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EARTHQUAKES AND PEBBLE BED REACTORS: TIME-DEPENDENT DENSIFICATION

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ABSTRACT

The neutronics behavior of a pebble bed reactor depends on the packing fraction of the pebbles. During the course of an earthquake, the packing fraction could increase because of the shaking of the reactor. In the absence of thermal feedback, the effective neutron multiplication constant (k_{eff}) could increase and hence create a criticality issue that needs to be examined. This paper presents the first half of such an examination: the densification of the pebble bed is modeled and quantified. A discrete element method-based recently developed code is used to simulate the position of pebbles over the course of an earthquake. The code is used to calculate the evolution of the packing fraction during the earthquake. The methodology was applied to modeling the evolution of the packing fraction for the entire course of the earthquake for a PBMR-400 reactor model hypothetically sited at the Idaho National Laboratory.

Key Words: pebble bed reactors, earthquake modeling

1. INTRODUCTION

The Pebble Bed Reactor is fueled with spherical elements that are distributed randomly throughout the core region. These spherical elements, or pebbles, can be packed in a variety of random arrangements [1], which in turn can affect the neutronics behavior of the reactor. One of the most important variables is determining the neutronic behavior is the packing fraction, which translates into an effective fuel density. During normal operation, the packing fraction will only vary slowly, over the course of weeks and then it stabilizes. During an earthquake, this packing fraction can increase suddenly. The PEBBLES code, recently developed at the Idaho National Laboratory (INL), can simulate this increase and determine the rate of change and the expected final packing fraction, thus allowing the effect of an earthquake to be simulated.

2. PURPOSE OF MODELING EARTHQUAKES

In an earthquake, the packing fraction of a pebble bed reactor is expected to increase. Loosely packed materials will settle and become more densely packed when they are subject to vibration. With a pebble bed reactor in an earthquake, the increase in densification from the shaking of the earthquake will cause the effective neutron multiplication constant (k_{eff}) to increase. In a previous study, in absence of thermal feedback, a postulated packing fraction increase from 0.60 to 0.64 caused k_{eff} to increase by 0.019 for a simulated reactor [1]. For a uranium fueled reactor, per that early bounding study, the thermal feedback was expected to offset this increase. In that previous study, the movement of the fuel was not simulated, thus, because of the lack of a model the packing fraction increase was estimated based on the concept of maximally random jammed states. A worst time for increasing the packing fraction was estimated from the free-fall time. The packing fraction increase was bounded by using the maximally random jammed state of 0.64 packing fraction mentioned above as well as the maximum theoretically possible packing fraction of 0.74%, which corresponds to a face-centered cubic crystalline lattice. Depending on both the rate of densification (since faster rates allow less time for thermal feedback) and the total increase of the packing fraction (since greater increases cause greater increases in k_{eff}) the reactor might be put into a highly supercritical condition in absence of an active emergency shutdown system. Thus, the estimation of the rate of densification and of the total density increase is necessary to determining whether the reactor is passively safe against the earthquake threat.

The determination of the rate and increase in density could be approximated by experiment using a shake table, and indeed this is necessary for the validation of any computer model. However, currently obtainable experimental data lack important features that are possible with a computer simulation. An experiment for calculating the total packing fraction can be performed by continually measuring the height of the top pebbles in a vat; however, the determination of the locations of all the pebbles in a physical experiment at all times of interest is difficult. In contrast, with the PEBBLES code, the positions of all the pebbles at any given time are known; therefore, the packing fractions can be calculated for different radii, heights and at different angles around the reactor core. Since different regions of the reactor differ in importance with respect to the behavior of the reactor, the ability to determine the packing fraction at different locations provides a better ability to perform reactor simulations. Therefore, the ability to simulate the motion and packing densification of the pebbles via computer modeling is vital to the determination of passive safety.

3. MOVEMENT CAUSED BY EARTHQUAKES

The movement of earthquakes has been well studied in the past. The magnitude of the motion of earthquakes is described by the Mercalli scale, which describes the maximum acceleration that a given earthquake will impart to structures. For a Mercalli X earthquake, the maximum acceleration is about 1 g. The more familiar Richter scale measures the total energy release of an earthquake [2], which is not useful for determining the effect on a pebble bed core. For a given location, the soil properties can be measured, and using soil data and the motion that the bedrock will undergo, the motion on the surface can be simulated. The INL site had this information generated in order to determine the motion from the worst earthquake that could be expected over a 10,000 years period [3]. This earthquake has roughly a Mercalli IX intensity. The data for such a 10,000 year earthquake are used for the simulation in this paper.

