Table 1 lists the referee's comments followed by the author's response. Table 2 list the details of the corrections in the revised paper.

Table 1. General responses to referee's comments

Referee/Author	Comment/Response
Referee	**1. The friction term needs to be addressed in the paper and its affect on the author's analysis discussed.**
Author	We had previously assumed to frictional force to be negligible. However the referee was right to raise this. The frictional force between the tip and particle has now been included in equation 6. It affects the model output as follows. As the coefficient of friction is increased the number peaks (i.e. frequency of peaks) remains unchanged whereas the sum of the peak magnitudes significantly increases (see figure 10). The upshot of adding friction is that it reduces the number of particle-particle impacts required to fit the model to the experimental results for the larger particles.
Referee	**2. I have found some plural / singular word typos that the authors might want to look at**
Author	The text has been read through and typos etc corrected

Table 2 Corrections in revised paper.

Revised document		Corrections
Page	**Line**	
6	**345**	Equation 6 updated with friction term, equation 7 deleted and equation numbers updated accordingly throughout text.
17	**412**	Figure 10 updated with results of model runs where the coefficient of friction is varied
27	**622**	Updated table to include results from addition of the friction force
39	**933**	Figure 20 updated with analysis of friction

Highlights

Numerical, physically based, model of a penetrometer in granular materials
Measurement of particle size and mass in asteroid regolith analogues
Measurement of particle size and mass of particles at the Huygens landing site on Titan

1   **Microstructral penetrometery of asteroid regolith analogues and Titan's surface**

2

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4

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7

8   We investigate essential aspects of penetrometer design required to measure particle properties on

9   asteroids using a combination of laboratory analogue regoliths and spaceflight data returned by the

10   Huygens probe from Titan. Penetrometery in granular material is complicated due to multiple and

11   interdependent mechanical processes that occur during penetration. A numerical impact model is

12   developed that simulates the behaviour of a penetrometer and its force sensor in a granular medium.

13   The model is based on the Huygens ACC-E instrument that successfully returned penetrometery

14   data from the surface of Titan. Penetrometry measurements are made in analogue asteroid regoliths

15   using a laboratory copy of ACC-E. The average particle size in the targets ranged from 0.1 to 0.9 of

16   the penetrometer tip diameter. To describe the structure seen in the data a number of metrics are

17   defined to characterise the peaks seen in the returned signal. The significance of the variation of the

18   metrics (such as peak height or width) with particle mass and radius are analysed in terms of

19   penetrometer properties such as impact velocity, elastic properties and data logging parameters.

20   We find the penetrometer can be used to measure average particle radius and mass adequately

21   for a mid-range of particle radii. Electronic noise effects mostly the results from very small and

22   very large particles. For high mass particles there is evidence that particle-particle impacts, within

23   the target are being felt by the tip that make any straight forward interpretations using peak

24   frequency a challenge. Using our numerical model the Huygens penetrometry data from Titan is

25   analysed. A particle diameter, of around half a centimetre, is found to be consistant with the

26 penetrometry data returned by Huygens. Recommendations and lessons learned, regarding data

27 interpretation techniques are made for asteroid penetrometry (or any other extraterrestrial surface)

28 when using this instrument.

29

30 **1. Introduction**

31   There are a number of reasons that make asteroids compelling objects for study. Firstly

32 asteroids are remnants left over from the formation of the early Solar System (e.g. Bouvier and

33 Wadhwa, 2010). Secondly it is evident that asteroids pose a risk to human civilisation due to their

34 large size and high impact speed (Chapman, 2004). Thirdly they are a potential resource for human

35 expansion into space (Rather et al., 2010) and may be visited by humans in the near future to test

36 technologies for exploring Mars (Augustine et al., 2009).

37   Asteroids inhabit the Solar System at a wide range of distances from the Sun which combined

38 with their small sizes make them a challenge to observe in detail, although their large number make

39 for good statistics on the variation of their global properties throughout the population. Spacecraft

40 missions to asteroids are therefore of high value as these can provide in situ measurements to relate

41 local processes on asteroids to the properties of the population as a whole. They are also required to

42 provide ground truths for remote observations and provide focused investigations on targets of

43 special interest. It is important to characterise the processes that have produced the asteroids that we

44 see today so we can more confidently infer the state of the early Solar System from asteroid

45 observations.

46   Surface morphology contains information regarding processes occurring after formation

47 (Noguchi et al., 2010). Studies of the geomorphology of asteroid surfaces using spacecraft (Sullivan

48 et al., 2002), together with high resolution imaging (Veverka et al., 2001; Saito et al., 2006), suggest

49 that regoliths, made up of loose granular material, are prevalent on asteroid surfaces. Modelling of

50 the motion of debris created by impacts suggests most asteroids will have a regolith (Scheeres et al.,

51 2002). Ground-based observations are consistent with many asteroids being covered in particles

52 sub-mm in size (Clark et al., 2002). The movement and mobility of this material over the surface

53 will depend on global properties like gravity, spin rate and shape (Richardson et al., 2004).

54 Mechanical properties of the regolith such as porosity, compressibility, angle of internal friction,

55 cohesion will also be important on a local scale for controlling geomorphologic features such as

56 slope steepness and crater morphology (Mantz et al., 2003 & Scheeres et al., 2010).

57   On the Earth the deposition of material over time results in a distinct stratigraphy in many

58 places. However the asteroid subsurface is thought to be heavily mixed from a gardening process

59 due to micrometeorite impacts (Housen et al., 1982). The role of gardening and space weathering on

60 the properties of the regolith is unclear (Willman et al., 2010). There may also be subsurface ice

61 present on some asteroids (Rivkin and Emery, 2010).

62   Asteroids have yet to be studied using penetrometry. A penetrometer can be used to

63 characterise the mechanical properties of the regolith particles measuring bulk properties such as

64 strength and cohesion. A carefully designed penetrometer can provide information regarding

65 microscale properties of the regolith. Determination of mass and size of the individual grains could

66 help refine models of the asteroid regolith, investigate subsurface layering and provide a ground

67 truth to remote observations.

68   The paper is organised with the following structure. First an overview of existing

69 penetrometry techniques are given followed by a review of relevant interpretation techniques. A

70 description of our numerical model of the a penetrometer and target is given that starts of with a

71 model of the particles impacting the penetrometer tip. Then we develop a model of the sensor

72 taking into account its coupling with the tip and particle impacts. The electronic processing of the

73 sensor's signal is briefly described. Our target model is outlined with details of how the simulated

74 target is set up and deals with impacts between particles. The sensitivity of the structures (i.e. the

75 peaks) seen in the data on penetrometer and target parameters is studied with the model. The

76 experimental set-up is described followed by the results and discussion of penetrometry in analogue

77 asteroid regoliths. In this section we also analyse the penetrometer signal from Huygens landing on

78 Titan to test our interpretation techniques.

79

80 **2. Extraterrestrial penetrometry**

81   Penetrometry is widely used on Earth for geotechnical measurements for civil engineering

82 and geological investigations and have been adapted for a variety of space missions (e.g. see Ball

83 and Lorenz, 2001). A penetrometer is in principle anything that can be pushed into the ground and

84 the resistance measured. Several deployment techniques are used on Earth depending on the task.

85 Quasi-static penetrometery are used in civil engineering such as the Cone Penetration Test (CPT)

86 where the penetrometer is pushed slowly into the soil from a ballasted truck. The resistance to

87 penetration is measured by a force sensor behind a shaped tip and a friction sleeve on the shaft

88 (Lunne et al., 2002). Also in civil engineering, hammer-impact, penetrometers are used in the

89 Standard Penetration Test (SPT) also known as the Dynamic Penetration Test (DPT). A weight is

90 dropped repeatadly from the same height onto the penetrometer. The number of impacts required to

91 drive the penetrometer to a given depth then gives an idea of the compaction of the soild (Rowe,

92 2001). SnowMicroPen (SMP) is a relatively small penetrometer developed for the characterisation

93 of snow properties for avalanche and engineering applications (Schneebeli et al., 1999). It has a

94 relatively fine depth resolution compared to the CPT and SPT penetrometers. The SMP allows

95 accurate in situ measurements in snow which are difficult to obtain by other methods.

96   Drop-impact penetrometers are used to conduct penetrometery in hard to access places

97 like seabeds, lakebeds and ice shelfs etc. Measurements of sea and lake floor properties are required

98 to support various activities such as seabed classification, dredging surveys, naval applications

99 (Harris et al., 2008). Weights and recording equipment, is mounted above the penetrometer shaft.

100 These types of penetrometer are accelerated under the force of gravity to generate the necessary

101   momentum to penetrate the target. Accelerometers are used to measure the resistance to penetration

102   and determine the properties of the target.

103   To be remotely deployable from spacecraft, terrestrial penetrometes have been

104   modified to meet mission and engineering requirements, resulting in some novel designs. In the

105   case of the unknown or poorly constrained properties of the target it may not be possible to optimise

106   the instrument for detailed investigation. The design may require a greater element of robustness

107   and survivability built in for reliability. Unfortunately some of the spacecraft hosting the instrument

108   for making the penetrometry measurements never reached their intended target or failed to

109   successfully deploy (Phobos 1 & 2, Beagle 2, Mars 96, Deep Space 2, Lunar A) for a variety of

110   unfortunate events. The penetrometers and penetrators were however extensively tested on Earth

111   under a variety of conditions and can be considered working in this respect. The type of

112   penetrometry measurements developed for both successful and unsuccessful missions are listed

113   below.

114

115   Handheld cone penetrometer (Costes et al., 1973) operated by astronauts visiting the Moon at

116   various locations as with Apollo 15 and 16 in 1971. They reached a maximum depth of 74 cm, and

117   mechanical properties of the regolith were measured (Carrier et al., 1973).

118

119   Deployed by a mobile lander at various locations as with Lunokhod in 1970 and 1973 (Cherkasov

120   and Shvarev, 1973) or planned with the tethered rover on Mars 2, 3, 6 and 7 landers

121

122   Dynamic penetrometer deployed from a stationary lander as with Venera 11, 12, 13 and 14 (Surkov

123   and Barsukov, 1985) and Vega 1 and 2 on Venus.

124

125 Hammer-driven Beagle 2 mole for Mars (Richter et al., 2002) and the Philae thermal probe for a

126 comet (Spohn et al., 2006).

127

128 Ballistic gravity accelerated, as on Mars 96 (Surkov and Kremnev, 1998) and Deep Space 2 (Gavit

129 et al., 1996) to investigate Mars. Lunar-A penetrators were intended to explore the Moon but the

130 mission was cancelled.

131

132 Harpoon anchoring system as with Phobos 1 & 2 lander (Sagdeev et al., 1988) for use on the

133 Martian moon or the Philae lander anchor for use on a comet (Kömle et al., 1997).

134

135 Landing spacecraft technique as with the use of strain gauges on the Surveyor foot pads used when

136 landing on the Moon (Vrebalovich et al., 1968) and the Huygens penetrometer on Titan (Lorenz et

137 al., 1994).

138

139   An important consideration for extraterrestrial penetrometer design is the deployment

140 technique from the host spacecraft. Deploying a terrestrial penetrometer on an asteroid is

141 problematic for several reasons. Firstly the equipment used for deploying a penetrometer such as in

142 CPT or SPT is expensive to launch into space due to their high mass. Secondly they cannot be

143 operated remotely. Thirdly the deployment mechanism would not work on an asteroid because the

144 gravity is too weak for the CPT reaction mass (i.e. the truck) to be effective in holding down the

145 penetrometer as it is pushed into the surface. For this reason a scaled-down CPT-type deployment

146 as with the Lunokhod is also ruled out. A Venera-type dynamic penetrometry experiment may work

147 if the penetrometer is very light compared to the lander.

148   Penetration in low-gravity environments, using percussive techniques, has been shown to be

149 possible with the Beagle 2 mole and Philae thermal probe. Mechanical properties of regolith

150 analogues can be determined from the progress of the devices. This is one possibility for use on an

151 asteroid but penetration theories relating to this technique are relatively underdeveloped. Ballistic

152 penetrators are a fairly mature technology on Earth and have been considered for asteroids

153 (Langevin, 1987) using the main spacecraft flyby velocity to give them enough momentum to

154 penetrate the surface. Using ballistic penetrators to make microstructure investigations, in an

155 asteroid regolith, will be complicated due to the high impact velocity, which requires the modelling

156 of additional physical processes during penetration such as heating to interpret the data. Penetrators

157 can alternatively be propelled into the surface as with the Philae harpoon-like anchor. As they

158 impact at lower velocity microstructural information can be obtained from penetrometry

159 measurements (Kargl et al., 2001) although the vertical resolution is limited by the extended nose.

160 Such penetrators can only be used once.

161   It is possible to insert a penetrometer, similar in design to that used in CPTs, using the large

162 momentum of a landing spacecraft as demonstrated by the Huygens probe on Titan (Zarnecki et al.,

163 2005). On a near-Earth asteroid a free-fall landing velocity will be only a few centimetres to metres

164 per second but the momentum will be high enough to drive the penetrometer in at constant speed if

165 its mass is high compared to the cross-sectional radius of the penetrometer (Paton, 2005). There are

166 several key elements to penetrometer (or penetrator) design that need to be considered for

167 quantitative detection and measurement of grain properties such as particle size and mass in the

168 target material. Tip shape, size and cross-sectional area are all important for mechanically resolving

169 impacts with individual particles i.e. a large tip impacting small particles will have many impacts

170 occurring at the same time on the tip. Good sensor sensitivity is also required to resolve individual

171 particle impacts. There will be a trade off between penetration speed and sampling rate when

172 resolving impacts from individual particles i.e. if penetration speed is increased then the sampling

173 frequency also needs to be increased to maintain a high resolution. An Analogue to Digital

174 Convertor with a good bit resolution is required to accurately determine the amplitude of the peaks

175 in the signal from the sensor.

176

177 **2.1 Penetrometry models**

178   Here we review penetration models that may be useful for improving our interpretation and

179 understanding of microstructoral information contained in penetrometery data from loose granular

180 materials. The mechanical interactions between two individual grains is easy to understand

181 intuitively but a bulk material containing many particles in contact is sometimes surprising in its

182 behaviour. This continuous and discrete nature of granular material leads to a complex behaviour

183 that may resemble that of a solid, liquid and a gas depending on the energy in the system (Jaeger et

184 al., 1996). For example when at rest the behaviour is that of a solid and the material will support its

185 own weight. Under small stresses a material such as sand will develop a network of force chains

186 that resist the applied force. Once a yield stress is reached the material will be set in motion and

187 flow, resembling the behaviour of a liquid. The flow of granular materials is different from liquids

188 as it is strongly dissipative which means energy can be quickly removed through collisions and

189 friction between the grains and constitutive equations used to describe gases cannot be used to

190 describe its behaviour. However if the material is highly agitated a kinetic theory of granular gases

191 can be applied but this is not a valid approach for many practical applications.

192   A general mathematical description of a hard penetrometer travelling through a softer solid

193 material (e.g. Allen et al., 1957) is given by the following penetration equation.

194   $-\dfrac{du}{dt} = \alpha u^2 + \beta u + \gamma$ (1)

195 where u is the speed, t is the time and α, β and γ are functions of space and time that are empirically

196 derived or based on physical properties of the target and penetrometer. The first term in the

197 equation represents the dynamic force, the second term represents a viscous force and the third term

198 represents the strength of the material. The dynamic force term includes the square of the speed

which is also found in the drag equation for calculating the dynamic forces in a fluid. This term is used to model the momentum transfer between the target and the penetrometer. This force is also dependent on the density of the particles in the target.

The second term is directly proportional to the velocity and a similar term is found in fluid dynamics for representing viscous forces that arise from shear stresses. In granular materials this is basically a friction drag between the penetrometer and the target. The frictional forces will be dependent on the microstructural properties of the particles such as its surface roughness and angularity.

The third term will be related to speed-independent forces that may include cohesion of the grains i.e. the strength of their bonds. It is well known that angular grains can interlock with each other to strengthen the material and resist deformation (Shinohara et al., 2000). Equation 1 has been widely adapted and used for interpreting penetrometry measurements (e.g. Kölme et al., 1997) in terms of a materials bulk properties such as strength and angle of internal friction.

Penetrometer data obtained from measurements into granular material often contain numerous peaks if the sensor is sensitive enough and the particles massive enough (Lorenz et al., 1994). The data can be characterised in a number a ways that can yield information regarding the particle properties. One approach is to measure the spacing between the peaks. Lorenz et al., (1994) made measurements in gravel targets placing the peak spacings into bins 5 ms wide. An empirical correlation between the temporal spacings of impacts and the particle radius was demonstrated with a chart of the results and with relatively large error bars.

Paton (2005) made similar measurements in granular targets but used a peak frequency method applied to the entire set of peaks in the data to try and improve the statistics. A monotonic correlation was found with the peak frequency and average particle size for targets containing medium sized particles. However the peak frequency, from tests in target with the smallest particles, and tests in targets with the largest particles required a physically based model of the

224 penetrometer and target to explain the results. Measuring particle radius using the peak frequency

225 method was found to be ambiguous if it was not known if the average particle radius was within the

226 range of monotonic correlation beforehand.

227 FIGURE 1

228 Another property of the peaks that could be related to physical properties of the peaks is the

229 peak height. Its magnitude is likely related to the dynamic forces on the tip as noted by Lorenz

230 (1994) and so related to particle mass and its elastic properties. This is a very useful measurement

231 as knowing the mass and size of the particle the solid density can be calculated. Paton and Green

232 (2008) showed the average particle size could be accurately determined using peak height and an

233 empirical relation relating particle size to the solid density, elasticity and penetration velocity.

234 Atkinson et al. (2010) made measurements in targets of glass and plastic bead targets up to 0.7

235 grams in mass. A statistically significant empirical relationship was found in the form of a power

236 law.

