The paper was published in the proceedings of the 17th African Regional Conference on Soil Mechanics and Geotechnical Engineering and was edited by Prof. Sw Jacobsz. The conference was held in Cape Town, South Africa, on October 07-09 2019.

Discrete element modelling of shear forces in soil behind integral bridge abutments

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ABSTRACT: An integral bridge is constructed without joints between the superstructure and substructure. This reduces the maintenance costs over the life of the bridge. However, since there are no joints present, the bridge can be viewed as a single structural element. This means that when the deck moves as a result of a temperature variation and the abutment moves relative to the backfill soil which it retains. In this study, the Discrete Element Method was used to model the soil behind an integral bridge abutment exposed to such thermal loading. Different particle shapes were modelled to study the effect of particle shape on the inter-particle shear forces in the backfill soil. It was found that the magnitude of these shear forces was linearly related to the sphericity of the particles modelled. Particles with lower sphericities (less smooth) experienced larger shear forces between them. It was also found that the shear forces between the particles decreased as the soil was cyclically loaded. Particles with higher sphericities experienced larger reductions of inter-particle shear forces as the number of cycles increased. The results suggest that, in order to limit the shear stresses within the soil, particles with higher sphericities should be used as backfill behind integral bridge abutments.

1 INTRODUCTION

The design of integral bridges excludes the use of bearings or expansion joints between the deck and the piers and abutments. The structure can therefore be viewed as monolithic. This is done to remove the maintenance and repair costs associated with these joints and bearings. A problem that arises as a result of the lack of these members is related to the thermal expansion and contraction of the deck of the bridge. When the bridge deck expands as a result of an outside temperature increase, the deck forces the abutment to move towards the backfill soil it retains. Similarly, when the temperature decreases, the deck contracts and the abutment move away from the soil. Therefore, due to daily and seasonal temperature variations, the backfill soil is exposed to a cyclical loading as the abutment moves relative to it (Clayton et al. 2006). In this study, the Discrete Element Method (DEM) was used to study the effect of particle shape on the inter-particle shear forces between backfill soil particles retained by integral bridge abutments, exposed to this cyclical thermal loading.

2 BACKGROUND

2.1 *Integral bridges*

Conventional bridges make use of expansion joints and bearings to accommodate for the relative movement between the substructure and the superstructure. This relative movement exists since the piers and abutments are only marginally sensitive to changes in air temperature and therefore remain spatially fixed, whereas the deck expands and contracts with daily and seasonal temperature variations (Clayton et al. 2006).

The joints and bearings used in conventional bridges are expensive to purchase, install, repair and maintain and are known to have relatively short lifespans. Replacing these members may result in traffic disruptions or cost implications. Failing to replace or maintain the joints or bearings when necessary may result in increased longitudinal deck loading and therefore could cause overstressing and damage to the weaker bridge components (Xu et al. 2007).

Integral bridges are designed to eliminate the problems associated with expansion joints and bearings. The deck and the abutments of integral bridges can be viewed as a single structural unit, since there are no joints or bearings between them. The use of integral bridges simplifies the construction process, reduces maintenance costs, removes the cost of movement joints and bearings, as well as provides greater earthquake resistance (Biddle et al. 1997).

One of the major problems with integral bridges arises from the temperature variations experienced by the deck. Since there is an integral connection between the abutments and the superstructure, the abutments are forced to move relative to the backfill soil retained by them. The abutments move away from the soil when the deck contracts as a result of a temperature decrease and move towards the soil when the bridge expands as a result of a temperature increase. Therefore, the soil retained by the abutments is exposed to a temperature-induced cyclic loading (Xu et al. 2007).