4. METHOD OF SIMULATION

The earthquake data were generated using the pebble mechanics simulation code PEBBLES [4]. The PEBBLES code, based on the discrete element method, is used for simulating the motion of pebbles in a pebble bed reactor. The code simulates the position and velocity of each pebble in the reactor core. The forces included in the simulation are the weight of the pebble, a normal elastic contact force between pairs of touching neighboring pebbles (i.e., a force calculated according to Hooke's law), static friction, and velocity-related tangential (dynamic friction) and normal damping forces. The external forces applied to the pebbles cause accelerations and torques. The accelerations and torques are then used to determine the linear and angular velocities that arise from them. The time derivatives that are used for these determinations are

$$\frac{d\mathbf{v}_i}{dt} = \frac{m_i\mathbf{g} + \mathbf{F}_{ci} + \sum_{i \neq j} \mathbf{F}_{ij}}{m_i} \quad , \tag{1}$$

$$\frac{d\mathbf{p}_i}{dt} = \mathbf{v}_i \quad , \tag{2}$$

and

$$\frac{d\boldsymbol{\omega}_i}{dt} = \frac{\sum_{i \neq j} \mathbf{F}_{\perp ij} \times r_i \hat{\mathbf{n}}_{ij}}{I_i} \quad , \tag{3}$$

where $\mathbf{v}_i$ is the velocity of pebble *i*, $\mathbf{p}_i$ is the position of pebble *i*, and $\boldsymbol{\omega}_i$ its angular velocity. $\mathbf{F}_{ij}$ is the total force on pebble i from pebble j, $\mathbf{F}_{\perp ij}$ is the tangential force on pebble *i* exerted by pebble *j* and $\mathbf{F}_{ci}$ is the force of the container wall on pebble *i*. The remaining variables, referring to pebble *i*, are the mass m_i, the radius r_i, the moment of inertia I_i, the normalized vector $\hat{\mathbf{n}}_{ij}$ pointing from the position of pebble *i* to that of pebble *j*, and $\mathbf{g}$, the gravitational acceleration. In the earthquake simulation, the walls of the reactor are displaced with time, thus affecting the force of the wall on the pebbles, $\mathbf{F}_{ci}$. This displacement of the walls causes the pebbles to move as they would with a real earthquake.

The displacement in the simulation can be specified either as the sum of sine waves, or as a table of displacements that specifies the x, y, and z displacements for each time. At each time step both the displacement and the velocity of the displacement are calculated. When the displacement is calculated by a sum of sine functions, the displacement is calculated by adding vector direction for each wave and the velocity is calculated from the sum of the first derivative of all the waves. When the displacement is calculated from a table of data, the current displacement is a linear interpolation of the two nearest data points in the table, and the velocity is the slope between them. The walls are then assigned the appropriate computed displacement and velocity. Figure 1 shows the total displacement for the INL earthquake simulation specifications that were used in this paper.