237 Although work characterising peaks in penetrometry has proved useful for interpreting the

238 properties of the target this approach does not fully describe the penetrometer and target in terms of

239 their physical properties and does not fully describe the mechanical processes that occur during

240 penetration. A more detailed approach is therefore required to be useful for penetrometer design and

241 that will place the interpretation of penetrometery data on a more secure footing.

242 Numerical models have been applied to the deformation of granular materials. In Finite

243 Element Modelling (FEM) material is treated as a continuum and each element contains mechanical

244 properties of the materials such as density, elasticity and yield stress. This type of model is useful at

245 capturing information regarding the stress paths in soils. It is possible that this technique can

246 capture dynamic properties of the target when used together with conventional penetration tests

247 (Jiang et al., 2007).

248   A type of numerical approach that is gaining popularity for modelling granular materials is

249   Discrete Elemental Modelling (DEM) where each element represents one particle. It can contain

250   information about the dynamical as well as mechanical properties. The model contains inter-body

251   force laws allowing the behaviour of an assemblage of grains and a deeper insight into the

252   behaviour of granular materials. Small time steps are required for computational stability that have

253   made the simulation of a large number of particles impractical (Sitharam, 2000). More recently,

254   using modern computing methods, large scale simulations have been possible (Walther, 2009).

255   DEM is particularly useful for analysis of penetrometer resistance in granular materials as it helps

256   to understand the complex mechanisms and stresses involved (Jiang et al., 2006).

257   A physically based numerical model has been developed for the interpretation of

258   measurements made in snow by the SMP (Johnson and Schneebeli, 1999). Here the force recorded

259   in the data was assumed to be due to elastic deformation and brittle failure of structural elements

260   and friction with the penetrometer and ice. The microscale properties have been converted to

261   macroscale properties, such as strength, and found to be in reasonable agreement with the

262   macroscale properties of snow obtained using different methods (Marshall and Johnson, 2009).

263   It would be desirable to apply a DEM model to investigate the dependence of the data on the

264   physical properties of the particles in a granular material. However naturally produced materials

265   have a wide range of properties that can not be efficiently explored using DEM models due to the

266   wide set of parameters and computation times involved. Therefore to improve penetrometer design

267   and to further understand the dynamics during penetration a physically realistic and computationally

268   efficient model is required. The following section outlines the development of a two-particle DEM

269   model that uses some simplifying assumptions to account for, what is in reality, a multibody

270   problem.

271

272   **3. Computer modelling of a penetrometer**

11

273   We develop our model based on the ACC-E penetrometer used during the Huygens mission to

274   Titan to make penetrometry measurements (Lorenz et al., 1994). It then allows us to validate our

275   model with laboratory measurements and discuss the elements of the penetrometer that require

276   optimisation for use on an asteroid. The ACC-E penetrometer, shown in figure 2, includes a

277   piezoelectric force sensor (PZT-5A) housed directly behind a hemispherical tip. The sensor is held

278   between two Vespel washers and is kept under a slight compression by a bolt passing through the

279   middle of the sensor. The sensor is positioned at the end of an aluminium support tube. The tube

280   steps down in radius towards a rectangular base at the other end, to which it is bolted. This base is

281   then attached to the 'top hat' fibreglass structure of the Huygens probe. The sensor works by

282   producing a charge when compressed along the axis of the penetrometer. It is converted into a

283   voltage by a charge amplifier and logged via an analogue to digital converter.

284   FIGURE 2

285   The following linear relationship was found during calibration of ACC-E using a rubber hammer to

286   supply the force pulse (Lorenz et al., 1994).

287    $$F_0 = \frac{V_0 - k_2}{k_1} \quad (2)$$

288   where k_1 and k_2 are 0.0157 and 0.0187 respectively when the output is below a threshold voltage of

289   1.892 V and V_0 is the voltage output when the calibration hammer strikes the centre of the tip.

290   Above the threshold voltage the values of k_1 and k_2 are 0.0031 and 1.5230 respectively. Above

291   3.319 V the values of k_1 and k_2 are 0.0004 and 3.0765. The essential structural design of the

292   penetrometer is illustrated in figure 3.

293   FIGURE 3

294   A numerical approach requires the identification of the important mechanical processes of the

295   penetrometer and the target for accuracy and computationally efficient modelling. First it is clear

296   the force felt by the sensor, that is housed behind a tip, will be dependent not only on the

297   mechanical impacts of the particles but also the mechanical properties of the sensor-tip assembly.

12

298   To fully model the penetrometer, its sensor and target the main modelling steps are identified

299   below.

300   1. The force generated by an impacting particle on the tip surface.

301   2. The force on the sensor produced by the motion of the tip when displaced by a particle impact.

302   3. Electrical processing of the signal generated when the sensor is compressed by the tip.

303   4. The target structure (location of particles) and the number of impacts between particles.

304

305   **3.1 Dynamic forces on the penetrometer sensor**

306   First we use Hertz's contact law (Hertz, 1882) to build a model of the force generated during

307   a single particle impact on the tip. Consider two elastic spheres that are in contact at a single point.

308   If a force is applied pushing them together this will cause the spheres to deform and the contact

309   point will be over a small area of their surfaces. This is from the classic contact law developed by

310   Hertz relating applied force to deformation. The dynamic case of two spheres impacting then

311   follows from this static case and derivations are found in several text books on the subject (e.g.

312   Atanackovic and Guran, 2000).

313   When the spheres collide they are deformed in a direction normal to the local surfaces that are

314   in contact. Considering spheres of uniform density and assuming the contact time is much smaller

315   than the period of free vibrations of the colliding bodies, the maximum force during the impact can

316   be calculated using the following equation adapted from Atanackovic and Guran (2000).

317    $$F_{\max} = 1.28 \frac{v_z^{1.2}}{X^{0.4}} \left(\frac{m_1 m_2}{m_1 + m_2} \right)^{0.6} \left(\frac{r_1 r_2}{r_1 + r_2} \right)^{0.2} \qquad (3)$$

318   where m_1 and m_2 are the masses of the colliding bodies, r_1 and r_2 are the radius of the two bodies

319   and X is defined as in equation 4.

320    $$X = \frac{1 - \sigma_1^2}{E_1} + \frac{1 - \sigma_2^2}{E_2} \qquad (4)$$

13

321   where σ_1 and σ_2 are the Poisson ratio and E_1 and E_2 are the elasticity of spheres 1 and 2. The

322   duration of contact between two spheres from Hertz's theory of impact is as in equation 5.

323      $$\Delta t_{pk} = 2.86 \frac{X^{0.4}}{v_z^{0.2}} \left(\frac{m_1 m_2}{m_1 + m_2} \right)^{0.4} \left(\frac{r_1 r_2}{r_1 + r_2} \right)^{-0.2} \tag{5}$$

324   The geometry of an impact between a penetrometer with a hemispherical tip, and a spherical

325   particle is examined in figure 4. The penetrometer is constructed with a force sensor between the tip

326   and the end of a cylindrical shaft. The impact point is located at a radial distance, r_1, from the centre

327   of the tip base and at an angle, α, to a line perpendicular to the direction of motion. As seen from

328   the particle the impact point approaches at an angle, α, to the flat side of the hemispherical tip. Once

329   in contact the particle will deform in the direction towards the centre of the tip and exert a force on

330   the tip. In addition there will be frictional forces generated as the tip and particle slide past each

331   other. The force will be in a direction parallel to the local surface of the tip as shown in figure 5.

332   This force then accelerates the tip compressing the force sensor. If the sensor produces a charge that

333   is proportional to the deformation of the sensor then the charge will be proportional to the force of

334   the impact.

335   FIGURE 4

336   Figure 4 also shows the basic geometry of the collision. The particle, represented by a sphere,

337   is static, and the tip, represented by a hemisphere is in motion, in a downward direction. The tip of

338   the penetrometer is traveling vertically into a regolith, with the velocity vector v_z. A particle will

339   strike the surface of the hemispherical tip at a velocity, $v\sin\alpha$. The sensor is then compressed

340   measuring the component of the force along the long axis of the penetrometer i.e. $F\sin\alpha$ and $\mu F\cos\alpha$

341   where μ is the coefficient of friction between the penetrometer tip and the impacting particle. For

342   metals on rocky materials this can be between 0.1-0.5 (Perrson, 2007).

343   Incorporating the geometrical effect of the hemispherical surface and the sensor

344   directional bias, equation 3 can be modified to the following equation 6.

14

345 $$F_{\max} = 1.28 \frac{(v_z \sin \alpha)^{1.2}}{X^{0.4}} \left(\frac{m_1 m_2}{m_1 + m_2} \right)^{0.6} \left(\frac{r_1 r_2}{r_1 + r_2} \right)^{0.2} (\sin \alpha + \mu \cos \alpha) \qquad (6)$$

346   Assuming equal-sized particles, the force felt by the sensor will depend on the

347 location of an impact on the hemisphere tip. If the friction coefficient is small those particles

348 impacting the side of the tip, i.e. at a glancing angle, will result in the lowest force and those

349 particles impacting the centre of the tip, head on, will produce the largest forces. If the friction

350 coefficient is very large then the largest force will be produced at a location displaced from the

351 centre.

352   Damped harmonic motion can be used to describe the motion of the tip if the sensor-tip

353 system is modelled as a spring-mass system, where the sensor is the spring and the tip is the mass.

354 This sensor-tip system is shown in figure 5. The sensor is elastic with a spring constant, k, and the

355 tip has a mass, m.

356   FIGURE 5

357   Harmonic oscillation of spring-mass systems is well known and for a damped harmonic

358 oscillator is,

359 $$m \frac{d^2 x}{dt^2} + \beta \frac{dx}{dt} + \omega_0^2 x = F_d \qquad (7)$$

360 where β is the damping coefficient, x is the displacement from the equilibrium position, ω_0 is the

361 angular frequency of the system and t is the time. The angular frequency can be expressed as

362 follows,

363 $$\omega_0 = \sqrt{\frac{k_{eff}}{m}} \qquad (8)$$

364 where m is the mass of the oscillator and k_{eff} is the effective spring constant. The spring constant, in

365 this case, can be calculated from the elasticity of the sensor which can be expressed as follows,

366 $$k_{eff} = \frac{EA}{l} \qquad (9)$$

15

367   where E is the elasticity, l is the thickness of the sensor and A is the area of the elastic material in

368   contact.

369   **3.2 Signal processing and electronic noise**

370   Electronic signals are often recorded using an Analogue to Digital Convertor which samples

371   the analogue signal at discrete time steps. Most ADCs use an internal capacitor to hold the sample

372   voltage as it takes some time to convert the signal to a digital value. To simulate the ADC the model

373   uses a time step that is smaller than the virtual ADC. The model then produces a simulated signal

374   that is high resolution in voltage and time. A virtual processed signal can then be produced from the

375   modelled signal from the sensor by performing a logic test on the voltage at each sample time step

376   and then assigning it to one of the ADC bit values that it is closest too. Electronic noise is

377   reproduced by using a random number generator to produce 1-bit high noise peaks of 'jumps' in the

378   data. The simulated noise is then added to the simulated ADC signal.

379

380   **3.3 A realistic target model**

381   The treatment so far can only model a very sparsely populated granular target where there is

382   sufficient room for the particle to bounce off the tip and not impact anything afterwards. In a real

383   granular material, a particle will be in contact with surrounding particles that will constrain its

384   movement and force it to slide across the surface of the tip. Therefore either inter-particle impacts

385   need to be simulated or some assumptions need to be made regarding the motion and effect of the

386   interaction of the particles. It is often encountered that DEMs of granular materials where the

387   motion of each particle is modelled can be highly demanding of computing resources. Here, in our

388   model of a granular material, we make some assumptions regarding the structure of the material and

389   the behaviour of particles around the tip so computer resources can be efficiently utilised. The

390   assumptions we make regarding the target are that the particles are perfectly spherical, the target has

391   a monodisperse distribution of particle sizes and are packed in a Face Centred Cubic arrangement.

392   In the laboratory such a structure is difficult to construct and cannot exist in naturally produced

393   granular materials due to their distribution of particles sizes and the random nature of their

394   deposition. To reproduce the random nature of the target structure in our model we set up a 3D

395   computer target populated with particles in a regular packing arrangement and then gave each

396   particle a random offset in the horizontal plane relative to its original location.

397   Figures 6a and 6b, shows the number of impacts within a radial distance from the centre of

398   the tip, r_p. Four target structures are investigated, one containing particles with a radius of 2 mm and

399   having a regular packed arrangement, the second containing particles with a radius of 2 mm and

400   having a randomised arrangement, the third containing particles with a radius of 6 mm and having a

401   regular arrangement and the fourth containing particles with a radius of 6 mm and having a

402   randomised arrangement. For the regular structure examples, in figure 6, the particles impact in

403   groups. Each level in the target has particles positioned in the same place as those above it. For the

404   randomised examples each particle will impact the tip at a unique location on the tip so generating a

405   continuous increase in the fraction of particles impacted with radial distance from the centre of the

406   tip. For a target, containing particles with a radius of 6 mm radius, a high percentage of the particles

407   impact the tip halfway between the centre and the edge. This is because there is more room further

408   away for the particles to impact. When the arrangement is randomised the amount of impacts

409   increases more smoothly with increasing radial distance from the centre of the tip. The changes in

410   gradients in figures 6a and 6b are due to the shape of the tip and that the particle locations are

411   randomised relative to a regular packing structure.

412   FIGURE 6

413   Due to the shape of the tip, particles impacting the centre will generate larger forces on the

414   sensor than those impacting the side of the tip (as described by equation 2). Therefore the

415   probability of a particle impacting the centre of the tip needs to be understood for interpreting the

416   results. Figure 6c shows the probability of a particle impacting the tip within half a radius of the

17

417 centre. The probabilities shown are calculated using two types of targets as in figures 6a and 6b (a

418 regular arrangement (FCC) and a randomised arrangement) for a range of particle sizes. The

419 simulated penetrometer is dropped into the targets and the probability can then be calculated as in

420 the following equation.

421 $P=n_4/n_8$ (10)

422 where n_4 is the number of particles that have impacted less than half a radius from the centre and n_8

423 the total number of particles that have impacted the tip.

424   The variation in the probability, with particle size, can be explained by the granular,

425 discreet, nature of the target. If the target particles become very small (e.g. a liquid) then the

426 probability of a particle impacting the central area of the tip (i.e. less than 4 mm from the centre)

427 would be the cross-sectional area of the central area divided by the full cross-sectional area of the

428 tip which in this case works out to be a probability, $P=0.25$. At the other extreme, when the

429 particles become much larger than the tip, the surface of the particle can be approximated as a flat

430 surface. The probability of the particle impacting the tip will then be $P=1.0$ because the tip's centre

431 is the most forward part of the tip. In figure 11 the probability, for the FCC arrangement, starts off

432 close to a value one would expect from a target for small particles. The probability of a particle

433 impacting the central area of the tip increases as the particles become larger because a higher

434 proportion of particles impact the central area compared to the outer area. The trend then reverses as

435 the particles have a radius comparable in size to the central area (i.e. 4 mm). At this point the

436 particles will be impacting the centre of the tip and points outside the central area. As the particles

437 become even bigger the probability will tend to unity as the surface of the particle becomes

438 increasingly flat relative to the surface of the penetrometer tip.

439   In DEM computing much of the computation time is taken up by tracking the motion and

440 collisions between the target particles. Our model reduces the computation time by only keeping

441 track of the motion of the penetrometer and particles that are in contact with the tip. Once a particle

18

442 has rebounded it is deleted from the target. Particles will interact with each other through collisions

443 and friction and these forces will be transfered to the tip. Therefore we need to capture the essential

444 characteristics of these processes using some sensible approximation with an appropriate

445 parameterisation (i.e. say a number of collisions that occur in the target per displaced particle).

446 To understand the behaviour of the particles and their interaction with the penetrometer we

447 first describe their motion in detail as follows. As the penetrometer moves deeper into the target the

448 particles at the centre of the tip will be pushed outwards causing them to spread out across the

449 surface of the tip. At the same time surface particles located further away from the centre of the tip

450 will impact the surface of the tip not already occupied by the first group of particles. As the

451 penetrometer becomes immersed in the target it will feel resistance from the constant stream of

452 particles sliding over the surface together with particles impacting the surface. There will be room

453 for more impacts on the tip surface as the particles that impact the front of the tip spread out across

454 the surface during penetration. This process is illustrated in figure 7 with the top two diagrams.

455 FIGURE 7

456 As the penetrometer travels deeper into the target an increasing volume of material will be

457 compressed and compacted by the tip. This process is illustrated in figure 7 with the bottom two

458 diagrams. Firstly the particles in the vicinity of the tip are pushed into the surrounding material

459 creating a zone of maximum compaction. The volume of this compaction zone will depend on the

460 packing density of the material. For example, a loosely compacted material will have some room

461 for movement to accommodate the particles displaced by the penetrometer. A densely packed

462 material will generate a large zone as there will be little room to accommodate the displaced

463 particles i.e. a larger amount of particles have to be compacted to make room for the penetrometer.

464 There will be collisions between particles as the material is compacted and set into motion by

465 the penetrometer. It is reasonable to assume the forces from these collisions will be distributed

466 amongst neighbouring particles so the forces on the penetrometer will be small. However for large

467   particles, where the impact forces between particles will be large (i.e. see equation 3) then the

468   penetrometer will be detecting particle-particle impacts, not just impacts on the tip. The total

469   number of impacts events detected by the penetrometer may not be simply the number of particles

470   impacting the tip. The maximum number of subsequent impacts, caused by the displacement of one

471   particle, can be calculated by considering how many particles need to be moved to accommodate

472   this particle.

473   The amount of volume that is available for manoeuvring the particles in the uncompacted

474   state will be equal to the volume of the void space in the uncompacted state minus the volume of

475   the void space in the compacted state. For one cell the volume available for accommodating the

476   displace particle will be $4r^3(\varnothing_0 - \varnothing_c)$ where $\varnothing_0$ is the porosity in the loose state and $\varnothing c$ is the

477   porosity in the compacted state. The maximum number of impacts, due to compaction of the

478   surrounding material, will then be as in equation 11.