2.2 *Discrete element modelling*

The Discrete Element Method (DEM), proposed by Cundall & Strack (1979), is a popular computational method which can be used to analyse, design and optimise bulk systems which contain granular materials of varying shapes. The method is performed by solving for forces, accelerations and displacements of individual particles. The particles are defined in terms of geometry and stiffness. The forces on the particles are found using a force-displacement law. These resulting forces are then substituted into Newton's second law to obtain the accelerations. The accelerations are then used with equations of motion to solve for the displacements of the particles. The Discrete Element Method is an example of cycling through a force-displacement law and the laws of motion.

The accuracy of the predictions of DEM simulations are largely dependent on the input parameters of the particles modelled. The input parameters required for DEM simulations include, however are not limited to, the particle-particle friction coefficient, particle-wall friction coefficient, the normal and tangential restitution coefficients, the type of contact model used as well as the Young's Modulus of the particles. These parameters are typically obtained by means of calibration tests (Coetzee 2016).

Another important aspect to be considered in DEM simulations is the type of particle shape approximation. Traditionally, particle shapes are approximated using single spheres or sphere-clumps. However, previous work has shown that using spherical particles may not necessarily provide an accurate representation for all types of particle shapes, as these shapes may not achieve the angular edges as required for certain granular materials. It is therefore recommended to model the shapes closer to their actual geometry, instead of using spheres to approximate the shape. However, this is known to drastically increase the computational costs for traditional, commercial DEM packages (Höhner et al. 2012, Govender et al. 2016).

3 BLAZE-DEM

Blaze-DEM, developed at the University of Pretoria by Govender (2015), is a Graphics Processing Unit (GPU) based DEM package which offers elevated computational performance levels for the simulation of spherical particles, as well as convex and non-convex polyhedra. The package makes use of the GPU as opposed to most commercial DEM packages, which traditionally make use of the Central Processing Unit (CPU) for performing the simulations.

Blaze-DEM exploits the difference in hardware designs between the CPU and GPU to obtain the elevated levels of performance. A major difference between the two processors is the number of cores and threads present. A core in a CPU refers to physical hardware which can be multithreaded, i.e. concurrently split into virtual threads capable of performing separate operations. The closest equivalent to a core in a GPU is the Streaming Multi-Processor (SM) (Govender et al. 2014).

The cores in CPUs are designed to be used for complex logical operations such as running an operating system, while still being able to perform arithmetical operations. GPUs, however, are designed to render graphics, which involves the simultaneous operation of potentially millions of pixels. This requires many parallel algebraic operations and therefore aids applications which require numerous parallel arithmetic operations. The computations performed in a DEM simulation can be viewed as a collection of these parallel arithmetic operations, which greatly benefits the computational efficiency of Blaze-DEM (Govender et al. 2014).

Since Blaze-DEM is currently a research code, numerous validation tests on the results it produces have been performed. These validation tests included DEM simulations of mill charge and hopper discharge tests for a number of spheres, as well as convex polyhedra. The results were compared to results obtained from experimental data as well as that obtained from CPU based DEM packages. The results obtained from Blaze-DEM were well in line with the experimental data and commercial DEM packages results (Govender et al. 2015, 2016 & 2018).

Further validations were performed by comparing the results obtained from Blaze-DEM to those obtained from the commercial code STAR-CCM+ by Siemens PLM (2017). The comparison involved analysing the lateral earth pressure coefficients and bulk densities of 90 000 cubic particles exposed to cyclic loading. It was found that the results were similar for both sets of simulations, with Blaze-DEM performing simulations 29 times faster. Blaze-DEM also has the option of performing simulations without a live graphics output, i.e. without displaying the DEM particles while the simulation is being performed. Previous tests have shown that this can further reduce the computational time 5-fold (Ravjee et al. 2018).

4 DEM MODELLING

4.1 *Integral bridge modelling*

To represent the backfill behind an integral bridge abutment, a hypothetical 30 m long bridge with 2 m high abutments was modelled for this study (Figure 1). A 350 mm high, 300 mm wide and 150 mm deep model space was used for the DEM simulations representing only the top portion of the backfill soil adjacent to the abutment, as this enabled the number of particles required in the simulations to be considerably reduced. All four sides, as well as the bottom of the model, were modelled as rough, rigid interfaces.