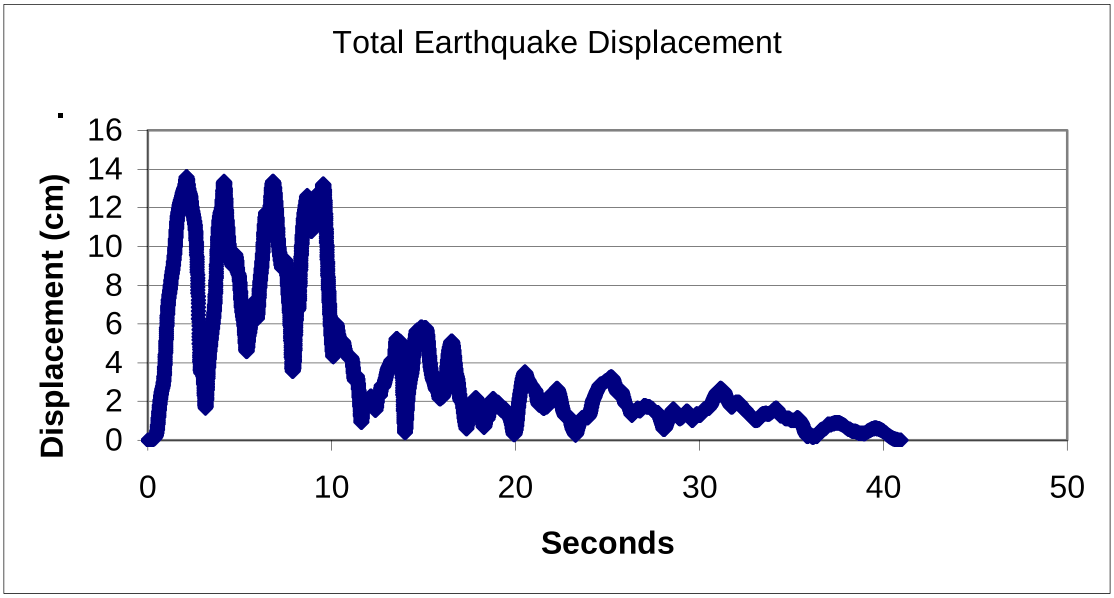

Figure 1 Total Earthquake Displacement

5. RESULTS

The results of the simulation carried out here show a substantially safer behavior than that implied by the previous bounding calculations [1]. The methodology was applied to a model of the HTR-10 reactor (an experimental reactor built in China), using data for the INL 30,000 year earthquake. In this example, the packing fraction increases from 0.590 to 0.610 over the course of the 41 seconds duration of the earthquake. The fastest increase rate was from 0.586 to 0.592 early in the earthquake simulation and took 0.7 seconds. For the PBMR-400 model (PBMR-400 is the new reactor that is to be built in South Africa), the total increase is from 0.615 to 0.626 over the course of the earthquake, and the fastest increase is from 0.613 to 0.621, and takes place over 2.5 seconds in the earthquake (the packing fraction can temporarily be higher or lower than the extrema if the earthquake is actively causing compaction by ground rising or expansion by ground falling). The largest total increase is 0.02 starting from a relatively loose pack and the fastest packing fraction increase rate is 0.0086 sec^{-1}. This is remarkably small when compared to the bounding calculation packing fraction increase rate of 0.129 sec^{-1}. Both computed increases and packing fraction change rates are substantially below the free fall bounding rate and packing fraction change of a transition from 0.60 to 0.64 in 0.31 seconds. The computed rate and the total packing fraction increase are in the range that can be offset by thermal feedback effects for uranium fueled reactors.