479     $$n_{\max} = \frac{1}{\phi_0 - \phi_c} \qquad\qquad (11)$$

480   This number can then be used in the model by adding extra impacts for each particle that impacts

481   the tip. The number of extra peaks should not be more than n_{max}.

482

483   **3.4 Other forces on the tip**

484   So far we have considered the forces generated by momentum transfer and friction between

485   the penetrometer tip and the impacting particle. There will also be forces due to the strength of the

486   material from friction and cohesion between the particles. The strength of loose granular material

487   will mostly be due to friction between the grains. We consider these forces here for a context in

488   which to interpret the forces generated by impacts with the tip. Figure 8 shows impact peaks

489   superimposed on a background force continuum that increases with depth. The increase in the

490   background force is due to the increase in overburden pressure which in turn increases the frictional

491 forces between the particles. The background force is calculated using the equation in (Kömle et al.,

492 1997) that is based on a soil mechanics model developed by Terghazi (1943).

493   FIGURE 8

494   The model is based on the angle of internal friction and the concept of slip surfaces produced

495 by a penetrating rod. The angle of internal friction is a measure of friction between particles and

496 increases with increasing particle surface roughness and angularity. The slip surfaces generate

497 shearing forces and the internal angle of friction is then a measure of the roughness between these

498 surfaces. In this way the microstructral properties of the material, the particles, is related to the

499 macroscopic behaviour of the material.

500

501 **3.5 Predicted sensor performance**

502   The model, developed so far, can now provide some insight into the performance of the tip-

503 sensor assembly of the penetrometer. For the sensor to have a chance of detecting individual

504 particle impacts, and resolving the forces of impact, a number design criteria need to be met. The

505 time between particle impacts on the tip needs to be larger than the contact time of the particles on

506 the tip. In addition the response time of the tip-sensor assembly, the part modelled using simple

507 harmoninc motion, needs to be smaller than both the contact time and time between impacts.

508 Finally the sensor itself needs to have a response time smaller than all the above. The following

509 study examines the significance of these criteria and highlight complications that could arise when

510 these are violated.

511   A penetrometer tip impacting a granular target may experience more than one impact at the

512 same time if the particles are smaller than the tip. This can be illustrated by comparing the time

513 between impacts with the contact time of impact. An approximation of the number of impacts

514 experienced by the penetrometer tip can be calculated by first dividing the target into cells of equal

515 volume that contain the particle and its share of the void space. The number of expected impacts,

516 assuming each particle impacts the tip a single time, is the volume excavated by the penetrometer

517 divided by the volume of the particle-void cell.

518   A naturally produced granular target will contain particles and pores with a range of sizes. The

519 volume taken up by solid material in the target excavated can be expressed in the macroscopic

520 terms of the volume of target material excavated and the porosity as in equation 12.

521 $V_S = V_T(1 - P)$ (12)

522 where V_T is the volume of the target and P is the porosity, which is defined as the volume of the

523 voids divided by the total volume. The minimum number of particle impacts is calculated by

524 dividing the excavated solid volume by the volume of an average-sized grain. Then the time

525 between impacts is calculated as follows.

526 $\Delta t_{imp} = \dfrac{1}{1-P}\dfrac{4}{3}\dfrac{r_2^3}{r_1^2 v}$ (13)

527   From equation 8 the time between impacts then depends on the packing density of the target

528 together with the radius of the penetrometer tip and the radius of the grains in the target. Figure 7

529 shows the variation of   and   with penetrometer tip size for particles of 1 mm and 10 mm

530 in radius. With our penetrometer with a tip radius of 8 mm, and for particles with a radius of 1 mm,

531 the contact time   is greater than the time between impacts,   . For particles of 10 mm in

532 radius the contact time is less than the time between impacts This suggests that for larger particles

533 each impact will be distinguished as a peak in the force in the surface of the tip while for smaller

534 particles the peak forces on the tip will be a combination of impacts occuring in close succesion.

535   FIGURE 7

536   When a particle impacts the tip it will accelerate the tip onto the sensor. It will then take some

537 time for the tip to be slowed down by the relatively elastic Vespel washers housing the sensor and

538 return it to the starting (equilibrium) position. The particle impact will be resolvable in the data only

539 when the tip begins its return leg, after compressing the sensor, as this will be the point of

540 maximum force on the sensor. The response time of the tip-sesnor assembly is a ¼ of its oscillation

541 period because this is the time it takes to compress the sensor. After this the force on the sensor will

542 fall and then an impact can be identified for sure. The response time of the tips-sesnor assembly for

543 our penetrometer (with a radius of 8 mm) is somewhere between the time between impacts for

544 particles with a radius of 1 mm and time between impacts for particles with a radius of 10 mm. So

545 for smaller particles this suggests that particles will be impacting too fast to be resolved by the

546 sensor.

547 In figure 7 the time between impacts decreases with increasing tip radius. The reason for this

548 is because, for constant velocity, the cross-sectional area of the penetrometer increases as the square

549 of the tip radius while the volume excavated (and the number of impacts) increases by the cube of

550 the tip radius.

551 In naturally produced granular material the size distribution of the particles in the granular

552 material and their random locations will sometimes cause a cluster of high frequency impacts for

553 particles with particles larger than 4 mm in radius so not all peaks will represent an individual

554 impact on the tip. However for particles less than 4 mm in radius a cluster of impacts at a low

555 frequency may occur and so there may be peaks in the sensor data that do correlate with individual

556 impacts on the tip.

557

558 **4. Numerical description of the model**

559 It is possible to solve equation 7 using an analytical approach to find the displacement, x, if

560 the driving force can be modelled using a simple mathematical functions such as sine or cosine.

561 This would require that the contact time of impact is exactly half the period of the time between

562 impacts. The contact time is however a complicated function of particle and tip masses, radii and

563 elasticity whereas the time between impacts (for particles of identical sizes and in a regular packing

564 arrangement) will depend on their packing density. With naturally occurring granular material it is

565   therefore more convenient to use a numerical model. Equation 7 can be rearranged and expressed as

566   a function of acceleration.

567    $$\frac{d^2x}{dt^2} = \frac{1}{m_{tip}}\left(F_d - \beta v_t - x_t k_{eff}\right)$$ (14)

568   where m_{tip} is the mass of the tip, F_d is the driving force from particle impacts, v_t is the velocity of

569   the tip relative to the shaft at time, t, and x_t is the displacement of the tip relative to its equilibrium

570   position at time, t. The DEM can be used to solve the equations. Each particle is first assigned a

571   location in space and the penetrometer is assigned a location together with a velocity. Explicit time

572   stepping is then used and the forces on the penetrometer tip from impacts with particles is as in

573   equation 15.

574    $$F_d = F_{max}\sin(\omega t) \qquad t < t_{pk}$$ (15)

575   where F_{max} is the maximum amplitude of a peak generated by an impact of a particle on the tip as

576   defined in equation 7 and the angular frequency, ω, corresponding to the width of the peak is

577   defined as in equation 16 below.

578    $$\omega = \frac{\pi}{t_{pk}}$$ (16)

579   Once the force on the tip, $F_{max,}$ has been calculated the acceleration of the tip can be

580   calculated using an iterative approach as illustrated in the following equations.

581    $$a_t = \frac{1}{m_{tip}}\left(F_{t-\delta t} - \beta v_{t-\delta t} - x_{t-\delta t} k_{eff}\right)$$ (17)

582   where

583    $$v_t = v_{t-\delta t} + a_{t-\delta t}\delta t$$

584    $$z_t = z_{t-\delta t} + v_{t-\delta t}\delta t$$

585   At the beginning of each time step the force acting on the tip is calculated,

586 $$F_i = F_{max} \sin\left(\pi \frac{t_{i-1} - t_c}{\Delta t_{pk}}\right) \qquad t_i - t_c < \Delta t_{pk} \tag{18}$$

587 where t_c is the time at which the particle first makes contact with the penetrometer tip. The start of

588 an impact occurs when the distance between the centre of the particle and the centre of the tip base

589 is equal to the tip radius plus the radius of the hemisphere. At this point $t_c = 0$ and equation 18 can

590 be used to calculate the force. If there are two or more impacts at the same time then the force on

591 the tip generated by the two particles is summed as in equation 19.

592 $$F_i = \sum_{j=1}^{j=n} F_j \sin\left(\pi \frac{t_{i-1} - t_j}{\Delta t_j}\right) \tag{19}$$

593 where n is the number of particles in contact with the tip. To model the particle-particle impacts

594 using equation 11 the number of particles in the target is multiplied by n_i. The radius of the particles

595 remains the same causing the surface of the particles to overlap each other. However this is not an

596 important limitation as we are primarily interested in the response of the penetrometer tip.

597   Figure 9 shows the force from particle-tip impacts and the force on the sensor due to the

598 displacement of the tip by the impact. Impacts that occur close together in time tend to create large

599 peaks as each successive impact provides extra impulses to the tip and pushes it further onto the

600 sensor. Information regarding the number of particles impacting the tip is then lost as it is

601 impossible to distinguish between individual peaks in the data from the sensor.

602   FIGURE 9

603

604 **4.1 A sensitivity study**

605   To asses the most important properties of the penetrometer and target for penetrometer design

606 we conduct a sensitivity study by varying the model parameters and comparing the simulated

607 penetrometer data. The number of and shape of the peaks in data depend on the penetrometer and

608 target properties as discussed in the previous section. These properties are listed together in table 1.

609 An important component of the penetrometer is the tip as its properties control the response of the

610 sensor to an impact. To investigate the influence of the tip the following properties of the tip can be

611 varied in the model: radius, density, elasticity of the surface. The tip-sensor assembly response to

612 the impact is also important and has two parameters that can be varied: elasticity of the washers and

613 the damping coefficient of the assembly. The performance of the data logging system (i.e. ADC)

614 will influence the data and in the model the bit height, sampling frequency and the number of bit-

615 flip peaks (noise) can be varied. The parameters of the target are particle radius and density, the

616 porosity of the target (which sets up the number and location of the particles in the model) and the

617 number of particle-particle impacts that are detected by the penetrometer.

618 TABLE 1

619 The data can be characterised and analysed using a variety of metrics that are diagnostic of

620 the penetrometer and the target. Two metrics that will be used here have already been discussed at

621 the end of section 2.1. These are the average peak height magnitude and peak frequency which give

622 information on the particle mass and particle size. Other useful metrics considered are the average

623 peak width, the summed magnitude of all the peaks and the summed width of all the peaks. The

624 average peak width is diagnostic of the penetrometer properties such as the elasticity of the tip-

625 sensor assembly and the mass of the tip. The total summed magnitude of all the peaks will be

626 correlated to the mass of the impacting particles. It differs from the average peak magnitude in that

627 it will be less sensitive to smaller peaks that may be due to electronic noise, and therefore more

628 representative of the particle properties in the target. It is also independent of knowing the number

629 of peaks in the data.

630 The results of the sensitivity study are summarised in table 2 as percentage changes in the

631 metrics for a given change in a penetrometer or target parameter. Increasing percentage changes in

632 the metrics are represented by increasing levels of shading. Two percentage changes are given in

633 the columns for each data metric. This is to reflect the decreasing or increasing influence a

634   penetrometer or target parameter may have on the metric with changing particle size or mass. The

635   metrics are calculated by first calculating the percentage change of a metric for each particle size for

636   a given percentage change in a penetrometer of target property. Then for the smaller particles (2, 3,

637   4, 5 mm radii) the average percentage change of the metric is calculated. Likewise the average

638   particle percentage change is then calculated for the larger particles (5, 6, 7, 8 mm radii). The range

639   of percentages that correspond to increasing darker shades are 0-1 % (no shading), 2-10 %, 10-50

640   %, 50-100 % and >100 % (black). The upper and lower rows for each data metric correspond to a

641   higher of lower change in the model parameter relative to a standard model set up as listed in table

642   2 except for the sampling frequency column where 50 kHz was used as the standard to compare

643   with.

644   TABLE 2

645   The data metrics are sensitive to model parameters in a variety of ways. Changing the

646   penetrometer velocity has a noticeable effect on all the parameters. This can be attributed to the

647   increased forces on the tip for higher impact speeds. Changing the elasticity of the Vespel washers

648   has a noticeable effect on the peak frequency for smaller particles (i.e. in table 2 the first column,

649   for elasticity is darker than the second column). This is because the peaks generated by the smaller

650   particles are under the resolution of the ADC so increasing the elasticity allows particle impacts,

651   previously unseen in the data, to be logged and detected. Changing the elasticity had a large effect

652   on the other metrics as increasing the elasticity makes the tip-sensor assembly more sensitive to

653   impacts creating larger peaks in the data which in turn creates peaks that are greated in height and

654   width.

655   Increasing the bit resolution increases the peak frequency for the smaller particle impacts as

656   more peaks can then be resolved. The other metrics increase in value also because of the addition

657   into the data of peaks from the smaller particles although this does not have very much effect on the

658   summed magnitude because of their small heights. Decreasing the sampling frequency has a

659 detrimental effect on the detection rate of the smaller particles because the width of the smaller

660 peaks are smaller than the time interval between samples. Increasing or decreasing the number of

661 noise peaks has a large influence on the peak frequency as one would expect. However for larger

662 particles the effect is larger because more noise particles could be 'seen' in the data because there is

663 room between the infrequent impacts for them to be detected. With the smaller particles, the high

664 frequency of impacts tends to absorb the small one-bit high noise peaks. The summed peak

665 magnitude was less sensitive on the number of noise peaks because these small peaks are not a

666 significantly contribution to the calculation of this metric.

667   Changing the number of particle-particle impacts felt by the penetrometer tip (i.e. a force

668 applied to the surface of the tip) effects all the metrics significantly. The peak frequency is less

669 effected by particle-particle impacts for small particles than for larger particles. This is due to the

670 insensitivity of the penetrometer to detecting impacts from small particles and the piling up effect of

671 high frequency impacts on the tip as seen in figure 9. The summed magnitudes is especially

672 sensitive to particle-particle impacts for large particles because the penetrometer is able to resolve

673 each impact which contributes to the result.

674   Results for selected combinations of penetrometer-target parameters and data metrics are

675 shown in figure 10 in detail. The data metrics shown are the peak frequency and summed peak

676 magnitudes as these are deemed to be the most useful. The peak frequency was chosen because it

677 relates to the size of the particles. The summed peak magnitudes was chosen as it relates to the mass

678 of the particles and is particularly insensitive to electronic noise. The penetrometer and target

679 parameters shown in figure 14 were chosen (friction, bit-flip noise and particle-particle impacts) as

680 these have the largest effects on the data metrics and are most likely to be unknowns when making

681 remote measurements.

682   FIGURE 10

683

684

685

4.2 Comparing penetrometry data

A direct and rationalised way to compare the output from the different models is to compare the distribution of peak magnitudes in the data. It would also help to further understand the intricacies of the penetrometer data. The peak magnitudes can be binned and plotted as a column chart in a similar way as when comparing the distribution of particle sizes in a granular material. Here, instead of using increments of the spatial dimension for the boundary of the bins, the bin sizes are in increments of the voltage where the bin size is fixed to the bit resolution of the ADC (0.02 V).

Figure 11a compares a model with and without bit-flip noise. The model without noise is a basic model with only the impact force of particles directly impacting the tip used to calculate the force on the sensor. The secondary particle-particle impact force calculations are not included. The noise is then added on top of the voltages produced by the simulated force sensor. It can be seen there are more small magnitude peaks resulting from the bit noise of 0.02V. There are also more peaks with a magnitude of 0.04 V which is twice the magnitude of the bit noise. This is because the small peaks with magnitude 0.02 V, produced by impacts, have now increased with the addition of the noise. Some of the noise peaks are lost when they are located on the wall of larger peaks.

Figure 11b compares a model with a high damping coefficient (500) with a model that has a low damping coefficient (100). These damping coefficient values are both lower than used in figure 14 which used a value of 1000. The model with a high damping coefficient brings the tip quickly to rest after being displaced by an impact. The model with a low damping coefficient oscillates around the equilibrium position several times before coming to rest. The model with the low damping coefficient produces more large magnitude peaks because the tip can more easily be displaced by an impact. Increasing the damping coefficient increases the relative number of low-voltage peaks.

709   Figure 11c compares models with secondary particle-particle impacts of different intensities,

710   one with large magnitude secondary peaks and one with small magnitude secondary peaks. There is

711   no obvious difference between the two models, in their distribution of peak magnitudes, except for

712   a small excess of larger peaks in the model with larger secondary peaks. The distribution of peak

713   magnitudes is similar to that produced by the model with low damping coefficient (β=500) which

714   may be expected as a model with a low damping coefficient will produce secondary peaks in the

715   data due to oscillations of the tip following a direct impact. For a very low damping coefficient

716   (β=100) the similarity disappears because the tip will be making numerous large oscillations, after a

717   direct impact.

718   FIGURE 11

719

720   **5. Experiment set-up**

721   This section describes a series of drop tests using a laboratory version of the ACC-E

722   penetrometer that was flown to Titan bolted to the underside of the Huygens probe (Lorenz et al.,

723   1994). The Huygens penetrometer was successfully used to constrain surface mechanical properties

724   of the surface as the probe impacted the surface (Zarnecki et al., 2005). Here we perform similar

725   measurements into a variety of asteroid regolith analogues. Seven different types of materials were

726   used including gravel, pebble, cobble and sili-beads.

727   A variety of natural and man-made targets were chosen to represent asteroid regoliths.

728   Monodisperse 2 mm radius sili-beads (man-made) were chosen because the particle size distribution

729   is very tightly constrained; essentially all particles are the same size, and they are nearly perfect

730   spheres. Their behaviour is much simpler than naturally produced gravel, pebble and cobble which

731   contain irregular particles and a wide size distribution of particles. Sili-beads, 0.5 mm in radius,

732   were chosen as they were close to the resolution limit of the penetrometer.