The abutment was rotated about its base 25 times in the active and passive directions to represent the thermal expansion and contraction of the deck. A rotation angle of 0.154° and a rotation rate of 0.154°/s (0.5 Hz) was used in the DEM analyses. The angle was calculated based on a linear thermal coefficient of expansion of 12 x 10^{-6} °C^{-1} for the concrete deck and a maximum effective deck temperature variation of 30°C. The rotation rate was obtained from previous work used to determine a rate slow enough not to induce inertial effects (Ravjee et al. 2018).

Before the abutment was rotated, the DEM particles were injected into the model space in a regular grid pattern from the top of the container. The particles were injected with an initial downward velocity of 5 cm/s and velocities of 1 cm/s in the in-plane directions of the grid. These in-plane velocities were applied to randomly distribute the particles within the container.

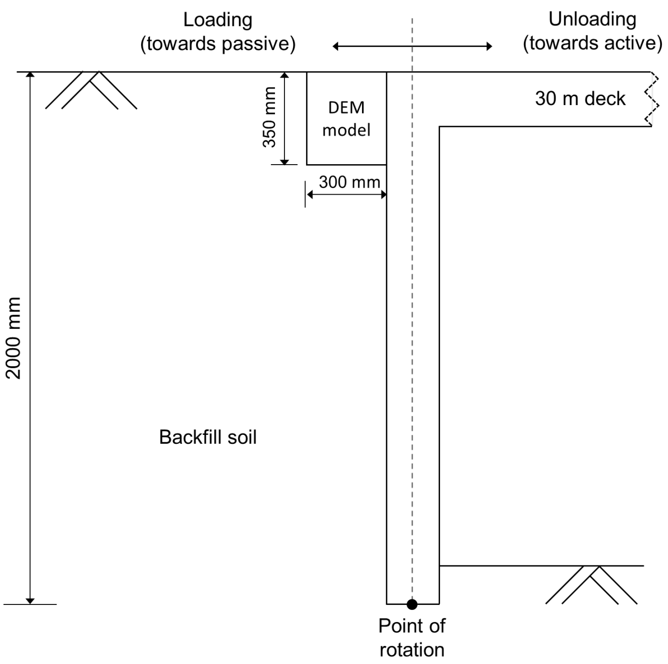

Figure 1. Model integral bridge deck and abutment

4.2 *DEM particle modelling*

A total of four particle shapes were modelled to study the effect of particle sphericity on the inter-particle shear forces in backfill soil retained by integral bridge abutments. These shapes, illustrated in Figure 2, were spheres, dodecahedrons, tetrahedrons and truncated tetrahedrons. The number of particles per shape were as follows:

- 140 000 spheres;
- 110 000 dodecahedrons;
- 100 000 truncated tetrahedrons; and
- 100 000 tetrahedrons.

The particle shapes were classified according to their sphericities. The definition of particle sphericity, proposed by Wadell (1935), is a measure of how closely the shape of a particle approaches that of a mathematically perfect sphere and was found to be a convenient parameter for this study. The sphericities, summarised in Figure 3, for the four particle shapes were calculated using Equation 1 as follows:

$$\psi = \frac{\pi^{\frac{1}{3}}(6V_p)^{\frac{2}{3}}}{A_p} \quad (1)$$

where ψ = sphericity of a particle shape, V_p = volume of a particle shape $[m^3]$ and A_p = surface area of a particle shape $[m^2]$.

A number of the material parameters used for the DEM particles were obtained from previous, similar work. A particle density of 2 650 kg/m^3 and a particle-wall friction coefficient of 0.70 was obtained from Xu et al. (2007). The linear spring-dashpot model (Coetzee 2017) was used for the simulations, which meant that normal and tangential restitution coefficients were required. Restitution coefficients of 0.50 and 0.60 were used for the normal and tangential directions respectively and a particle-particle friction coefficient of 0.45 was used for each of the four particle shapes considered in this study, similar to work performed by Coetzee (2016).

