Memorandum

ITASCA
Consulting Group, Inc.

Date: March 16, 2017

To: PFC 5 Documentation Set

From: David Potyondy

Re: Material-Modeling Support in PFC [fistPkg25] (Example Materials 3)

Ref: ICG7766-L

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TABLE OF CONTENTS

1.0 EXAMPLE MATERIALS

The PFC 5.0 FISHTank produces linear, contact-bonded, parallel-bonded, flat-jointed and user-defined materials. Examples for each material are provided in the Example Materials memos. Each example serves as a base case, and provides a material at the lowest resolution sufficient to demonstrate system behavior. There is a material-genesis project for each material, and these projects are in the **`fistPkgN/ExampleProjects/MatGen-M`** directory, where **`N`** is the version number of the PFC 5.0 FISHTank, and **`M`** is the material type. There are separate 2D and 3D projects for each material, and both projects are contained within the same example-project directory. An example for the user-defined material is provided in the following subsection.[1]

[1] The microstructural arrangement and stress-strain curves obtained with the current FISHTank may vary slightly from those shown here, which may have been generated by an earlier version of the FISHTank.

1.1 User-Defined Material Example

The user-defined material example is in the **`MatGen-Hill`** example-project directory. A hill material is created to represent a typical aggregate base layer of an asphalt-surface roadway (Potyondy et al., 2016).[2] We denote our aggregate material as the AG_Hill material with microproperties listed in Table 1. The material is dry while being created in a cylindrical material vessel (of 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 1. The material is then subjected to triaxial testing. The material is tested dry and wet. The wet material has a 20 kPa suction added between all grains that are within 3 mm of one another at the end of material genesis.[3] During each triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient moduli of the dry and wet materials (see Figures 2 and 3).[4] The hysteretic response is the expected behavior, and the resilient modulus is increased for the wet material.

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[2] A hill material is defined as a granular assembly in which the hill contact model exists at all grain-grain contacts. The hill material behaves like an unsaturated granular material, and the grain-grain system behaves like two elastic spheres that may have a liquid bridge — refer to Potyondy (2016) for a comprehensive description of the model. The hill contact model is referred to in commands and FISH by the name **`hill`**, and is provided as a dynamic link library (DLL) file that is loaded into *PFC3D* at runtime. The DLL file is named **`contactmodelmechanical3dhill005_64.dll`**. The DLL file is produced using the C++ Plug-in feature of PFC3D 5.0. The hill contact model is loaded into PFC3D at runtime by the command {**`load contactmodelmechanical hill`**}, which assumes that the DLL file is located in the directory {**`PFC500\exe64\plugins\contactmodelmechanical3D`**} where **`PFC500`** is the installation location. The version number of the hill contact model is given by the command {**`list contact modellist`**} and listed in the "Minor" column.

[3] The suction is typical for aggregates with gravimetric moisture content ranging from 5 to 10 percent.

[4] The confinement is similar to that defined in resilient modulus laboratory protocols, and axial strains correspond with vertical strains in the aggregate base layer for typical traffic loads.

Table 1 Microproperties of AG_Hill Material*

Property	Value
Common group:	
N_m	AG_Hill
$\{T_m, N_{cm}\},\ \alpha,\ C_\rho,\ \rho_v\,[\mathrm{kg/m^3}]$	$\{4,\mathrm{hill}\},\ 0.7,\ 0,\ 2650$
$S_g,\ T_{SD},\ \{D_{\{l,u\}}\,[\mathrm{mm}],\ \phi\},\ D_{mult}$	$0,\ 0,\ \{14,20,1.0\},\ 1.0$
Packing group:	
$S_{RN},\ P_m\,[\mathrm{kPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$	$10000,\ 150,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$
$C_p,\ n_c,\ \mu_{CA},\ v_{\lim}\,[\mathrm{m/s}]$	$0,\ 0.58,\ 0,\ 1.0$
Hill material group:	
$E_g\,[\mathrm{GPa}],\ \nu_g,\ \mu,\ \alpha_h,\ \psi\,[\mathrm{kPa}]$	$29,\ 0.15,\ 0.4,\ 0,\ 20$

* Hill material parameters are defined in Table 2 of Potyondy (2016).