733   The gravel, pebble and cobbles are unconsolidated materials formed by the weathering and

734   erosion of rocks on Earth. The size distribution of the particles will be modified by processes such

735   as size sorting in fluvial beds. On asteroids the erosion process is expected to be dominated by

736   impacts. The distribution process will then be controlled by the gravity with the least massive

737   particles ejected with the highest velocities and escaping (Housen and Wilkening, 1982). Seismic

738   shaking events, due to impacts or tidal disruption, are expected to sort the regolith materials

739   according to their density and size (Miyamoto et al., 2007). The shape of the particles on an asteroid

740   will have sharper edges compared to those in our samples as particle in terrestrial material is more

741   rounded from weathering processes.

742   Gravel and pebble materials were chosen with around the same average particle size as the 2

743   mm radius sili-beads, to check that the average properties of naturally-produced materials can be

744   measured in the same way using a penetrometer. Two cobble materials, with high mass particles

745   (4.5 mm and 2.5 mm average radii), were chosen to investigate the effect of tip oscillations on the

746   measurements. A cobble material with a particle radius of 3.4 mm was chosen as an intermediate

747   material. All the materials had a high silicate composition, a ubiquitous asteroid material. These

748   terrestrial materials will have a similar strength to those found on an asteroid.

749   To characterise gravel, pebble and cobbles the three axes of 100 particles from each material

750   were measured using a Vernier Calliper. From these measurements mean particle radius and mean

751   particle sphericity for each material was calculated. The sphericity could then be calculated using

752     $\Psi = \sqrt{\dfrac{S^2}{LI}}$ (20)

753   where S, I and L are the lengths of the short, intermediate and long axes.

754   TABLE 2

755   ACC-E was attached to the underside of a small base plate (5 cm radius), as shown in figure

756   16, and a large weight was placed on the topside. The total weight of the apparatus was 1.5 kg.

757   ACC-E was dropped from a height of 0.8 m and allowed to free-fall. The added weight ensured a

758   constant velocity during penetration and the base plate stopped penetration after a known distance.

759   The impact speed was calculated using the equation, $v = \sqrt{2gz}$ where g is gravitational acceleration

760   and z is the drop height. The air drag on the apparatus was calculated to be only about 0.3 N just

761   before impact. This was small when compared to a constant gravitational force of 15 N and so was

762   not included in the calculation of the impact velocity. The calculated impact speed was 5 m s^{-1}.

763   A spacecraft landing on an asteroid a few kilometres in radius is likely to impact at this speed

764   if allowed to freefall onto its surface from a high altitude. The impact speed climbs to about 100 m

765   s^{-1} when the asteroid radius is about 100 km. A lower impact speed is most likely as the most

766   numerous and easily accessible asteroids are in the near-Earth population and are relatively small.

767   The mechanism for dropping ACC-E was a hand release system. A cable tie was attached to the

768   base plate at the centre, as shown in figure 16, so it could be held between the forefinger and thumb

769   of the experimenter. This ensured ACC-E aligned its long axis with the local gravitational field

770   prior to release and so entered the target with zero angle of attack. The data was recorded on an

771   oscilloscope at a sampling rate of 100 kHz. It was triggered to record by the first peak signal

772   generated by ACC-E as it made contact with the target.

773   FIGURE 12

774   A computer program was used to count the peaks and measure their height. Figure 18 shows

775   how the peaks were counted in the ACC-E data. The points in the data were examined sequentially

776   in the direction of increasing time. If both sides of the data point under question had neighbouring

777   points lower than itself then it was counted as a peak. Sometimes a lower point was found to the left

778   but when searching to the right; a data point of the same value was sometimes encountered, forming

779   a plateau region. If this happened the program stepped along to the right until it located a data point

780   with either a higher or lower value than the plateau region. If the point was of a higher value then

781   the program ignored the plateau region and carried on searching. If the point was of a lower value

782   then the plateau was counted as a peak. Each peak was then added to a counter and the peak height

783 was stored in an array. To calculate peak height the value of the preceding trough was subtracted

784 from the value of the peak. Data generated from the first 5 cm of penetration, where ACC-E was

785 travelling at an almost constant speed through the material, minimised any speed-dependent effects

786 on the results. Five drops were made into each target to obtain good statistics on the peak frequency

787 and magnitude.

788

789 **6. Results and discussion**

790   Figure 13 show samples of output from the ACC-E penetrometer for drops into each material

791 (except 0.5 mm radius sili-beads which is essentially made up of bit noise). The signal has been

792 converted into Newtons using equation 20. There are several noticable trends in the figures that

793 appear be related to the target properties. Firstly the number of peaks in the data are less for targets

794 with larger particles. For a given volume excavated by the penetrometer the number of particles

795 excavated will decrease as the particle size increases. Assuming that each particle makes a single

796 impact on the tip and each impact produces a peak in the data then the number of peaks would be

797 less for targets with larger particles. Another noticable trend is the targets with the larger, more

798 massive particles, exhibit peaks with larger magnitude. This may be expected as the momentum

799 transfered to the tip will be higher for more massive particles.

800   FIGURE 13

801   Another noticable feature of the data in figure 13 is the peaks seem to ride upon a background

802 force that reaches different heights for each target. Figure 14 shows this background force more

803 clearly. Sili-beads, which are very close to spherical in shape, have a large ratio of peak to trough

804 magnitudes compared to other targets containing similar sized particles. This may be due to

805 shearing forces generated in the target when particles are forced to slide past each other. The 2.2

806 mm radius granular target, for example has higher background force, is of similar size to the sili-

807 beads, but more irregular in shape and so will be more difficult to penetrate as the particles will lock

808   together. It is also interesting to note the average peak magnitude, in both cases, is approximately

809   the same suggesting their magnitude is controlled by the mass of the particles. The gravel targets

810   with large particles, that are comparable in size to the tip, also produce large peak to trough

811   magnitudes. In this case the average background force is low probably because there are very few

812   particles in contact with the surface of the tip at any one time. However for the target with the

813   largest particles the background forces are high which is perhaps due to the significantly higher

814   mass of the particles as the mass increases cube of the particle radius while the size increases as the

815   square of the particle radius.

816   FIGURE 14

817   Figure 15 shows the model compared to the penetrometer output by using the binned peak

818   magnitudes method. The model parameters used are as in table 1 in section 3.1. No variation of the

819   parameters had to be made to obtain a good match between the model and penetrometer output for

820   the targets except for 4.4 mm cobble and 7.4 mm gravel. For these targets the number of particle-

821   particle impacts felt by the tip had to be set to a non-zero value. In the case of 4.4 mm the number

822   of secondary impacts was set to $n_{pp}=1$ which means for every particle-tip impact there is one

823   particle-particle impact that is felt by the tip. In the case of 7.4 mm the number of secondary

824   impacts had to be set to $n_{pp}=2$ which means for every particle-tip impact there are two particle-

825   particle impact that is felt by the tip.

826   FIGURE 15

827   Figure 16 shows number of impacts calculated from the laboratory measurements compared

828   to the number of peaks calculated from the model. Also plotted is the number of particles excavated

829   from the hole made by the penetrometer. A general downward trend in the number of impacts with

830   particle radius is observed between particle radii of 0.6 and 4 mm with a levelling of after that. For

831   large particles the number of peaks is several times larger than the number of particles excavated.

832   This is unexpected if one assumes one impact peak in the data per excavated particle. Considering

833   the adjustments made in figure 15 were required to fit the model to the measurements it may be

834   particle-particle impacts become forceful enough to be felt by the tip and so increase the number of

835   peaks in the data. For smaller particles the number of peaks is less than the number of particles

836   excavated by the penetrometer. This is due to the merging of peaks as predicted in figure 5 where

837   the the tip oscillation period is larger than the time between impacts for targets up to particle with a

838   radius of 4 mm.

839   FIGURE 16

840   There is a curious peak for 2 mm radius sili-beads in figure 16 from the measurements. This

841   could be due to the 2 mm sili-beads having a low porosity and therefore a higher density of particles

842   for a given volume. The peak frequency then rises again for smaller particles because bit-flip noise

843   is free to dominate as there are no or few peaks from impacts large enough to produce peaks that

844   can absorb the smaller bit-flip noise peaks.

845   Figure 17 shows the summed peak magnitudes plotted against particle mass (top line). There

846   is a general upward trend with increasing particle mass as one would expect as the momentum

847   transfer to the penetrometer tip is greater for larger particles. There is a significant drop for 4.4 mm

848   radii gravel (mass of ~1 gram) in the laboratory measurements which is repeated in the model. In

849   the model this drop is due to the probability of particles impacting the central, more sensitive,

850   region decreases with increasing particle size (there is less room as the particles become larger) and

851   explained in section 3.4. Secondly the electronic noise from bit-flip noise has an increased effect

852   (see figure 10), bringing down the summed peak magnitudes, as the spacing between the peaks

853   becomes larger with larger particles. This effect is kept in check as the particles become larger and

854   the spacings between peaks reduces again as impacts between particles are felt by the tip. The dip is

855   also seen in the average peak magnitude in figure 17 (bottom line).

856   FIGURE 17

857   Particles that impact the centre of the tip will, in principle, produce the largest peaks in the

858   data. By selecting only the largest peaks it then maybe possible to reduce the influence of the

859   numerous small peaks in the data generated electronic noise, secondary impacts and the ambiguity

860   of the peak magnitude due to not knowing the radial distance from the centre. Here we select the

861   top five largest peaks from drops into each material (i.e. the largest peaks from 5 drops for each

862   target) as there is a high probability that at least one particle will impact close to the centre during

863   each drop. The average magnitude of the 5 largest peaks is calculated and plotted in figure 18.

864   There is a good agreement between the model and experiment results for the smaller particles but

865   the values of the peak magnitudes for the large particles are smaller than those produced by the

866   model. This discrepancy is, as explained for figure 17, due to a smaller number of particles are

867   impacting the centre of the tip for targets as the particle size increases. The effects of the noise

868   peaks in the data is not important as we have selected the largest peaks in the data.

869   FIGURE 18

870

871   **6.1 Particle radius at the Huygens landing site**

872   The Huygens probe landed on Titan and used its ACC-E penetrometer to measure the

873   hardness of the surface (Zarnecki et al., 2005). The returned signal can be divided into four distinct

874   stages. In the first cm of penetration the force on the penetrometer is small indicating a relatively

875   weak material, perhaps a coating of aerosols that have been deposited from the atmosphere. This is

876   followed by a large peak implying an impact with something hard, perhaps one of the ice pebbles

877   seen on the surface by DISR. For the following 5 cm or so there is an irregular plateau at an

878   intermediate force that suggests penetration of a material with the strength of wet clay, lightly

879   packed snow and wet or dry sand. Following this is then a smoother force profile that rises and

880   descends which has not been analysed as this corresponds to the fordome of Huygens impacting the

881   surface, compressing the material around the penetrometer. The returned signal from the

882   penetrometer has been compared to laboratory analogues and has been constrained to a granular

883   material whose particle sizes are not coarser than sand, granules and small pebbles.

884   Attempts have been made to determine the particle diameter in the first 5 cm of

885   penetration as this is important for understanding fluvual processes on Titan. This is difficult

886   because the peak magnitudes in the Huygens data are small, close to the noise level, and the 10 kHz

887   sampling frequency restricts the depth resolution to about 1 mm. A diameter of 2 mm has been

888   derived by comparing the signal with plastic and glass beads (Atkinson et al., 2010). In other work a

889   diameter of 5 mm was found by Paton (2005) using a peak frequency method based on a model of

890   the penetrometer derived from impacts into asteroid regolith analogues.

891   Here we apply a new model to the Huygens data, building on previous work, to

892   establish a size for the particles at the landing site on Titan and to test our interpretation techniques

893   as if the data had been returned from an asteroid. Figure 19 shows our data from laboratory tests

894   with ACC-E, compared to results from the simulated penetrometer measurements in Titan regoliths

895   targets containing ice particles. A power law has been plotted from Atkinson et al. (2010), that they

896   obtained from drops of a laboratory version of ACC-E penetrometer into granular targets.

897   FIGURE 19

898   The peak magnitudes obtained from our experiment agree quite well with Atkinson et

899   al., (2010) for the smaller, lower mass, particles but for larger particles our values are higher. This is

900   probably due to the different selection criteria used in each case. We select the largest peaks with

901   the assumption that they are single particles impacting the centre of the tip. However particle-

902   particle impact forces may be transmitted to the tip at a high enough frequency that they overlay

903   and there is a superposition of forces on the tip.

904   The peak magnitudes from our experiment and Atkinson et al. (2010) are both larger

905   than the theoretical peak magnitudes calculated for impacts into a Titan regolith. This may be

906   explained by considering the difference in size of ice particles and asteroid analogue particles for a

907   given mass, i.e. it can then be expected that a penetrometer impacting a target of smaller, high

908   density, rock particles will experience a higher frequency of impacts than a penetrometer impacting

909   a target of larger, low density, ice particles. The superposition of the higher frequency impacts will

910   create larger peaks in the data than one would expect from a single impact. Therefore it may be

911   expected that a penetrometer impacting into larger ice particles will generate smaller peaks, on

912   average, because there is less of a tendancy of impacts to be superimposed on the tip.

913   Atkinson et al. (2010) make impacts into targets of plastic and glass beads over a

914   range of masses. A power law is fitted to the peak magnitude values generated by both materials.

915   Low density plastic beads, with a mass of about 0.04 g, generate peak magnitudes that are smaller

916   in magnitude than those predicted by the power law. The power law fits the results for the high

917   density glass beads around 0.04 g quite nicely. This dependance of peak magnitude on particle

918   density would then be expected considering the discussion in the previous paragraph. For a higher

919   mass particle (about 0.3 g) the plastic bead target generates peaks that are larger than from a glass

920   bead target of around the same mass. This result is unexpected and may possibly be due to the

921   selection criteria applied (the plastic target may generate more candidate peaks that are on average

922   larger than those found in the glass bead target).

923   A further, more comprehensive, analysis can be made by comparing the distribution of

924   peak magnitudes from out numerical model and the measurements from Titan obtained by the

925   Huygens probe. The model was initialised with an impact velocity is 4.6 m s^{-1} and the particles

926   were assumed to be made of solid ice with a density of 930 kg m^{-1}. The other parameters of the

927   model were kept the same as in table 2. The number of 1-bit peaks due to the noise and the

928   coefficient of friction are treated as free parameters. The number of noise peaks used are 0, 5 and 10

929   per 10 ms. The coefficient of friction is varied from 0 to 0.4. The peak magnitudes are measured

930   and binned as first described in section 3. The binned data is then compared to the actual binned

931　data from the Huygens measurements using a chi-squared goodness of fit factor. The results are

932　shown for simulations in targets with radii of 2, 3, 4 and 5 mm below in figure 20.

933　FIGURE 20

934　　　　A best fit value is found for a 3 mm radius particle model with a coefficient of friction

935　of 0.3 and 0.4. The fit is also good for the 4 mm radius particle models with a coefficient of friction

936　of 0 and 0.3 although the fit using a coefficient of friction of zero is probably unrealistic. Our results

937　in asteroid regolith material, suggest that the pebbles around 4 mm in radius (1 gram in mass) will

938　generate particle-particle impacts that are felt by the tip. This is equivalent to an ice particle with a

939　radius of 6 mm. Therefore it is unlikely that the ice particle sizes considered here will produce high

940　enough particle-particle impact forces to be registered by the penetrometer. Figure 21 shows the

941　best fit of the model (using ice particles with a radius of 4 mm) to the Huygens measurements in

942　binned and profile form (voltage against time).

943　FIGURE 21

944　　　　The particles could be even larger if one considers the particles are mostly striking the

945　sides of the tip because the sample size is small. Another aspect of the Huygens data that could

946　support large particles in the Titan regolith is the downward trend. This is hinted at in figure 18 for

947　targets with 2.2 mm radius particles. Also there is a dip in the Huygens data. In figure 18 the plot

948　for particles with an average radius of 7.4 mm has distinctive dips that are comparable in size of the

949　particles. This could be due the frictional forces generated by particles pass the over the tip are

950　briefly reduced. The dip in the ACC-E data, in figure 25, corresponds to about 10 mm which may

951　be diagnostic of the diameter of the ice particles near the surface at the Huygens landing site.

952

953　**7. Conclusions**

954　　Aspects of penetrometer design, for use on an asteroid, were investigated using a combination

955　of experiment and modelling. Hertz contact law was used to model the impact force between the

956   particles and the surface of the tip. Damped harmonic motion was applied to the tip to model the

957   force experienced by the force sensor mounted behind the tip. The model reproduced the magnitude

958   and width of peaks measured in the data when assuming they were due solely to momentum transfer

959   between the particles and the tip.

960   Laboratory tests were made in a number of asteroid regolith analogues using a copy of

961   the Huygens ACC-E penetrometer. An investigation was made to determine the average particle

962   radius by counting the number of peaks in the data. The accuracy of the penetrometer between

963   particle radii of 2 mm and 4 mm was +/- 0.5mm. Measurement of particle mass was also

964   investigated and between the range of 0.1 and 0.9 grams the accuracy was +/- 0.2 grams.

965   To improve the capability of the penetrometer to measure particle size and mass a

966   number of key design recommendations are as follows.

967   1. A tip oscillation period less than the shortest contact time during impact.

968   2. A conical tip to increase the sensitivity of the tip at the sides.

969   3. A sampling rate of the order of the contact time during impact, or of the tip oscillation period.