To reduce the computational times of DEM simulations, it is recommended to use the largest possible time-step, such that particle behaviour remains stable. Results from previous work showed that a value of 1 x 10^{-5} seconds was the largest possible time-step which could be used, with the chosen rotation rate, without causing unpredictable particle behaviour, and was therefore used for all simulations (Ravjee et al. 2018).

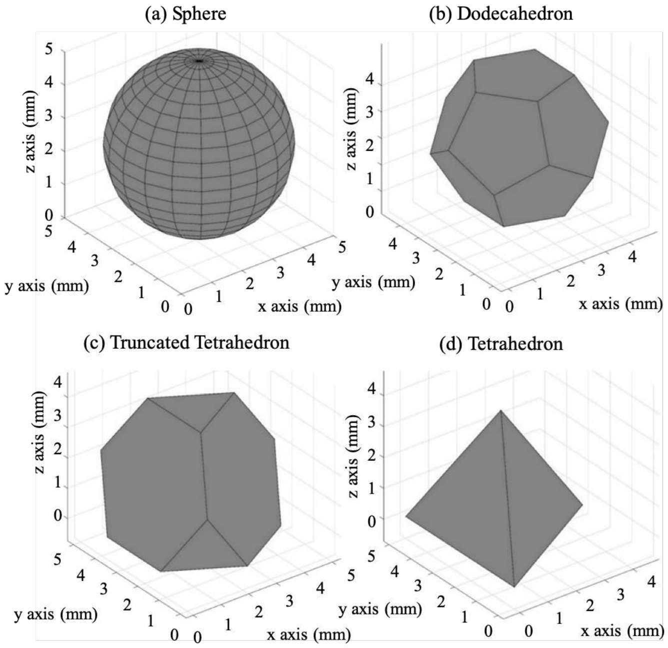

Figure 2. DEM particle shapes modelled

It is common practice to reduce the Young's Modulus of DEM particles to reduce the computational costs of the simulations (Coetzee 2016). A Young's Modulus of 70 MPa was used in the simulations, i.e. a reduction factor of 1 000 to a theoretical stiffness of 70 GPa. This was done following a validation exercise which showed the performance of the DEM models using particles with Young's Modulus values ranging from 70 MPa to 70 GPa to be similar. The modulus reduction resulted in the computational efficiency increasing over 30-fold (Ravjee et al. 2018).

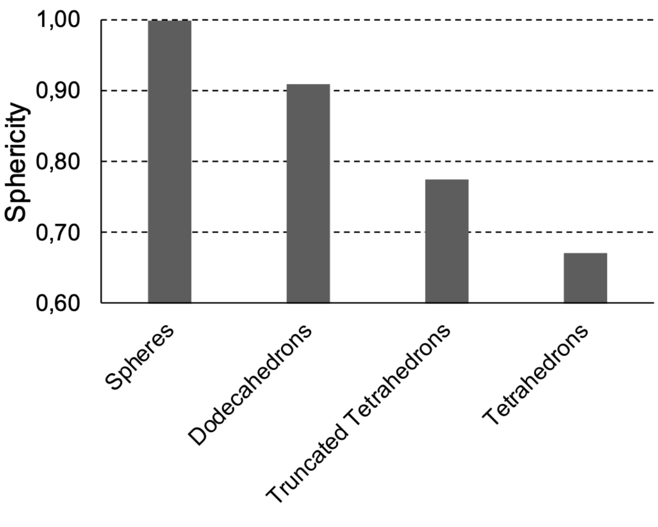

Figure 3. Particle sphericities

5 RESULTS OF DEM MODELLING

The inter-particle shear forces between the particles for the four different shapes were obtained from the DEM simulations. Figure 4 plots the number of particles subjected to various inter-particle shear forces for the different particle shapes for the first and last displacement cycles of the abutment. For this study, the average inter-particle shear forces for the entire DEM model space were considered for the different particle shapes and number of cycles.