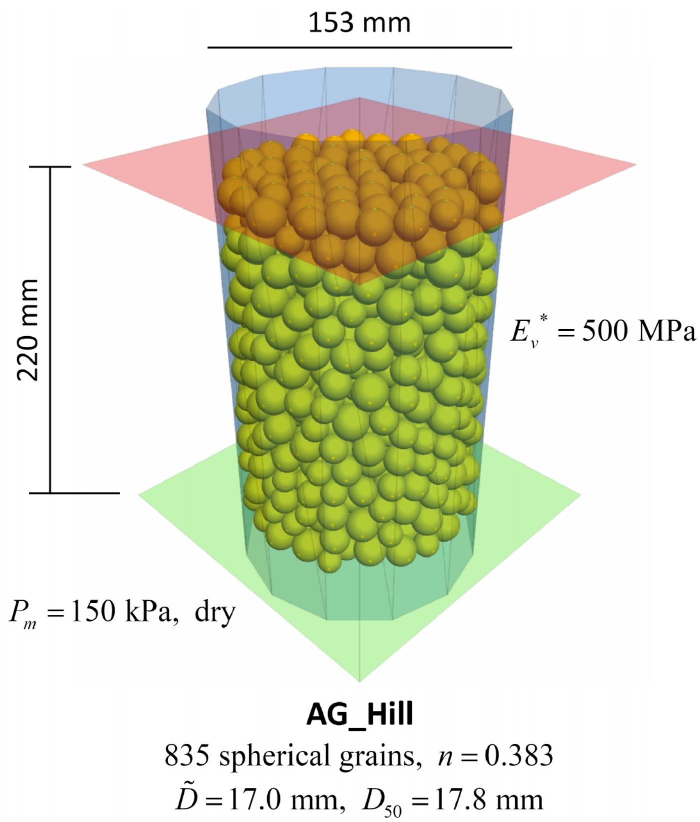

Figure 1 Dry AG_Hill material packed at 150 kPa material pressure at the end of material genesis.

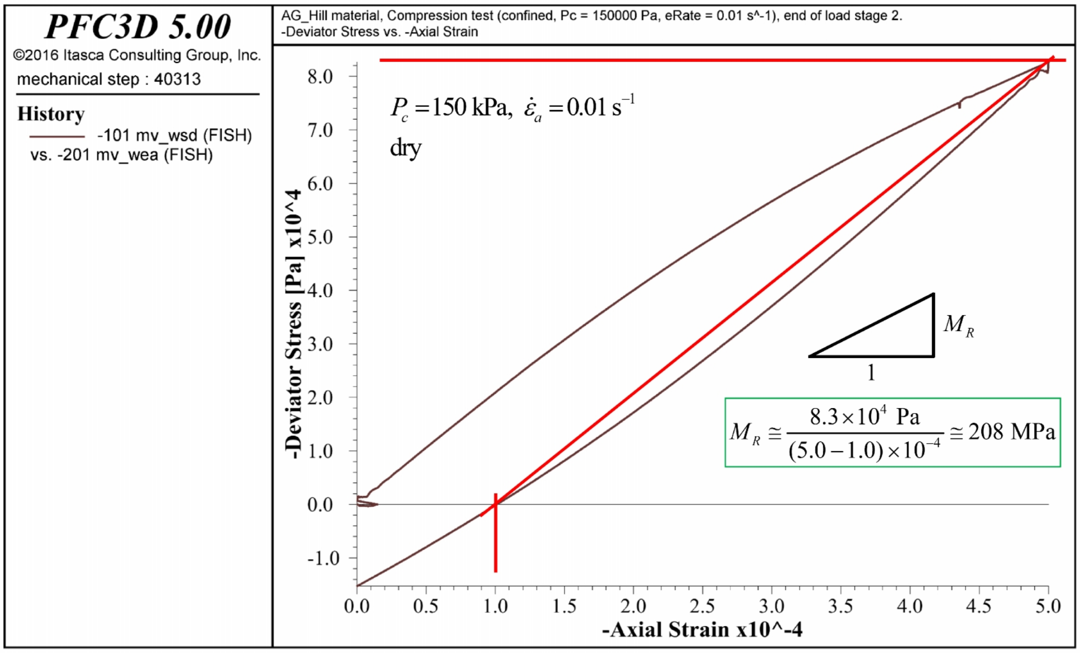

Figure 2 ***Deviator stress versus axial strain for dry AG_Hill material tested at 150 kPa confinement, and measurement of resilient modulus.***