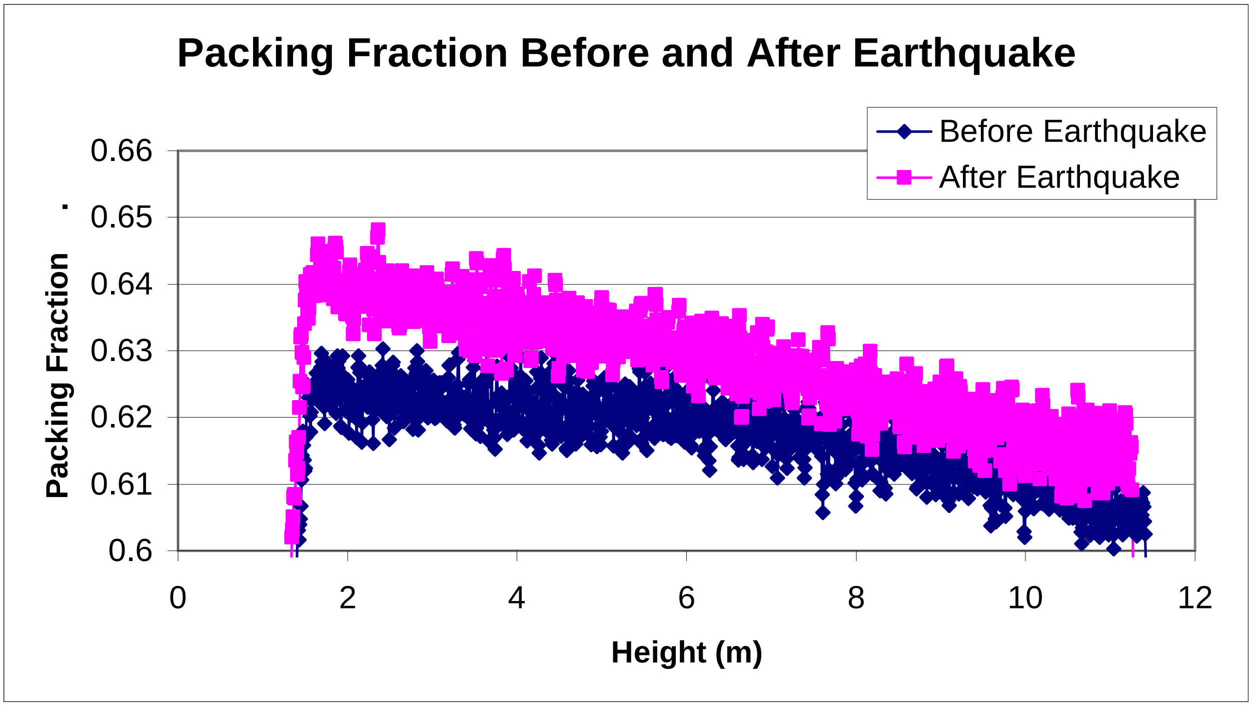

Figure 2 Before and After Earthquake Packing Fraction

The simulation also showed a unique behavior that tends to lessen the effect of the packing shifts. In pebble bed reactors, the top of the reactor tends to have higher activity because the fuel is fresher and less hot (i.e., cooler) in the top portion. However, for the PBMR-400 model, the bottom portion of the reactor had both faster increases in packing fraction and more increases in packing fraction. As Figure 2 shows, the bottom packing fraction of the reactor increases from 0.625 to 0.64. The top fraction increased from 0.605 to 0.615. The basic mechanism causing this difference is that the bottom tends to absorb some of the motion of the earthquake so the upper region of the reactor undergoes less vibration. Figure 3 shows this effect over the course of the earthquake with different regions in the model ranging from 2 to 3 meters above the core outlet chute to 10 to 11 meters above it. Logically, if the packing fraction increases, then there must be some damping effect on other portions of the reactor because the region that increases in packing fraction is absorbing some of the motion. This effect tends to lessen the effect of the earthquake on the overall reactor neutronic behavior.