The average inter-particle shear forces for the four particle shapes are presented in Figure 5 for the 25 cycles of the abutment. The figure illustrates that the shear forces in the backfill decreased as the number of cycles increased. Figure 6 depicts the average inter-particle shear forces plotted against the sphericities of the respective particles. A linear trendline, with a linear coefficient of correlation of 0.935, could be fitted for the four particle shapes suggesting that the inter-particle shear forces in the backfill soil are inversely proportional to the sphericity of the soil particle shape. Particles with higher sphericities, such as perfect spheres, produced lower average shear forces between them, whereas particles with lower sphericities (tetrahedrons) had higher average shear forces between the particles.

To study the effect of the cyclic displacement of the abutment, the percentage of reduction in average inter-particle forces for the particle shapes is shown in Figure 7. The reduction percentage was calculated from the first cycle of loading to the last (25th) cycle. The figure suggests that the reduction percentage of shear forces is linearly proportional to the particle sphericity. A coefficient of determination of 0.91 was obtained from the linear trendline fitted between the data. These results suggest that as the particle sphericity decreased, the percentage reduction of mobilised shear forces between the particles also decreased during cyclic displacement of the abutments.

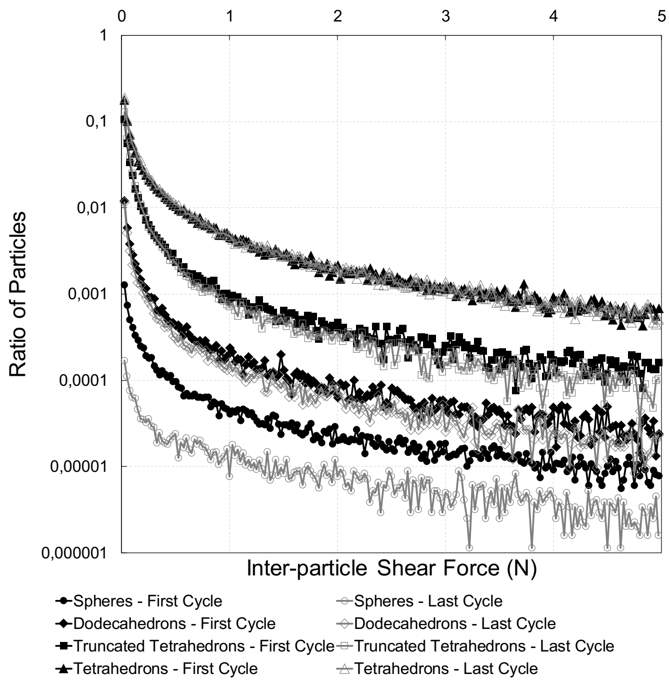

Figure 4. Inter-particle shear force histogram for first and last cycles of different particle shapes

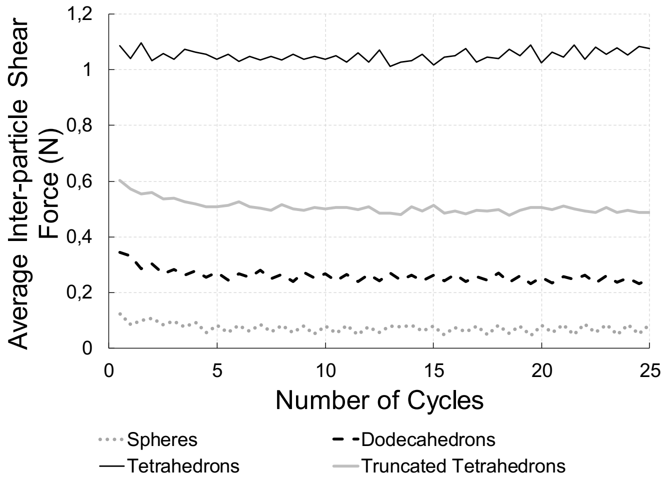

Figure 5. Average inter-particle shear forces for 25 cycles of the model abutment