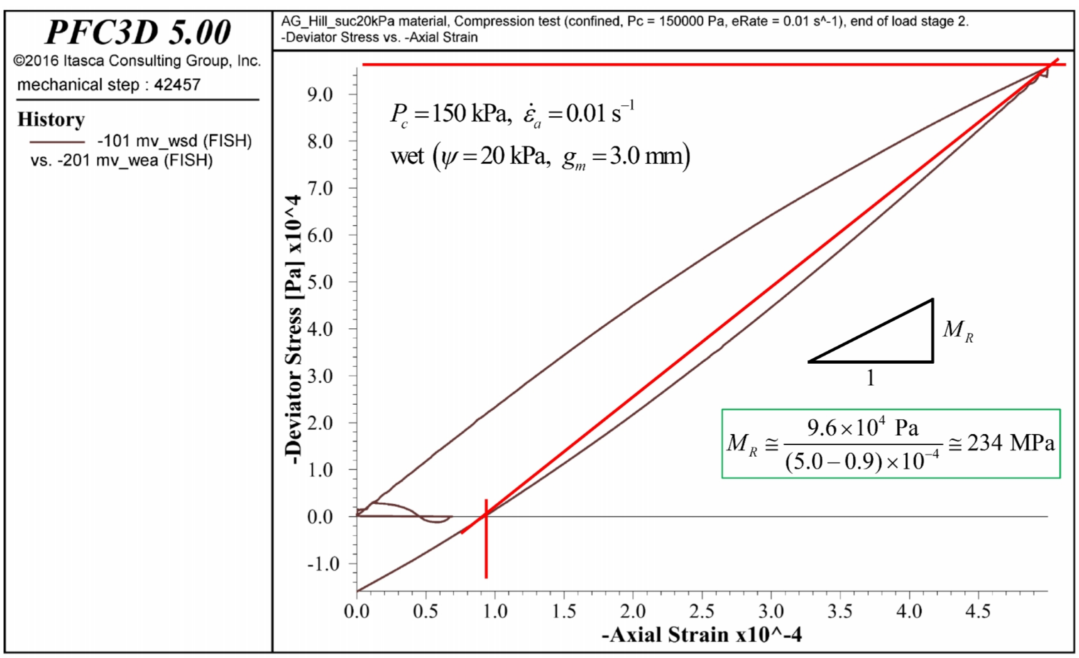

Figure 3 ***Deviator stress versus axial strain for wet AG_Hill material tested at 150 kPa confinement, and measurement of resilient modulus.***

The user-defined material example is modified to replace the spherical grains with clumped grains by replacing the call to **`mpParams.p3dat`** in **`MatGen.p3dvr`** with a call to **`mpParams-Clumped.p3dat`**. The new material is denoted as a hill clumped material with microproperties listed in Table 2. The clumped material has two grain shapes. The first shape is a dyad consisting of two spherical pebbles, and the second shape is a peanut consisting of three spherical pebbles. The clumped grains are drawn from a uniform size distribution with diameters ranging from 14 to 20 mm, and with 75% of the grains being dyads and 25% of the grains being peanuts. The diameter of each clumped grain is the diameter of a sphere with the same volume as the grain. The material-creation and testing procedures for the clumped material are the same as those for the AG_Hill material.

The clumped material is dry while being created in a cylindrical material vessel (of 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 4. The porosity of the clumped material (0.337) is less than that of the spherical material (0.383) — the dyads and peanuts have packed to a denser state than the spheres. The clumped material is then subjected to triaxial testing. The material is tested dry and wet. The wet material has a 20 kPa suction added between all grains that are within 3 mm of one another at the end of material genesis. During each triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient moduli of the dry and wet materials (see Figures 5 and 6). The hysteretic response is the expected behavior, and the resilient modulus is increased for the wet material. The clumped material is stiffer (370 and 407 MPa) than the spherical material (208 and 234 MPa), with increased stiffness attributed to reduced porosity.