970   The ACC-E penetrometer, as it stands is suitable, for measuring particle size and mass in an

971   asteroid regolith if the range of particle sizes has already been already constrained to between 2 and

972   4 mm in radius. However, for a regolith with small particles, i.e. less than 2 mm in radius, the

973   penetrometer needs to be modified to make it more sensitive to the lower masses it will encounter,

974   by following the aforementioned design recommendations. For larger particles the measurements

975   will complicated by the addition of secondary particle-particle impact peaks. For remote

976   measurements it is therefore best to use the metrics of peak height and frequency as a guide. Then

977   to resolve any ambiguities the model needs to be compared to the data by using the method of data

978   binning described in this paper.

979   Finally our model was applied to the Huygens measurements as a test of the method and

980   found the particles radius at the landing site are between 3 and 4 mm, larger than previously derived

40

981 in other work. It is recommended that data interpretation of data from penetrometry into granular

982 material, such as an asteroid regolith, requires a thorough and comprehensive analysis as the

983 physical processes are complicated and interdependent on each other.

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1152   **Figure captions:**

1153   Figure 1. Definition of peak metrics used in Paton (2005) and Paton and Green (2008) that are

1154   thought to be correlated to the physical properties of particles in a loose granular material such as an

1155   asteroid regolith. The peak height is obtained by subtracting the preceding trough from the

1156   following peak. The peak width is actually the half-width and is obtained by subtracting the time of

1157   the trough from the time of the following peak.

1158

1159   Figure 2. The ACC-E penetrometer used by the Huygens probe to measure the hardness of the

1160   surface of Titan. The penetrometer has the force sensor mounted behind a hemispherical tip. The

1161   force sensor is connected to flight representative flight electronics for signal processing and to an

1162   Analogue to Digital Convertor (ADC) for data logging.

1163

1164   Figure 3. Particle impact on a hemispherical tip. Notice that the angle, α, is dependant on the radial

1165   distance, *r*, from the centre of the tip.

1166

1167   Figure 4. A penetrometer model based on a spring-mass system. The force felt by the sensor due to

1168   the tip will be proportional to the elasticity and the deflection of the tip from its equilibrium

1169   position.

1170

1171   Figure 5. Comparison of contact times between particle and tip with the tip oscillation period and

1172   the average time between particle impacts. The contact time between particles with radii of 1 mm

1173   and 10 mm and the penetrometer tip are plotted for a range of tip radii. The contact time is shown to

1174   increase with increasing tip radius. The average time interval between particle impacts on the tip for

1175   particle radii of 1, 4 and 10 mm. This decreases with increasing tip radii. The oscillation of the tip is

1176   plotted with tip radius.

1177   Figure 6. The top two charts (A & B) show the predicted fraction of particle impacts on the tip that

1178   occur within a radial distance 4 mm from the centre for two types of particle arrangements. The

1179   uppermost chart is for a target made up of particles with a radius of 6 mm. The second one down is

1180   for a target made up of particles with a radius of 2 mm. The chart at the bottom shows the

1181 probability of a particle impacting within half a tip radius (4 mm) of the centre for a range of

1182 particle sizes.

1183

1184 Figure 7. The top two diagrams show a plan view diagram of the tip (left) and side view (right)

1185 showing the location of impacts on the tip during the initial stage of penetration and their

1186 subsequent direction of motions over the surface of the tip. The bottom two diagrams show the

1187 evolution of the particle-particle impacts generated during compaction of the target around the

1188 penetromater due to penetration. On the left is shown the tip entering the target. Particles on top are

1189 driven into particles below causing impacts between the particles. On the right is shown the

1190 penetrometer deeper in the material with a compaction zone surrounding it. Here the particle-

1191 partical impacts occur at the edge of the compact zone. There may also be impacts between

1192 particles in the compaction zone as they are forced out of the way by the advancing tip.

1193

1194 Figure 8. Simulated force profile due to particle impacts on the penetrometer tip. The straight solid

1195 line is a continuum due only to the overburden pressure in the target. Above that the jagged profile

1196 is the force on the tip due to particle tips added to the continuum. The particles used in the computer

1197 simulation for this illustration are 2 mm in radius and are have a density of 3 g m^{-3}.

1198

1199 Figure 9. Superposition of peaks due to multiple impacts on the penetrometer. The plot in the upper

1200 chart is the force generated during the impact of particles (right hand scale) on the tip modelled

1201 using Hertz theory. Note the middle peak is merged with a neighbouring peak. This is due to two

1202 particles impacting the tip at the same time. The signals in the upper part of the chart show the

1203 resulting voltage produced by the penetrometer due to the compression of the force sensor caused

1204 by the forces in the upper chart. Note information is lost regarding the forces due to the particle

1205 impacts on the tip. Model parameters: $\beta=1000$, $E=0.5\text{x}10^9$ N m^{-2}, $r_2=0.002$ m.

1206

1207   Figure 10. Sensitivity of peak metrics (peak frequency and summed peak magnitudes) on the

1208   variation of the model parameters. The left column shows the effect of varying the parameters on

1209   the peak frequency. The right column shows the effect of varying the model parameters on the

1210   summed peak magnitudes. The rows correspsond to the model paramters of ADC sampling

1211   frequency, bit-flip noise and particle-particle impacts.

1212

1213   Figure 11. Comparison of data from the penetrometry model. Top left shows the distribution of

1214   peak magnitudes vs. voltage from a model without simulated electronic bit flip noise (black) and

1215   from a model with electronic bit flip noise (grey). Top right shows distribution of peak magnitudes

1216   vs. voltage from models with a high and a low damping coefficient. One model has a damping

1217   coefficient of 500 (black) the other has a damping coefficient of 100 (grey). The damping

1218   coefficient of the model used to simulate the ACC-E penetrometer is 1000 (e.g. figure 15). Note

1219   that the distributions spread out with smaller damping coefficient. Bottom shows distribution of

1220   peak magnitudes vs. voltage from models with secondary particle-particle impacts included. One

1221   model has low voltage secondary impacts (black) and the other has high voltage secondary impacts

1222   (grey).

1223

1224   Figure 12. The experimental set up and release mechanism. The penetrometer is shown at the top

1225   with a hand-released mechanism using a cable tie. At the bottom is the penetrometer target

1226   contained in a bucket.

1227

1228   Figure 13. Examples of penetrometry measurements made in granular targets. The average particle

1229   radius for the figures reading from left to right and above to below are 1.8 mm, 2.0 mm, 2.2 mm,

1230   3.4 mm, 4.4 mm and 7.4 mm.

1231

1232   Figure 14. Averaged measurements in granular materials. A moving average of 100 points was

1233   applied to all the measurements. For each type of target there were 5 measurements made. These 5

1234   measurements were then averaged together for each type of target.

1235

1236   Figure 15. Comparison of binned peak magnitudes from the model and from the laboratory

1237   measurements. For targets with an average particle radius of 3.4, 4.4 mm and 7.4 mm the model

1238   was fitted to the measurements by adjusting the number of secondaty particle-particle impacts. The

1239   number of secondary impacts are shown on the relevant plots.

1240

1241   Figure 16. Model compared to laboratory measurements using the peak frequency. The error is

1242   calculated by taking the standard deviation from 5 measurements made of each target (except the

1243   0.57 mm sili-beads which had 3 measurements made).

1244

1245   Figure 17. Model compared to laboratory measurements using the sum of peak magnitudes data

1246   metric. The error is calculated by taking the standard deviation from 5 measurements into each

1247   target (except the 0.57 mm sili-beads which had 3 measurements).

1248

1249   Figure 18. Model compared to the laboratory measurements using the sum of the 5 largest peaks in

1250   each measurement or model run.

1251

1252   Figure 19. Average peak magnitudes compared from laboratory measurements and model

1253   simulations of penetrometry on Titain. The average peak magnitude is calculated by dividing the

1254   summed magnitude by the number of peaks in the data. The power law from Atkinson et al. (2010)

1255   is plotted as a dotted line.

1256

1257　Figure 20. Various permutations of the model of the Huygens penetrometer on Titan compared to

1258　the actual measurement made by the Huygens penetrometer on Titan. Two parameters of the model

1259　were varied and for each permutation of the model using a chi-squared goodness of fit test. A low

1260　value indicates a good fit between the model and measurement.

1261

1262　Figure 21. On the left is the binned peak magnitudes from the Huygens measurement and the

1263　binned peak magnitudes from the model with the lowest chi-squared value in figure 24. On the right

1264　is the signal generated by the modelled ACC-E sensor compared to the signal from the Huygens

1265　measurement. The model only reproduces the peak magnitudes and so no interpretaions regrading

1266　the slight downward trend seen can be made. The model result is plotted with an offset of 1 volt to

1267　make the illustration clearer.

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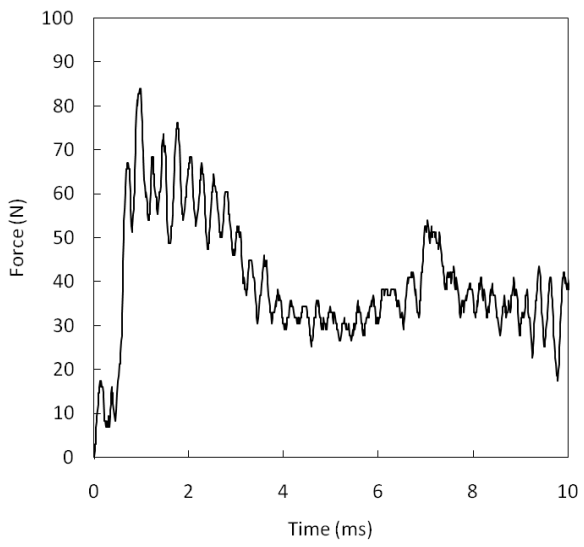**Figure 1**
Click here to download high resolution image
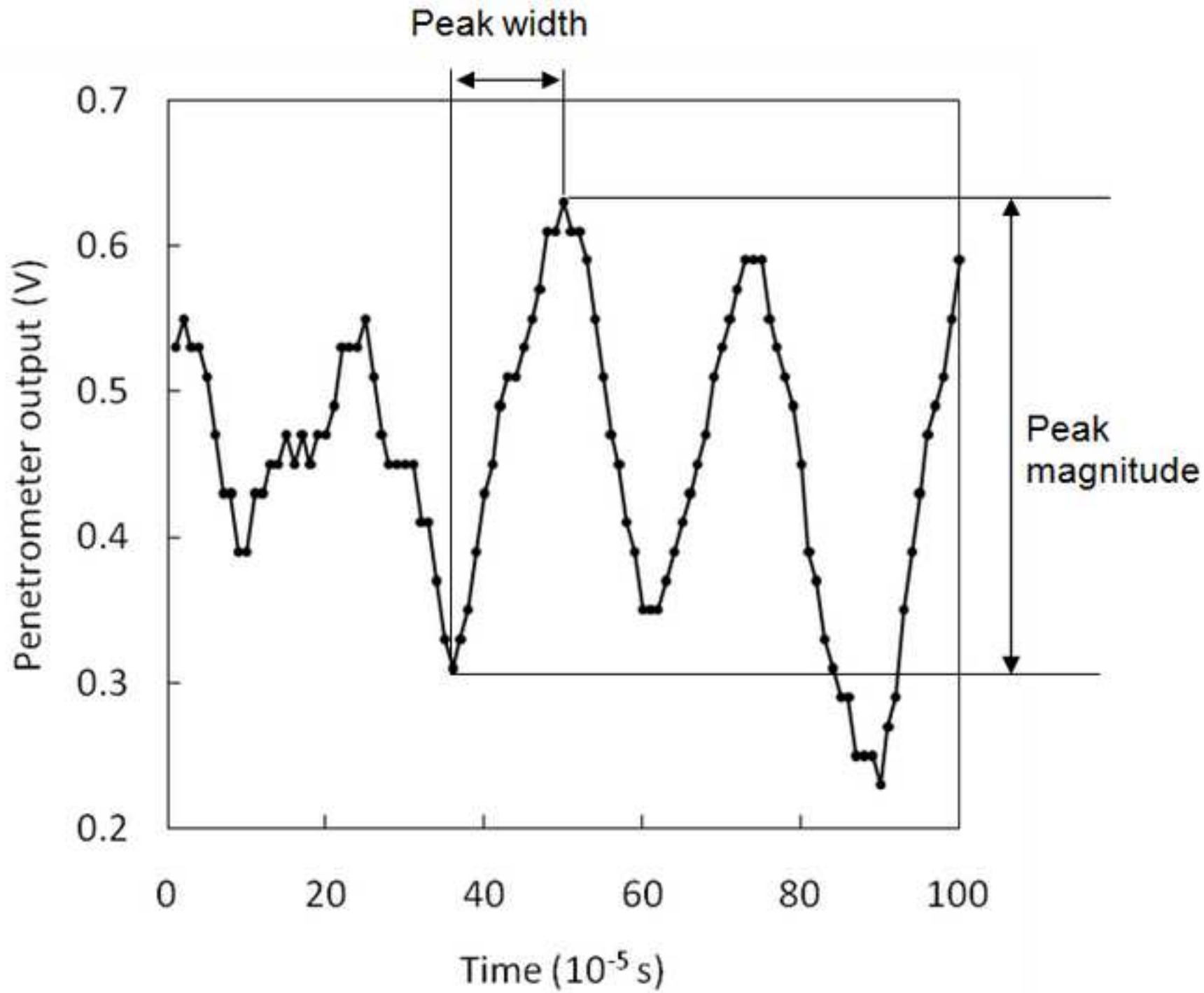
Figure 2

Figure 3

Figure 4

Spring
constant, k

Rigid
structure

Spring

Elasticity, E

Mass,
m

Mass,
m

Sensor
assembly

Tip

Impacting
particle
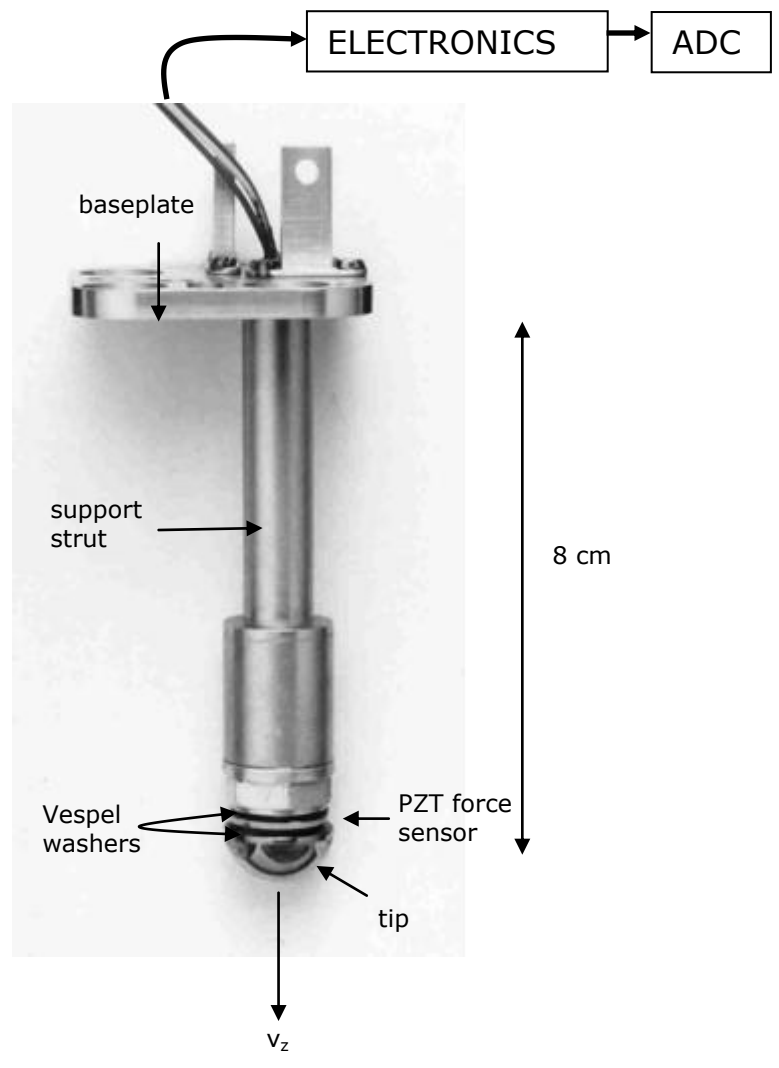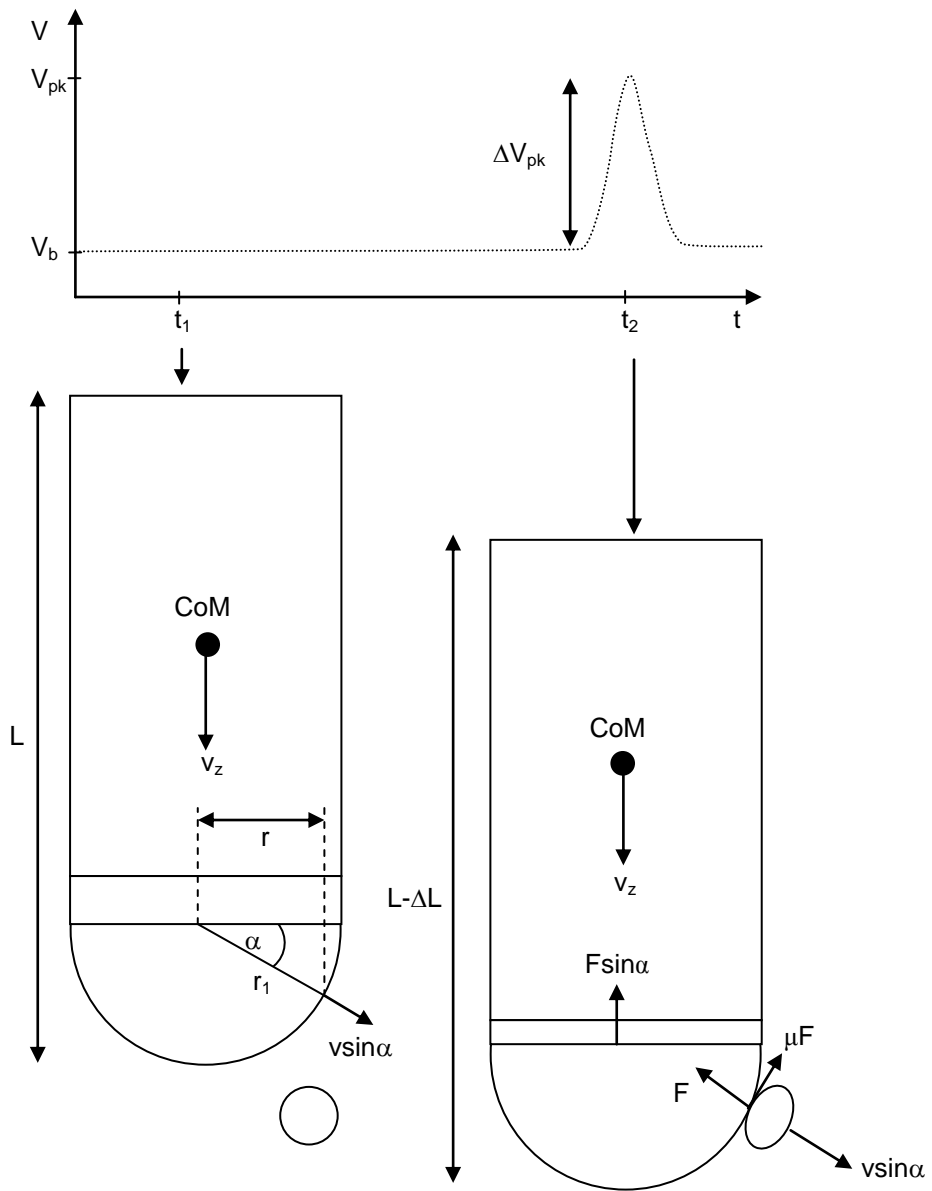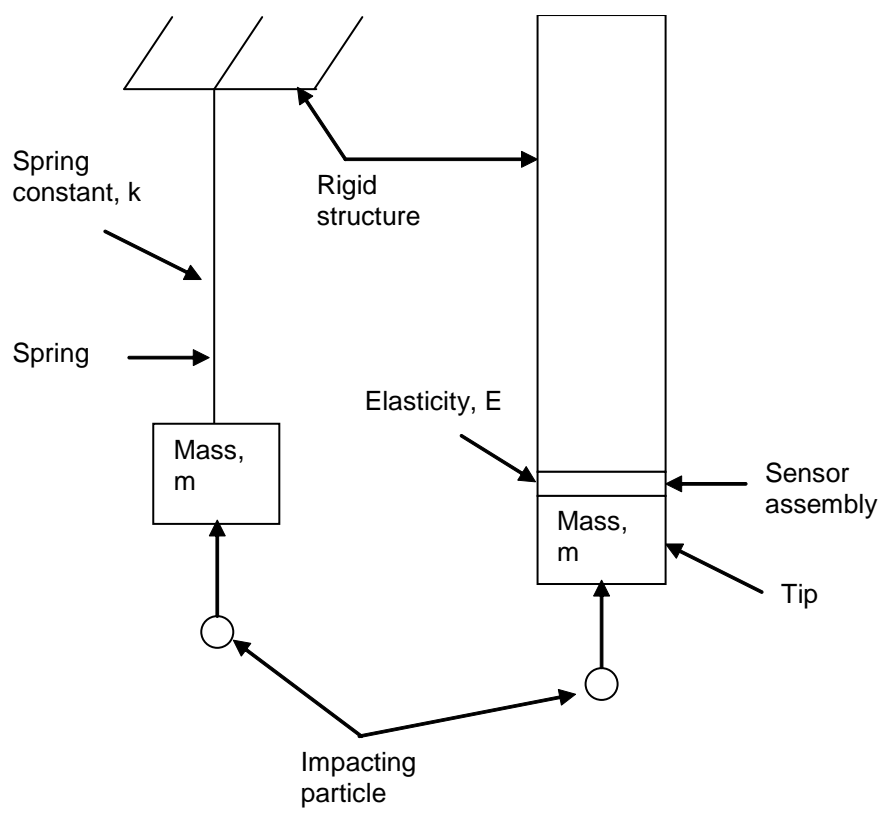
Figure 5
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Figure 6