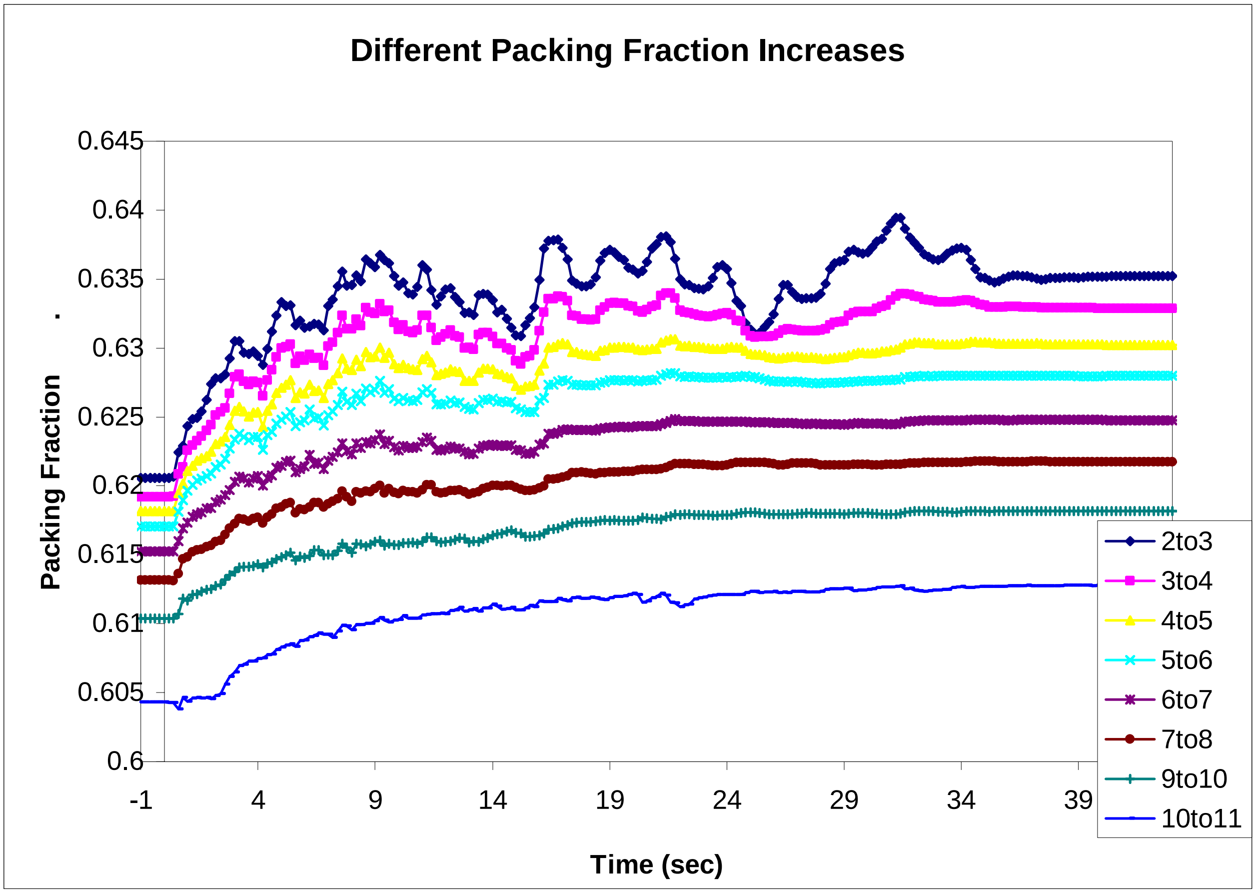

Figure 3 Differential Packing Fractions

During the course of the earthquake, the boundary density fluctuations (that is the oscillations in packing fraction near a boundary) are observed to increase in amplitude. Figure 4 shows the packing fraction before the earthquake and after the earthquake in the radial direction. These were taken from 4 to 8 meters above the fuel outlet chute in the PBMR-400 model. All the radial locations have increased packing compared to the packing fraction before the earthquake, but the points that are at boundary density fluctuation peaks increase the most. This effect can be seen in Figure 5, which shows the increase in packing fraction before the earthquake and after.