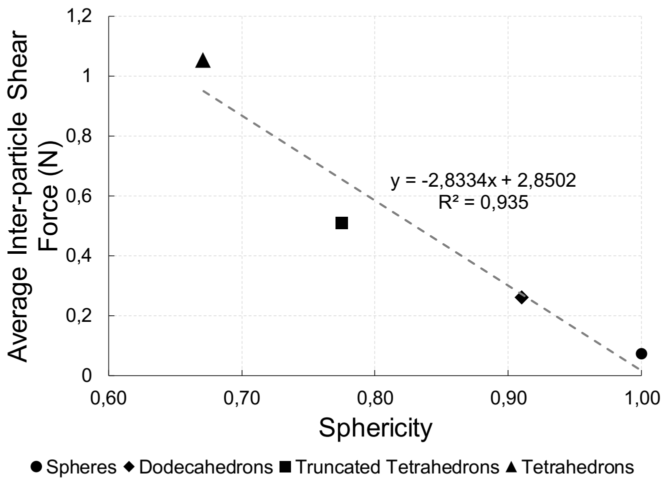

Figure 6. Average inter-particle shear forces after 25 cycles versus particle sphericity

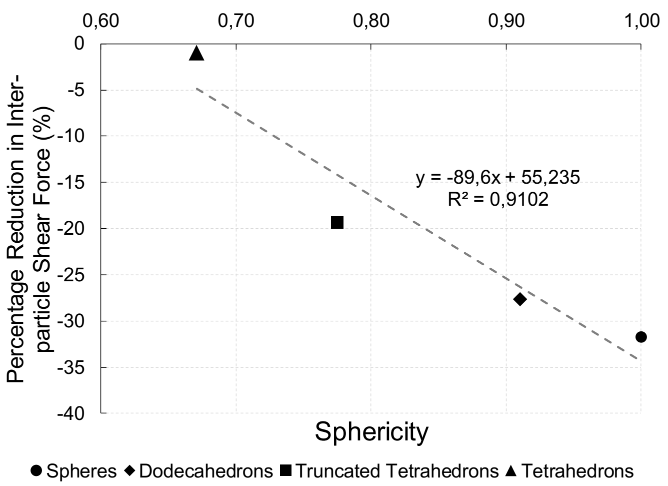

Figure 7. Effect of particle sphericity on percentage decrease in average inter-particle shear forces from first to last cycles

6 CONCLUSIONS

In this study, the discrete element method was used as implemented in a research code, Blaze-DEM, to study the effect of particle sphericity on the shear forces between the soil particles used as backfill material behind by integral bridge abutments. The backfill was subjected to cyclic thermal-induced displacements of a hypothetical, model integral bridge abutment. The particle shapes modelled included spheres dodecahedrons, tetrahedrons and truncated tetrahedrons.

The results from this study suggested that the magnitude of the shear forces between the particles was linearly related to the particles sphericity. Particles with higher sphericities had lower average shear force intensities than the more angular particle. It was also observed that the average inter-particle shear forces decreased as the number of cycles increased. However, the percentage reduction in shear force was also linearly related to the sphericity of the particle shapes. This magnitude of reduction in percentage of shear forces increased as the particle sphericity increased. These results suggest that particle shapes with higher sphericities should be used as backfill behind integral bridge abutments to limit the shear forces present within the soil. However, the results from this study suggest that, to limit the change in inter-particle shear forces within the backfill soil, particles with higher angularities should be used as backfill material.

7 RECOMMENDATIONS

Recommendations for future work include studying the inter-particle shear force distribution within the backfill soil. This will enable a better understanding of the shear stresses acting on the abutment. Further recommendations are to study other types of particle shapes, such as non-convex polyhedra, i.e. particle shapes with lower sphericities than those considered in this study.

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