Figure 7
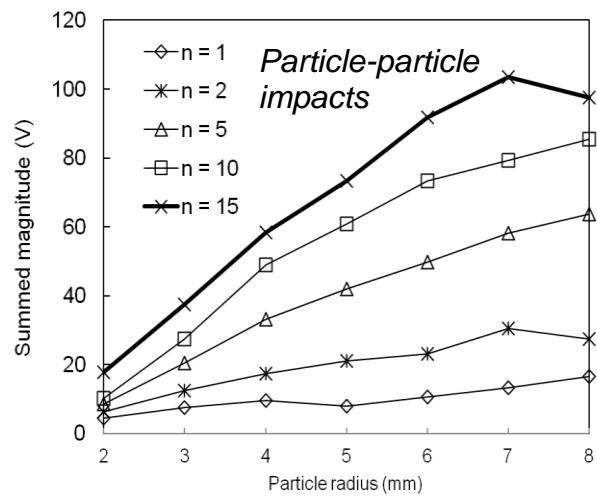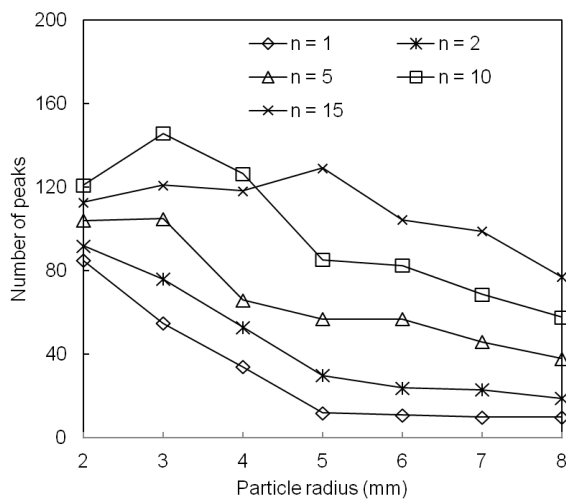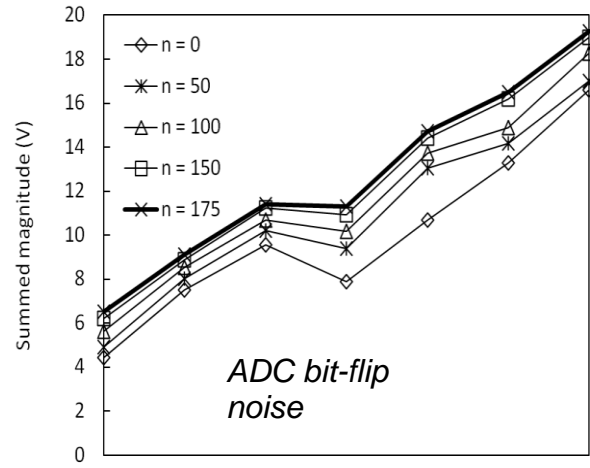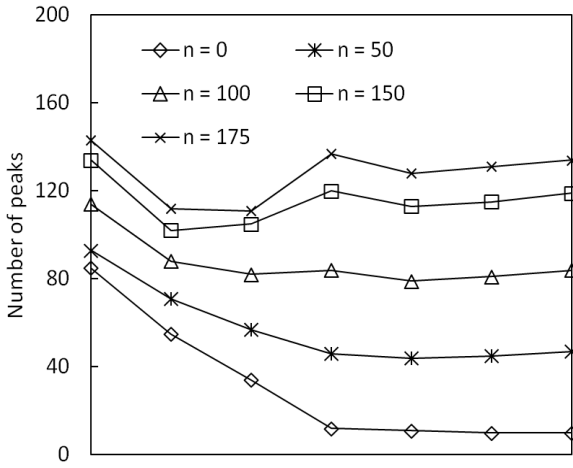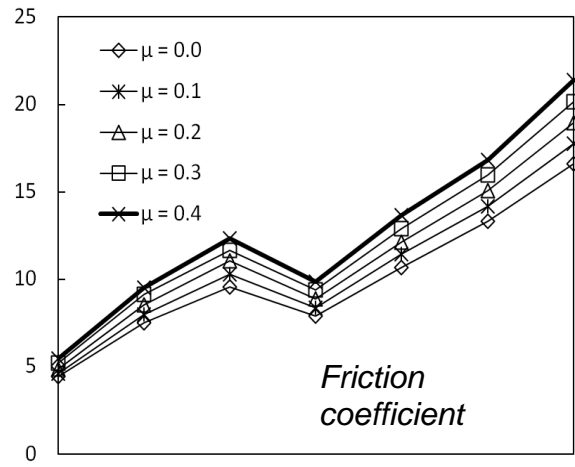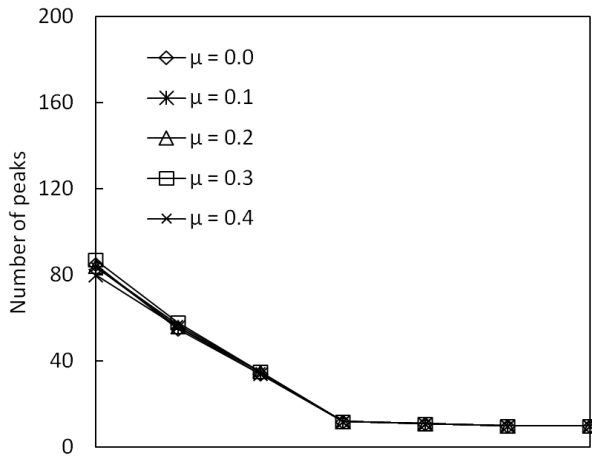
Head-on view

Side view

Tip

Direction
of motion
of tip

Surface

Start of penetration

Tip immersed in the
material

undisturbed material

movement of
particles in
compacted zone

particle-particle impacts occur
at the edge as material is
compacted and due to
difference in relative motions
inside the compacted zone

Figure 9

Figure 10

Figure 11
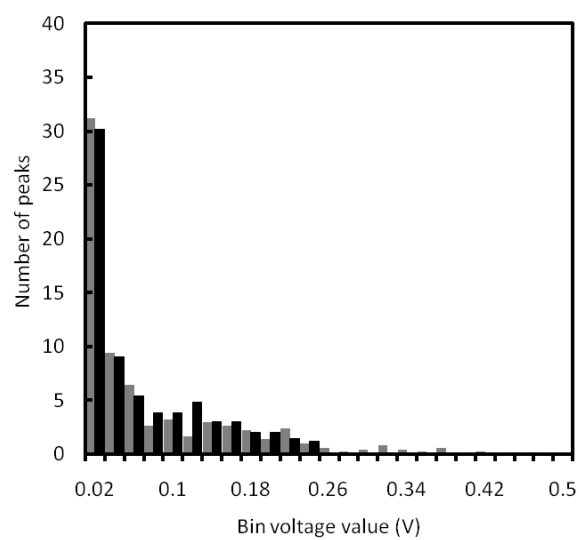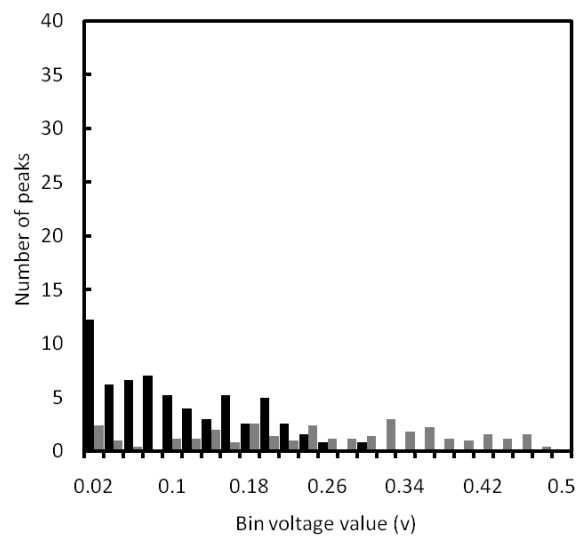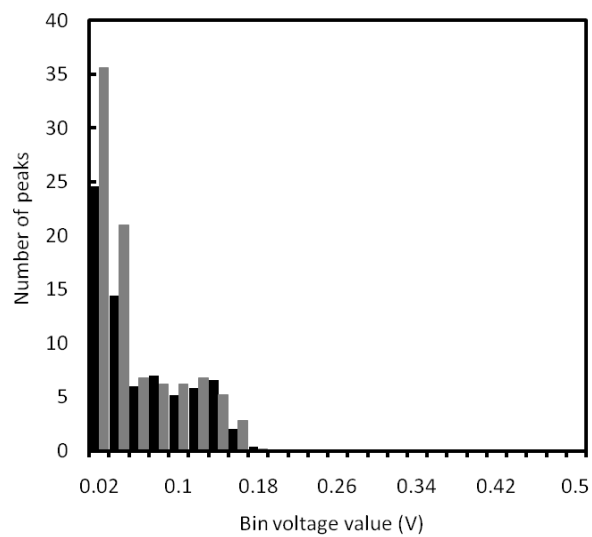
Figure 12
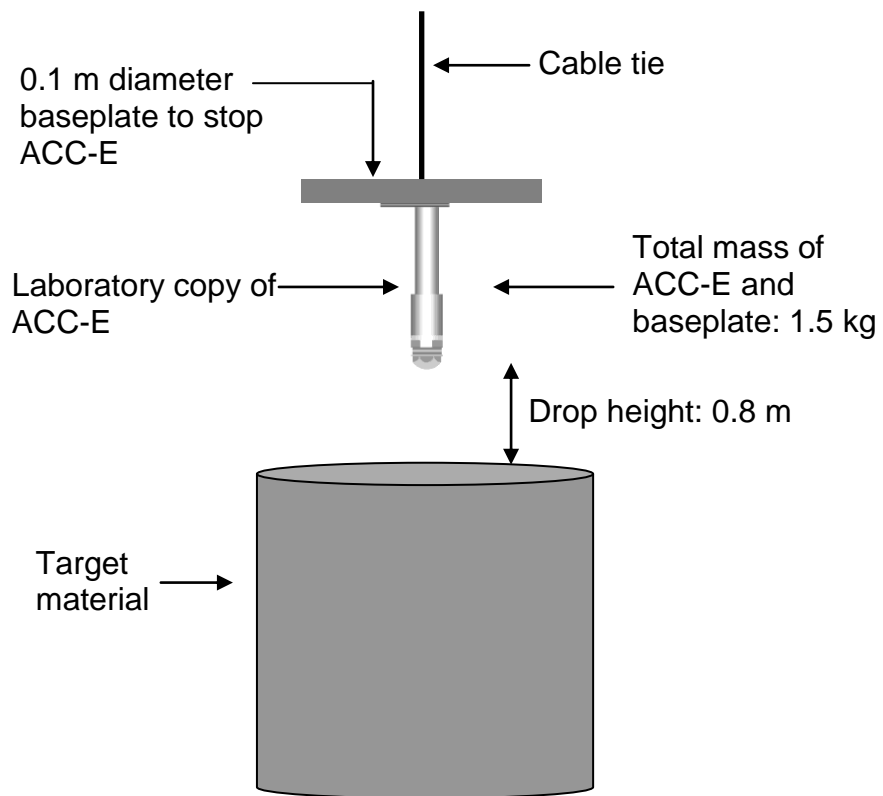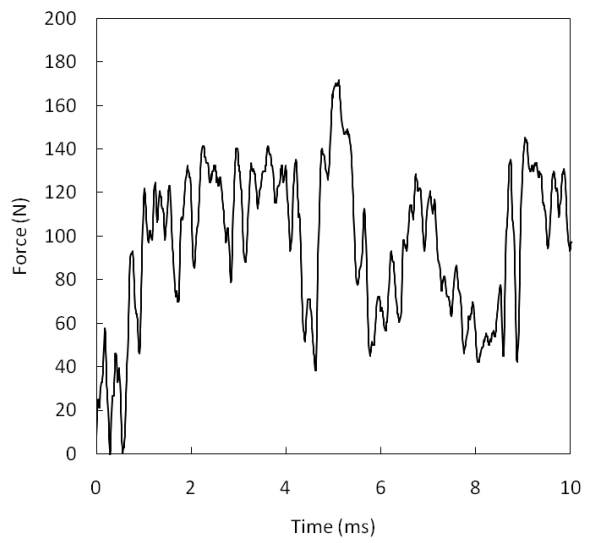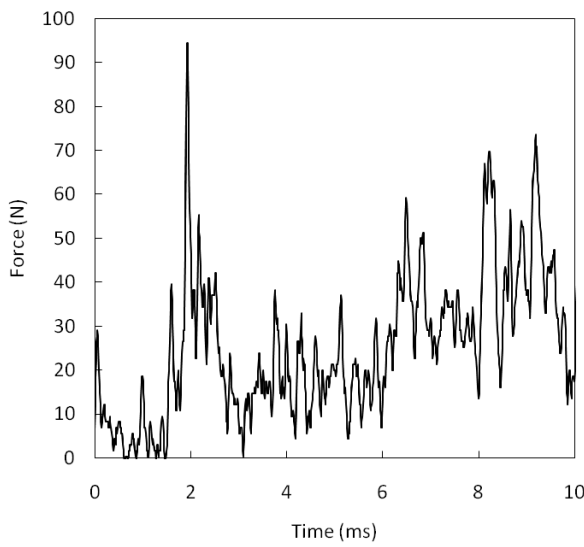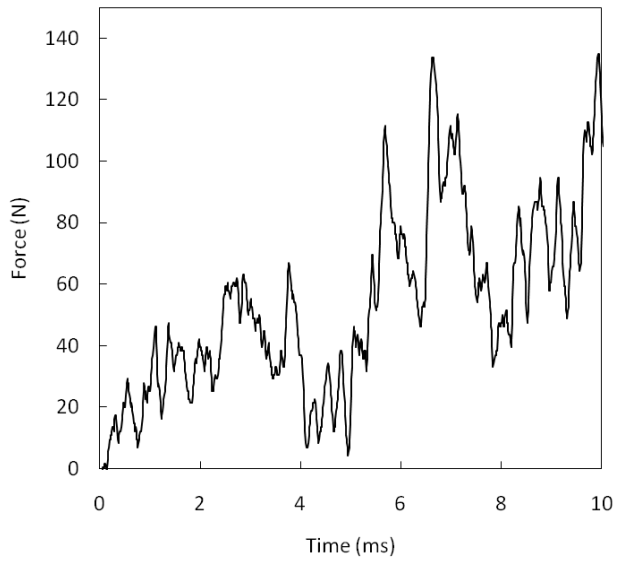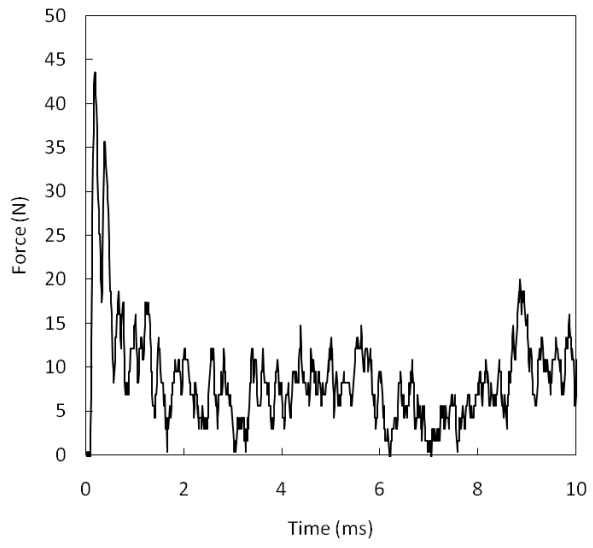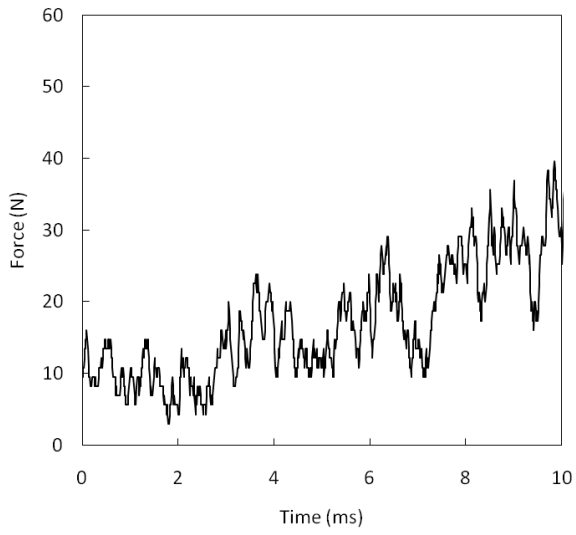
0.1 m diameter baseplate to stop ACC-E