Table 2 Microproperties of AG_Hill Clumped Material*

Property	Value
Common group:	
N_m	AG_Hill [clumped]
$\{T_m, N_{cm}\},\ \alpha,\ C_\rho,\ \rho_v\ [\text{kg/m}^3]$	$\{4, \text{hill}\},\ 0.7,\ 0,\ 2650$
$S_g,\ n_{SD},\ T_{SD},\ \{N_{ct},\ D_{\{l,u\}}\ [\text{mm}],\ \phi\},\ D_{mult}$	$1,\ 2,\ 0,\ \left\{\begin{matrix}\text{dyad}, & 14, 20, 0.75 \\ \text{peanut}, & 14, 20, 0.25\end{matrix}\right\},\ 1.0$
Packing group:	
$S_{RN},\ P_m\ [\text{kPa}],\ \varepsilon_P,\ \varepsilon_{\lim},\ n_{\lim}$	$10000,\ 150,\ 1\times10^{-2},\ 8\times10^{-3},\ 2\times10^{6}$
$C_p,\ n_c,\ \mu_{CA},\ v_{\lim}\ [\text{m/s}]$	$0,\ 0.43,\ 0,\ 1.0$
Hill material group:	
$E_g\ [\text{GPa}],\ \nu_g,\ \mu,\ \alpha_h,\ \psi\ [\text{kPa}]$	$29,\ 0.15,\ 0.4,\ 0,\ 20$

* Hill material parameters are defined in Table 2 of Potyondy (2016).

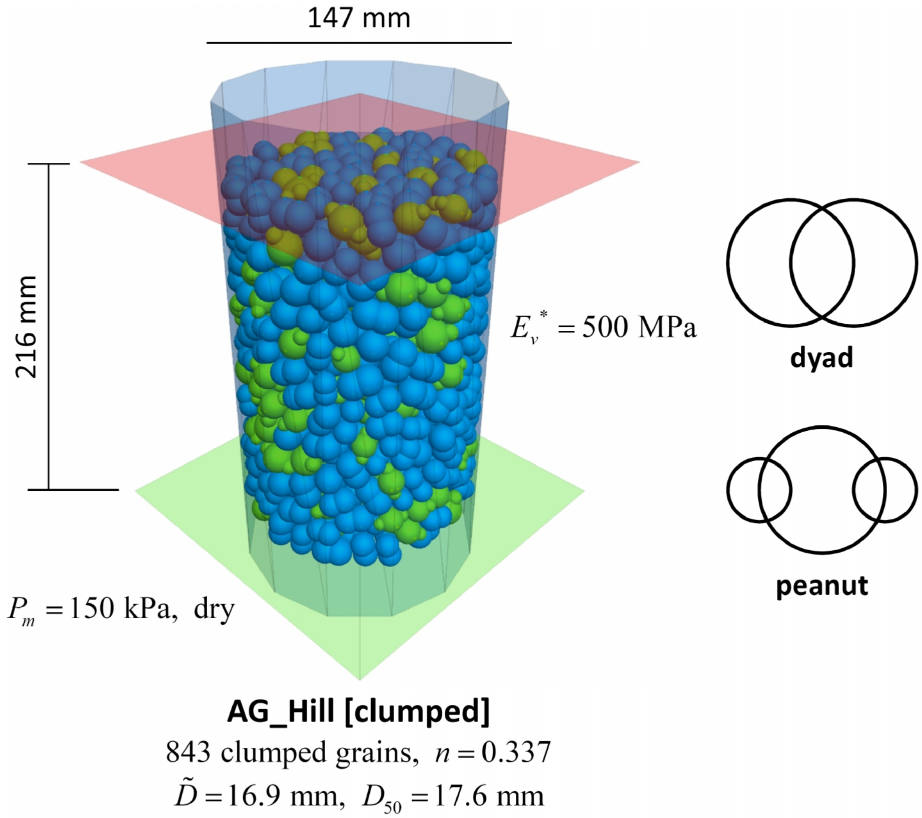

Figure 4 Dry AG_Hill clumped material packed at 150 kPa material pressure at the end of material genesis.