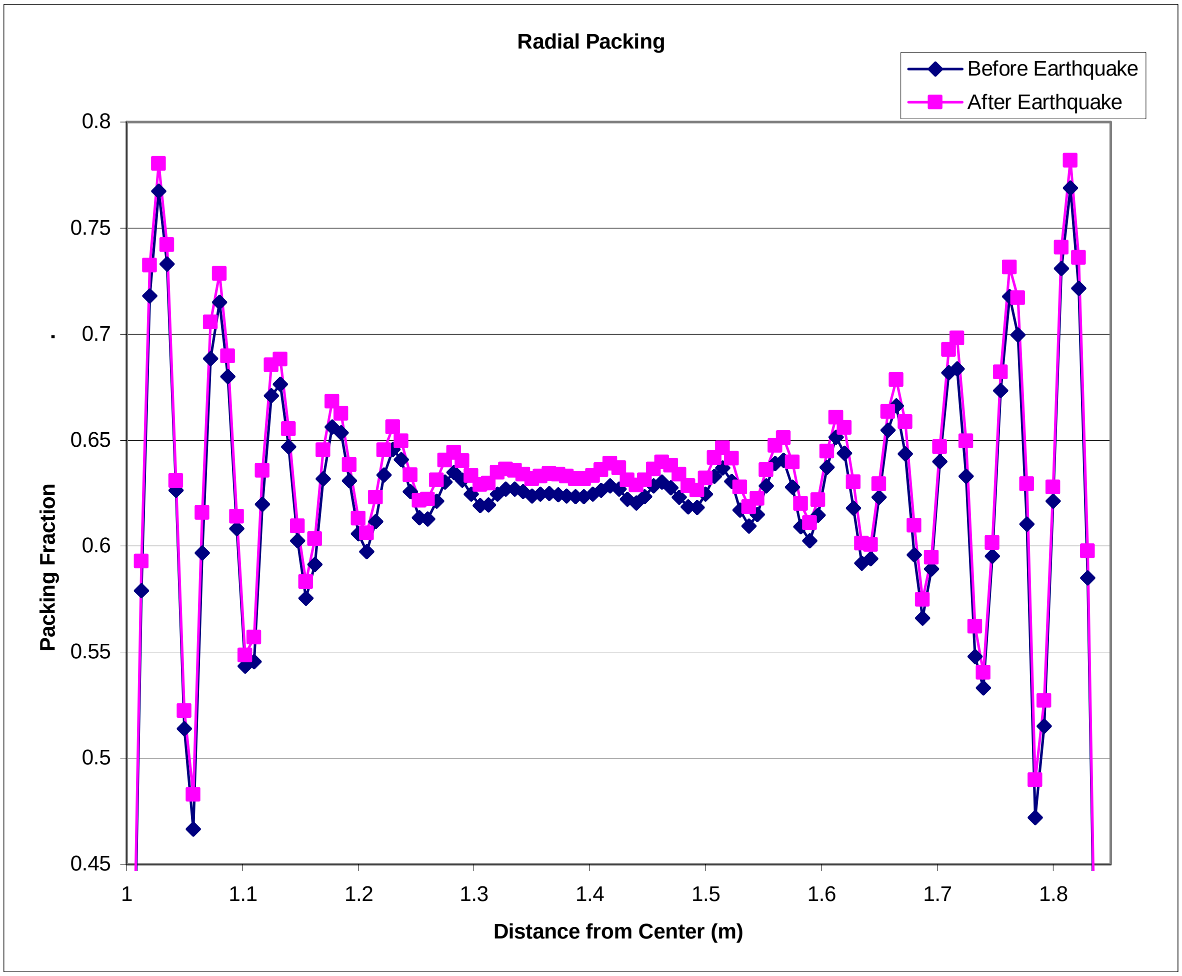

Figure 4 Radial Packing Before and After Earthquake

In the PEBBLES code, the packing fraction increase is only weakly sensitive to the values used for the static and dynamic friction factors. Both static and dynamic friction coefficients are functions of both the temperature of the graphite and of the composition of the gas around the pebbles. Therefore, if the packing increase were determined experimentally to be highly sensitive to these features, the code would need to be coupled with thermal hydraulics and neutronics codes to provide more realistic results. The same earthquake definition applied to the PBMR-400 model was run with a 0.35 static friction coefficient and a 0.25 kinetic friction coefficient. With this input, the packing fraction from 2 to 10 meters started at 0.6187 and increased to 0.6273 for a difference of 0.0086. This is about 20% less than the simulation with a 0.65 static friction factor and a 0.4 kinetic friction factor used in the rest of the paper, and for which packing started at 0.6152 and increased to 0.6258 for a total increase of 0.0106. The increase was larger with the higher static friction factor because the lower static friction had a higher initial packing fraction to start with. Due to the weak sensitivity of the packing fraction increase to friction coefficients, a fully coupled module incorporating all the effects should show similar packing fraction results, and may therefore not be needed for licensing purposes.