Cable tie

Laboratory copy of ACC-E

Total mass of ACC-E and baseplate: 1.5 kg

Drop height: 0.8 m

Target material
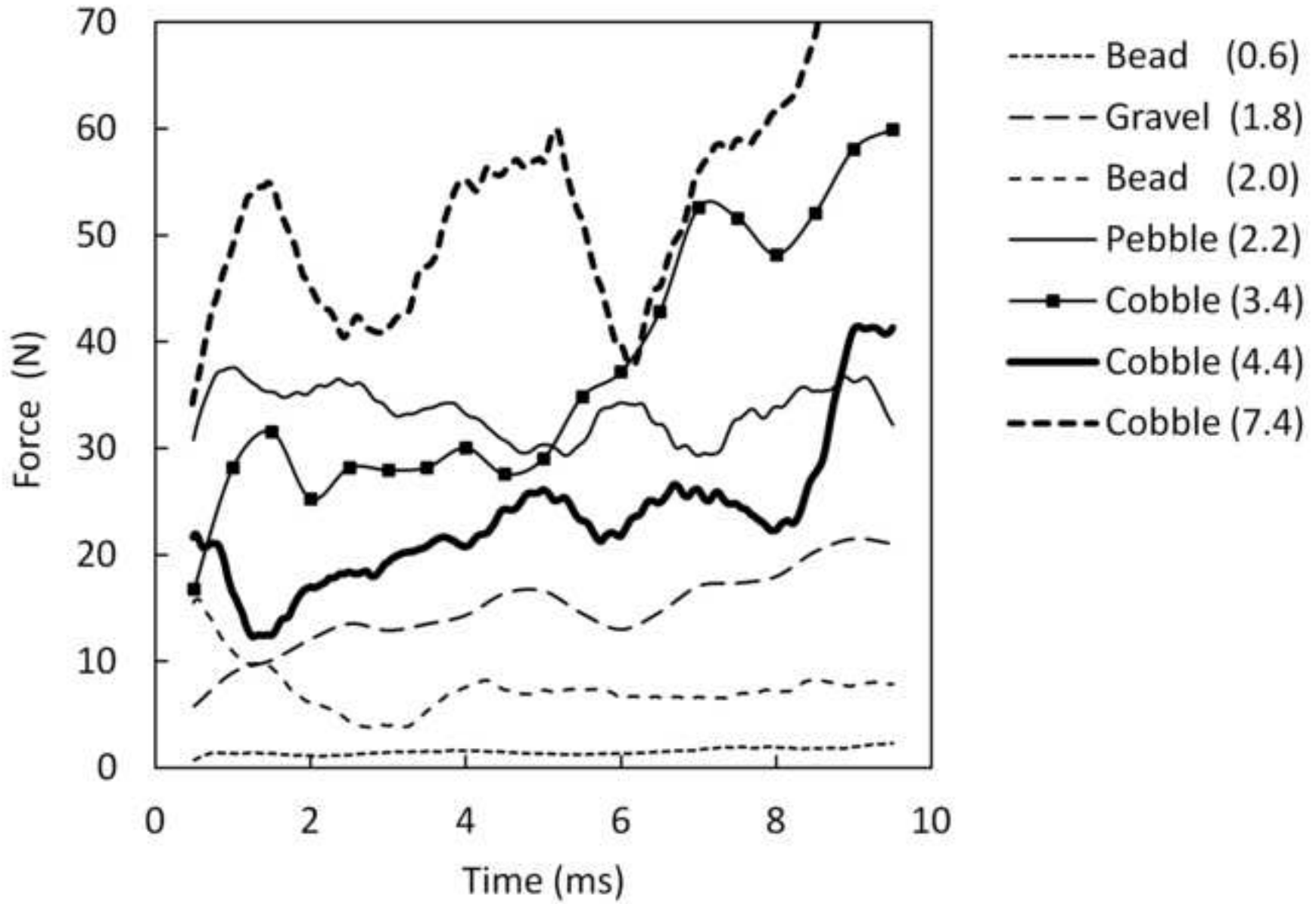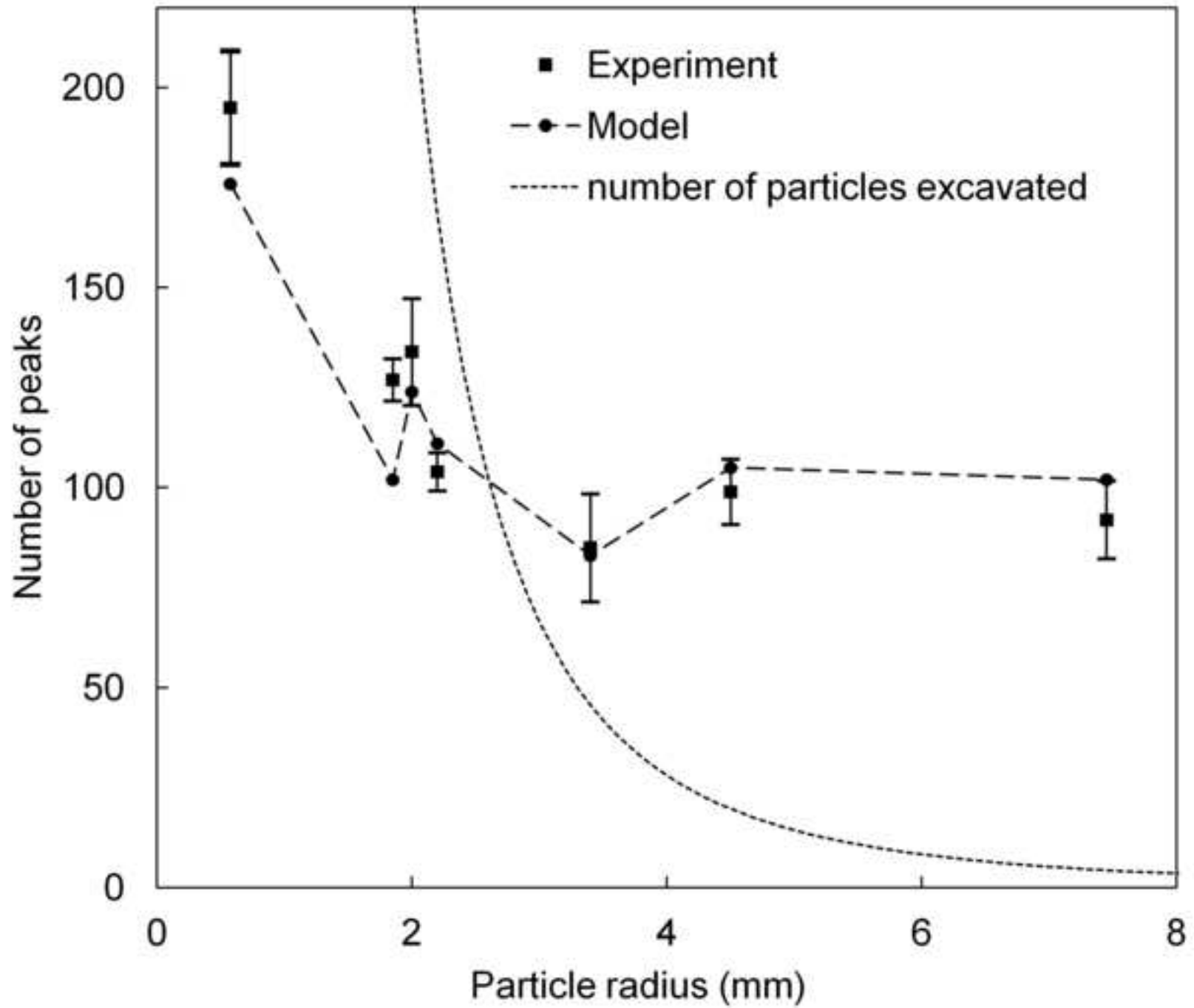
Figure 13

Figure 15

Figure 17
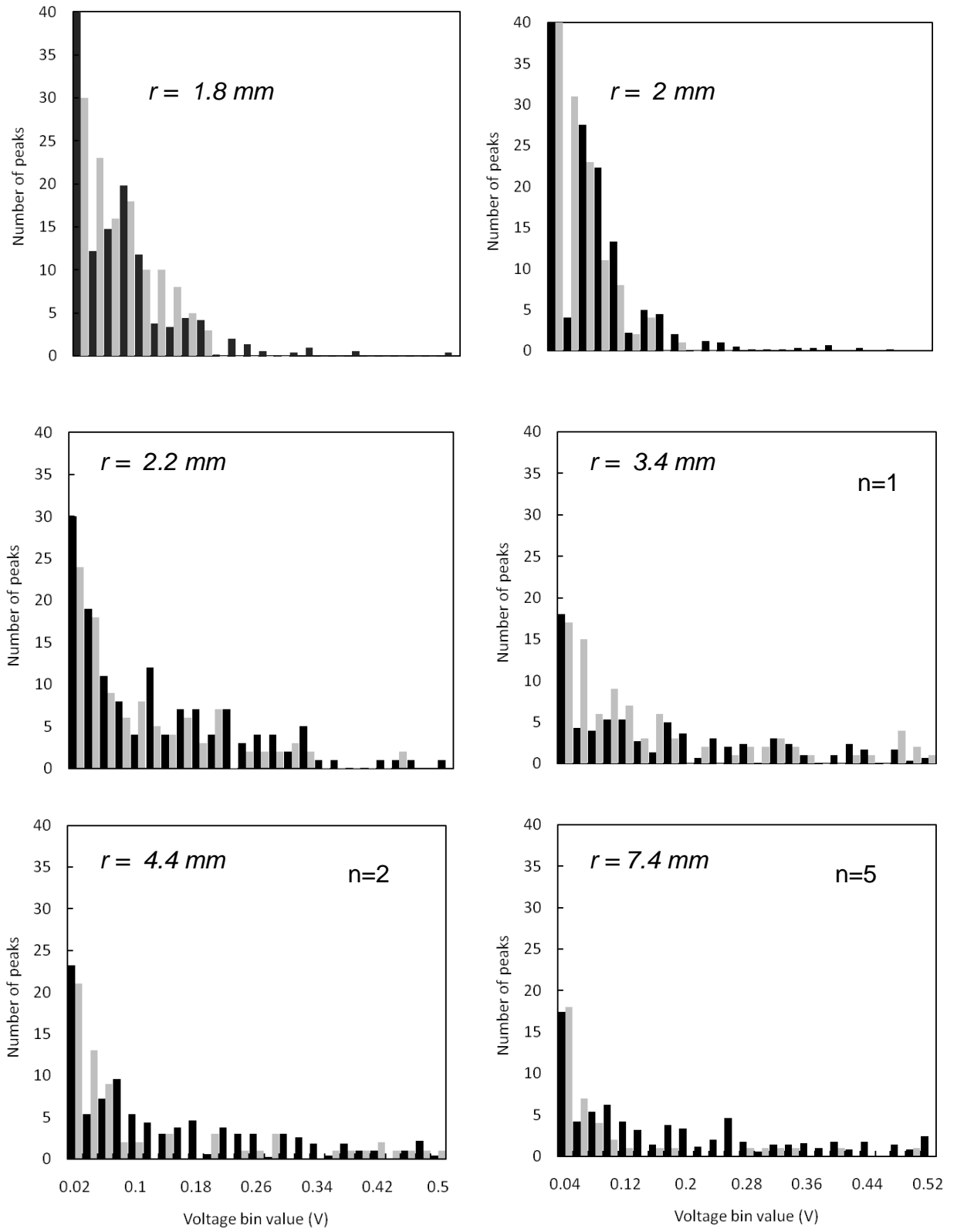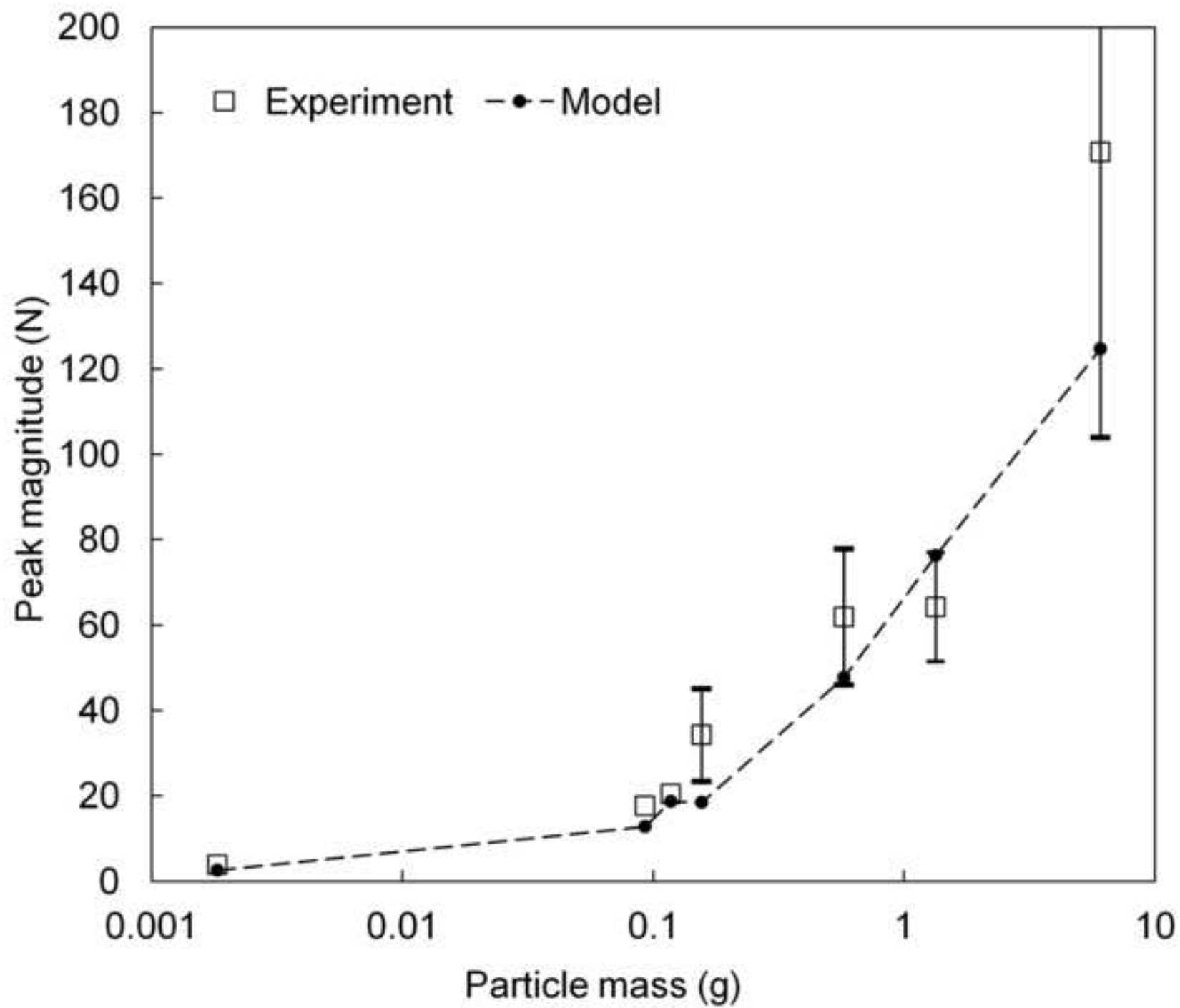[Click here to download high resolution image](#)
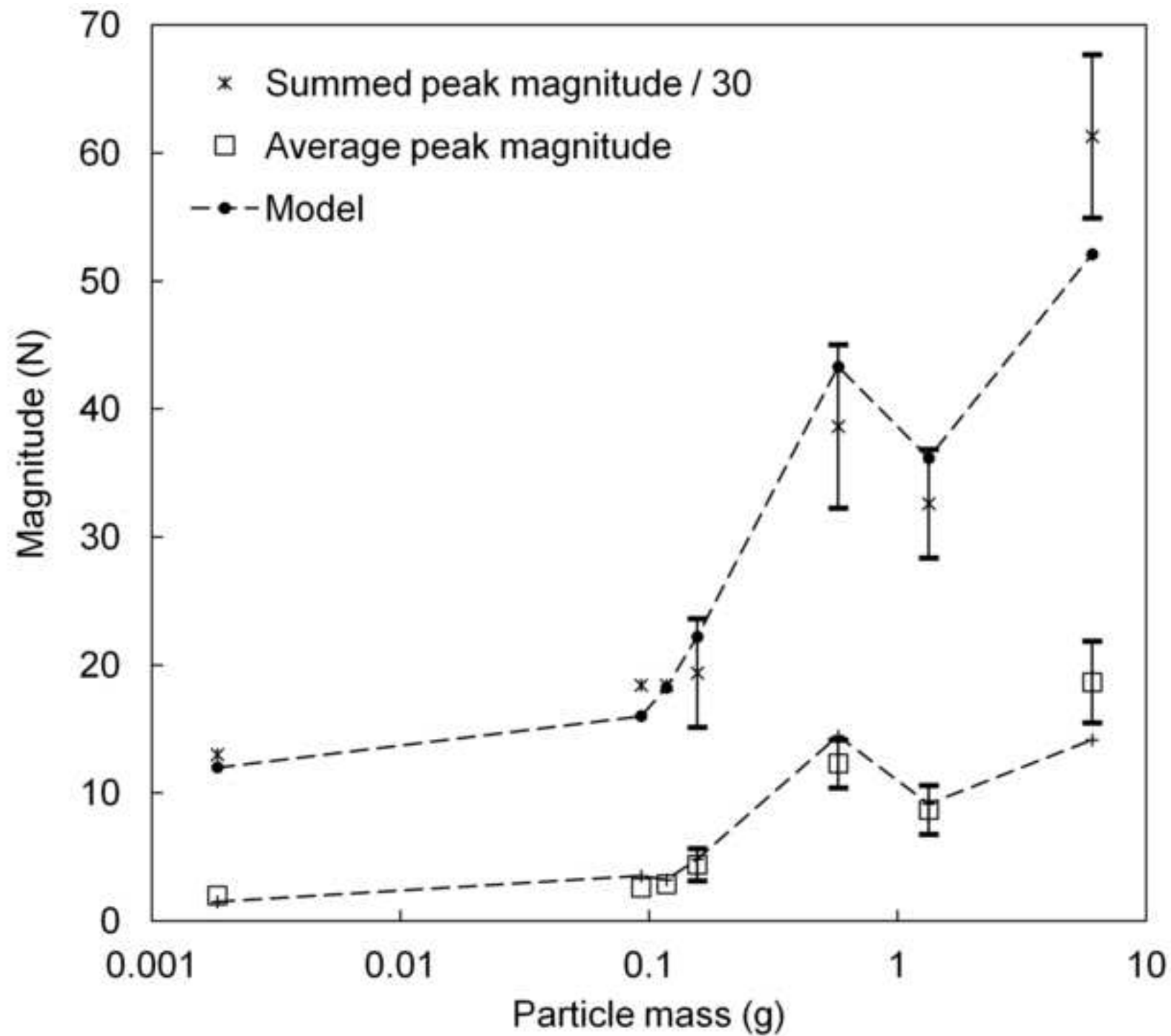
Figure 18