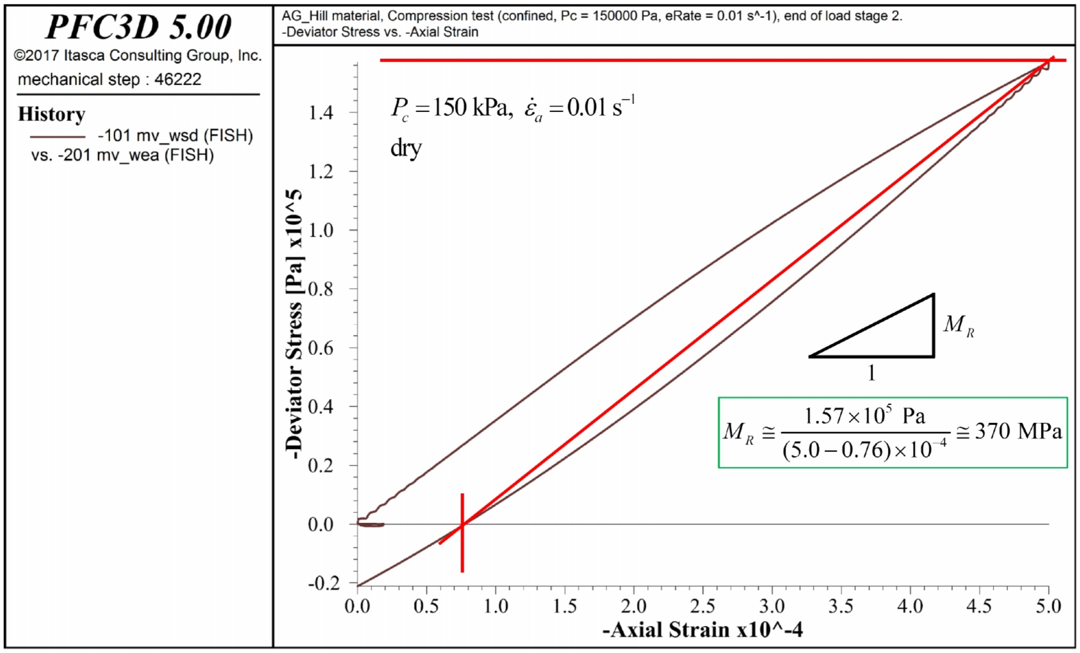

Figure 5 Deviator stress versus axial strain for dry AG_Hill clumped material tested at 150 kPa confinement, and measurement of resilient modulus.

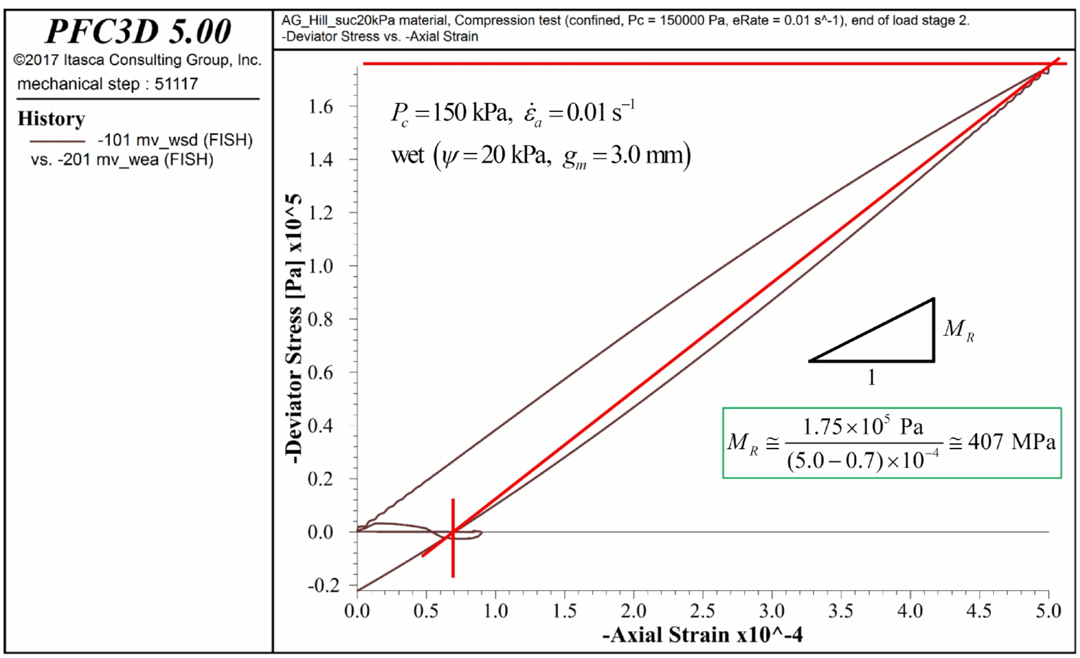

Figure 6 Deviator stress versus axial strain for wet AG_Hill clumped material tested at 150 kPa confinement, and measurement of resilient modulus.