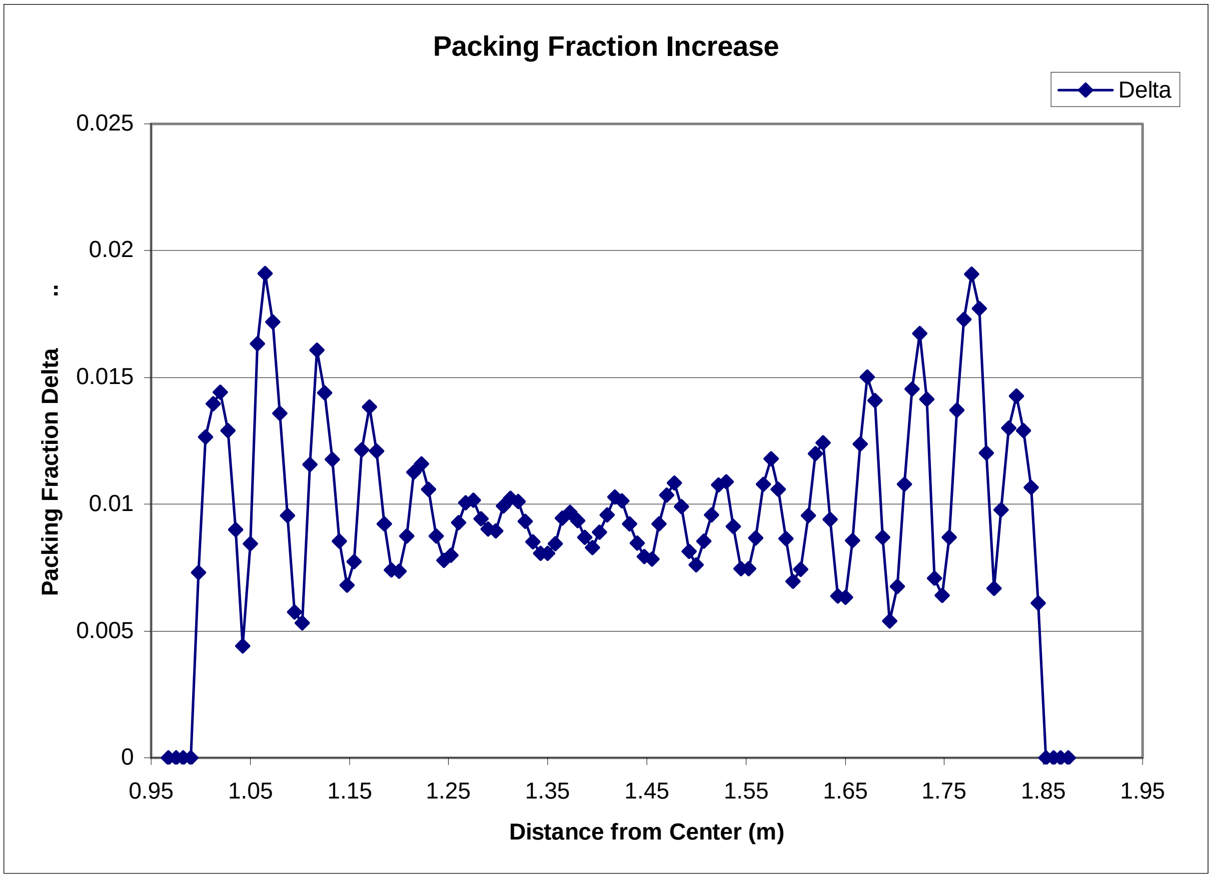

Figure 5 Dif ference in Radial Packing Fraction

6. FUTURE WORK

In the future, the PEBBLES pebble mechanics code will need to be coupled with a thermal hydraulics code and with a neutronics code, to determine the total effect of an earthquake on the reactor. However, in light of the finding that the results are substantially insensitive to the friction factors, it is safe to assume that this coupling will be loose only, with data from the PEBBLES code passed to a coupled neutronics-thermal-hydraulics code. The feeding of packing fraction changes data to a neutronics code with thermal-hydraulics feedback will among other things produce temperature profiles that depart from the initial steady-state ones. These new temperatures will have to be taken into consideration in further PEBBLES modeling (through changes in the friction coefficients) in order to determine whether the assumption of adequacy of loose coupling is indeed valid. In addition to the above application, the PEBBLES code will need to be further verified and validated against actual data densification from shaking table experiments.

7. CONCLUSION

The increase of the packing fraction of the pebbles in a pebble bed reactor that occurs with an earthquake can be simulated with the PEBBLES code. This increase is both a slower and smaller total increase then shown by the previous bounding calculations [1] and is within the range where thermal feedback effects can offset the increase in k_{eff} that bed densification causes.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. A.M. Ougouag, W.K. Terry, "A Preliminary Study Of The Effect Of Shifts In Packing Fraction On K-Effective In Pebble-Bed Reactors", *Proc. M&C 2001*, Salt Lake City, Utah, USA, September 2001, on CD-ROM, (2001)
2. J.R. Lamarsh, *Introduction to Nuclear Engineering 2nd Ed.*, pp. 591-593, Addison-Wesley Publishing Company, Reading, Massaschusetts, (1983)
3. S. J. Payne, "Development of Design Basis Earthquake (DBE) Parameters for Moderate and High Hazard Facilities at TRA," INEEL/EXT-03-00942, http://www.inl.gov/technicalpublications/Documents/2906939.pdf (2003).
4. J. J. Cogliati, A. M. Ougouag, "Pebbles: A Computer Code For Modeling Packing, Flow And Re-Circulation Of Pebbles In A Pebble Bed Reactor" *Proc. of High Temperature Reactor Technology*, Sandton, South Africa, October 1-4 2006, on CD-ROM (2006).