Figure 19

$y = 37.79x^{0.33}$

Legend:
◇ Laboratory experiment (see figure 18)
□ Model of ACC-E on Titan ($\mu = 0.4$)
△ Model of ACC-E on Titan ($\mu = 0.0$)

X-axis: Particle mass (g)
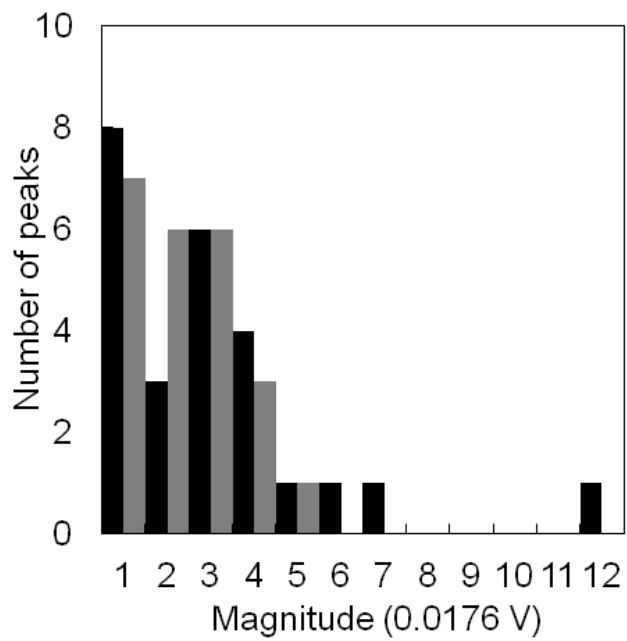Y-axis: Average peak magnitude (N)
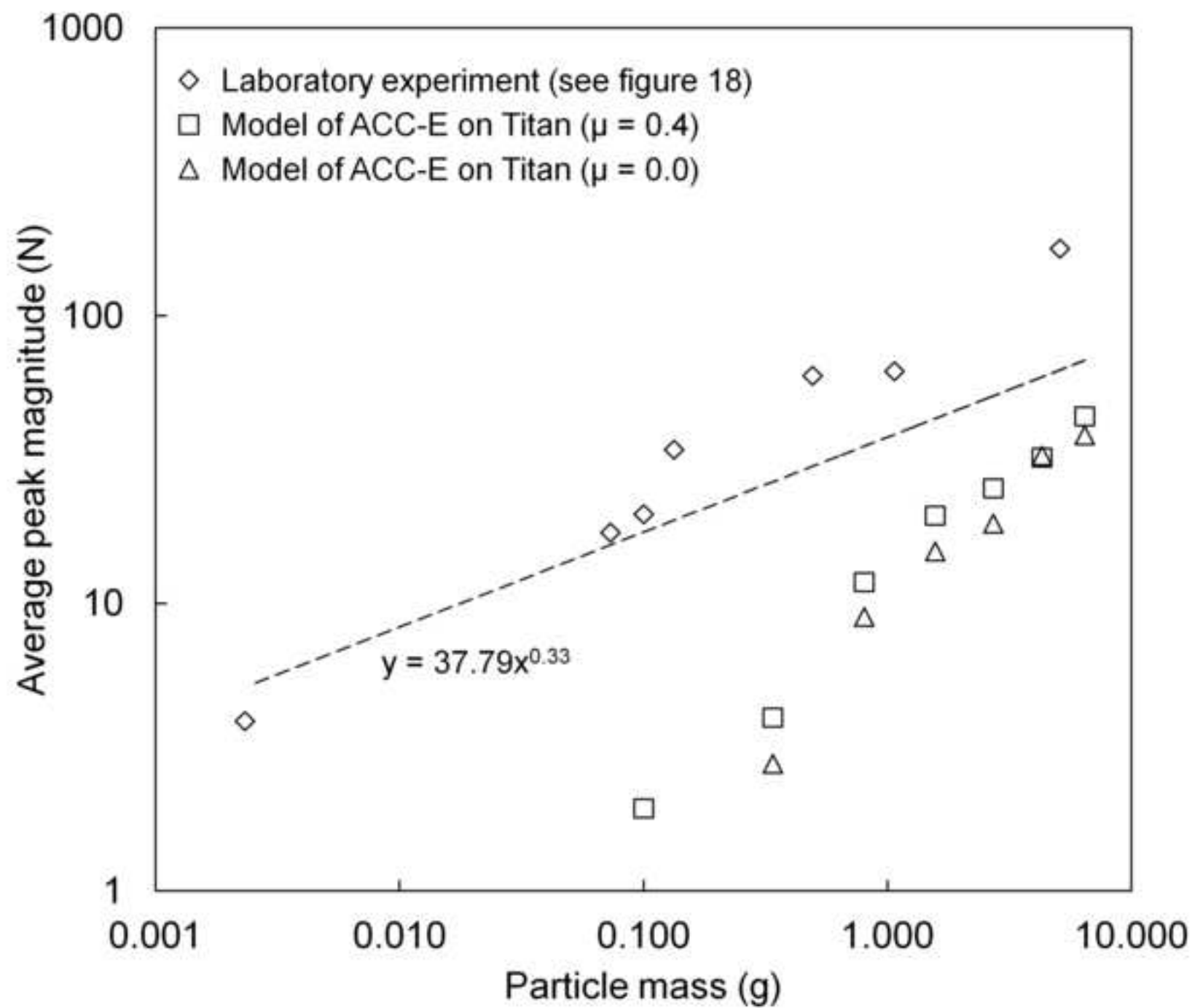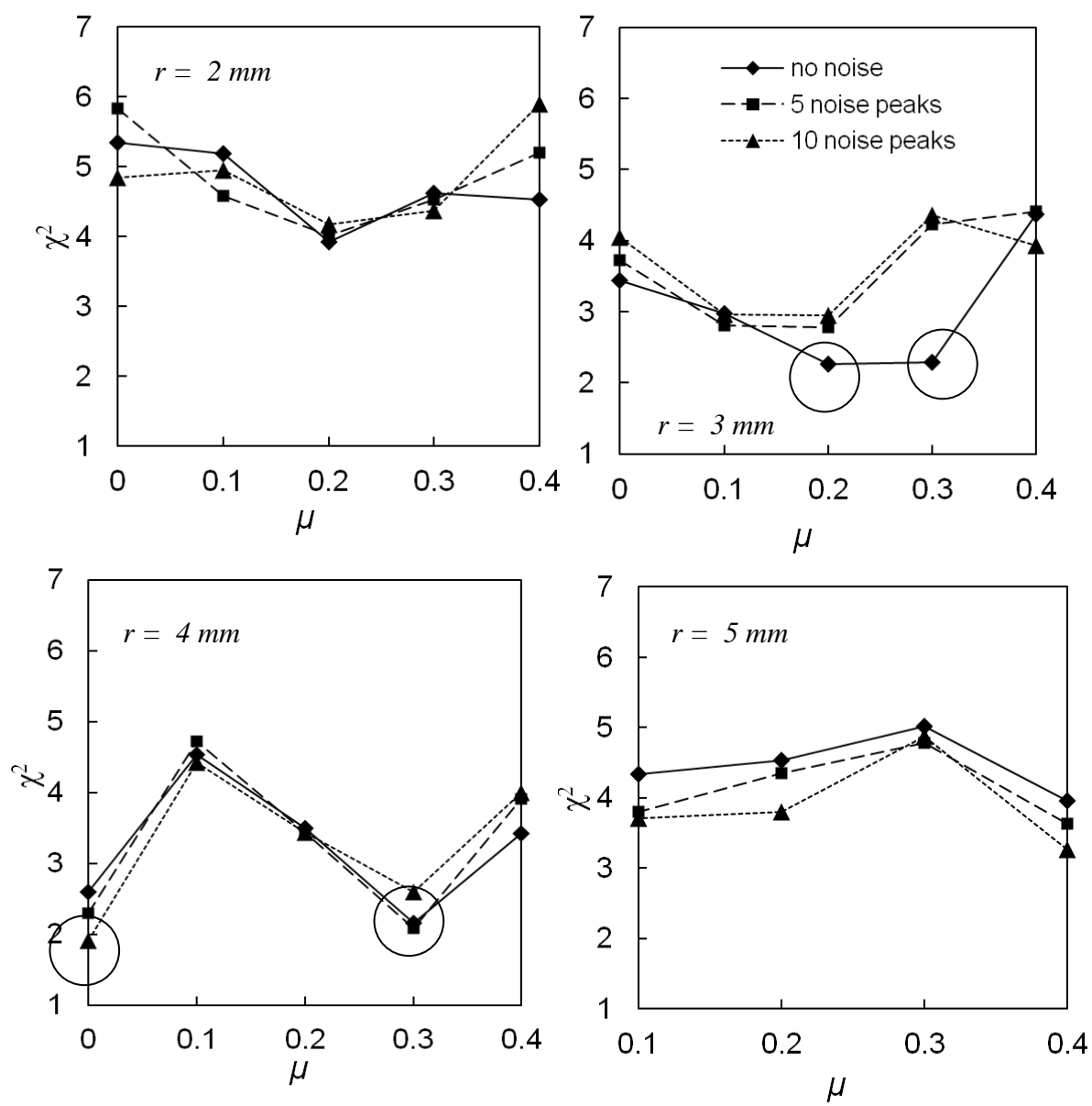
Figure 20

Figure 21
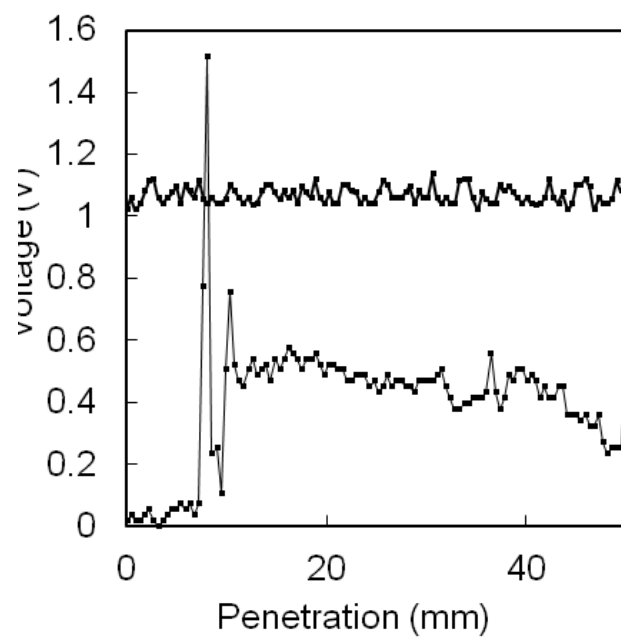
Table 1

Table 1 List of parameter values used for the model of ACC-E

Penetrometer / sensor	
Tip radius (mm)	8
Density (kg m^{-2})	8000
Elasticity of sensor (N m^{-2})	10^8
Damping constant	1000
Thickness of Vespel washers (mm)	2
Elasticity of Titanium tip surface (N m^{-2})	120×10^9
Poisson's ratio for Titanium	0.33
Velocity (m s^{-2})	5
Penetration depth (cm)	5
ADC bit resolution (V)	0.02
Sampling rate (s)	10^{-5}
Number of noise peaks per second	10^4
Magnitude of noise peak (V)	0.02
Target	
Particle radius (mm)	1-14
Particle density (kg m^{-2})	3000
Particle-tip coefficient of friction	0.4
Elasticity of particles (N m^{-2})	53×10^9
Poisson's ratio for particles	0.25
Numerical details	
Time step (s)	10^{-7}

Table 2

Table 2 Sensitivity of data peak metrics on model parameters.

	Washer Elasticity		Penetrometer Velocity		Bit resolution		Sampling freq.		Interparticle impacts		Bit-flip noise		Friction coeff.	
	10^{-9} N m^{-2}	10^{-7} N m^{-2}	7 m s^{-1}	3 m s^{-1}	0.04 V	0.01 V	100 kHz	10 kHz	14	1	50	150	0.1	0.4
Number of peaks	+	+	-	+	-		+	+	+	+	+	+ >10^3	+	
	-	-	-	-	+		-	-	+	+	+	+		
Average peak height	+	+	+	+		+	+	-	+	-	-	-	+	+
	-	-	-	-	-		-	-	+	-	-	-	+	+
Average peak width	+	+	+	-	-	-	+	+	-	-	-	-	+	+
	-	-	+	+	+	+	-	-	-	-	-	-	+	+
Summed peak height	+	+	+	+		+	+	+	+	+	+	+	+	+
	-	-	-	-	-		-	-	+	+	+	+	+	+
Summed peak width	-	+	+	-	-	-	+	+	+	-	-	-	+	+
	-	-	-	-	+	+	-	-	+	+	-	-	+	+

Table 3

Table 3 Measured material properties, r is the average radius, σ is the standard deviation of the distribution of particle radii, ρ is the bulk density of the target measured in the laboratory, P is the porosity calculated from the known solid density (2.7 kg m^{-3} for gravel and 2.5 kg m^{-3} for the sili-beads) and Ψ is the average sphericity calculated from laboratory measurements (the one sigma deviation is ~0.1 for all materials).

Material	A	B	C	D	E	F	G
Type	S-beads	Gravel	S-beads	Pebble	Cobble	Cobble	Cobble
r / mm	0.57	1.81	2.0	2.21	3.38	4.45	7.43
σ / r	-	0.19	-	0.18	0.16	0.14	0.14
ρ / g cm^{-3}	1.74	1.85	1.74	1.85	1.67	1.56	1.56
P	0.30	0.26	0.30	0.26	0.33	0.37	0.37
Ψ	1.00	0.60	1.00	0.63	0.68	0.65	0.63